LEATHER INDUSTRY WASTEWATERS: PERFORMANCE OF POLYMER-BASED HYBRID MATERIALS IN COAGULATION-FLOCCULATION AND SLUDGE REDUCTION

by

Begüm Uzluk

B.Sc. in Chemical Engineering, Istanbul Technical University, 2020

Submitted to the Institute of Environmental Sciences

in partial fulfillment of the requirements for the degree of

Master of Science

in

Environmental Technology

Boğaziçi University

2025

LEATHER INDUSTRY WASTEWATERS: PERFORMANCE OF POLYMER-BASED HYBRID MATERIALS IN COAGULATION-FLOCCULATION AND SLUDGE REDUCTION

APPROVED BY:

Prof. Dr. Ferhan Çeçen . . . . . .
Thesis Advisor

Prof. Dr. Neslihan Semerci . . . . . .

Assoc. Prof. Dr. Başak Güven . . . . . .

DATE OF APPROVAL: 28/11/2025

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisor, Prof. Dr. Ferhan Çeçen, for her invaluable guidance, continuous support, and encouragement throughout the course of this study. Her profound knowledge, insightful suggestions, and constructive feedback have been a constant source of inspiration and have significantly contributed to the successful completion of this work. I am also grateful for her patience and understanding, which motivated me to overcome challenges and maintain my determination during difficult stages of the research.

I am sincerely thankful to UZ-AR Group for granting me access to their laboratory and equipment, as well as for providing financial and technical support, which together made the completion of this research possible.

I also extend my gratitude to the Çorlu Leather Organized Industrial Zone Directorate (Çorlu Deri İhtisas ve Karma OSB Bölge Müdürlüğü) for kindly allowing me to collect wastewater samples. I am particularly grateful to the esteemed environmental engineers at the facility for their willingness to answer all my questions and for generously sharing their profound knowledge of the treatment system. I would also like to thank all the staff of the wastewater treatment laboratory for sharing their facilities with me and providing assistance whenever I needed support.

Finally, I would also like to acknowledge my father, Bülent Uzluk, General Manager of UZ-AR Group and a Chemical Engineer (M.Sc.), for his professional insights and support during this study. In addition, I am grateful to my mother, Lale Uzluk, also a Chemical Engineer (M.Sc.), for her valuable perspectives and encouragement. Above all, I am profoundly grateful to my beloved parents, whose unwavering support, both financially and emotionally, has sustained me throughout this journey. Their patience, encouragement, and love have been indispensable.

ABSTRACT

LEATHER INDUSTRY WASTEWATERS: PERFORMANCE OF POLYMER-BASED HYBRID MATERIALS IN COAGULATION-FLOCCULATION AND SLUDGE REDUCTION

Leather industry effluents are among the most challenging wastewater types, requiring treatment strategies that provide high pollutant removal with reduced chemical use and environmental impact. This study develops hybrid coagulants by combining inorganic coagulants with organic polymers such as polyDADMAC and polyamine, supported by PAM as a flocculation aid. Sixteen hybrid formulations were screened under six treatment scenarios (M1–M6) using twenty-two real wastewater samples collected during high- and low-activity periods at the Çorlu Organized Industrial Zone WWTP, one of Türkiye's tannery wastewater centers. The best-performing formulations were optimized and compared with the conventional 40% alum process, focusing on COD, TOC, TSS, heavy metals, and sludge characteristics. Phase-based jar tests enabled separate evaluation of liquid and solid phases, allowing more precise performance interpretation and mass balance assessment. Environmental performance was examined using an entropy-weighted TOPSIS approach incorporating sludge management, long-term robustness, chemical burden, and treatment efficiency. Biodegradability of the organic polymers was additionally evaluated using U.S. EPA BIOWIN predictions to assess their environmental persistence. Overall, hybrid coagulants significantly reduced dosage requirements and sludge production while maintaining high removal efficiencies even at natural pH. Although the polymers showed limited biodegradability, their low dosing minimized long-term concerns. The findings position hybrid coagulants as a technically effective and environmentally conscious alternative to conventional coagulation and highlight the importance of future research supported by life cycle assessments of polymer systems. The study also suggests that comparable or improved performance may be achieved with more biodegradable materials and broader testing across different industrial wastewater types.

ÖZET

DERİ ENDÜSTRİSİ ATIKSULARI: POLİMER BAZLI HİBRİT MALZEMELERİN KOAGÜLASYON-FLOKÜLASYON VE ÇAMUR AZALTMADAKİ PERFORMANSI

Deri endüstrisi atıksuları, yüksek kirletici yükleri ve değişken karakteristikleri nedeniyle arıtılması güç atıksu türleri arasında yer almakta olup bu durum, yüksek giderim sağlarken kimyasal tüketimini ve çevresel etkileri azaltan arıtma yaklaşımlarına olan ihtiyacı artırmaktadır. Bu çalışma, söz konusu ihtiyaca yanıt olarak, geleneksel inorganik koagülantların polyDADMAC ve poliamin gibi organik polimerlerle birleştirildiği ve PAM ile desteklendiği hibrit koagülant sistemlerine odaklanmaktadır. Bu sistemleri değişken işletme koşullarında değerlendirmek üzere, on altı hibrit koagülant formülasyonu altı arıtma senaryosu (M1–M6) kapsamında test edilmiş ve hem yüksek hem de düşük faaliyet dönemlerini temsil eden yirmi iki gerçek atıksu örneği Çorlu Deri Organize Sanayi Bölgesi Atıksu Arıtma Tesisi'nden temin edilmiştir. Tarama aşamasında en iyi performansı gösteren formülasyonların dozları optimize edilerek COD, TOC, TSS, ağır metaller ve çamur özelliklerinin incelendiği ileri değerlendirme aşamasında geleneksel %40 alum prosesiyle karşılaştırılmıştır. Bu aşamada uygulanan faz bazlı yaklaşım, sıvı ve katı fazların ayrı değerlendirilmesini sağlayarak performans analizinin daha hassas yürütülmesine ve kütle dengesi çalışmalarına olanak tanımıştır. Çevresel performans; çamur yönetimi, kimyasal yük, uzun dönem etkiler ve arıtma verimliliğini birlikte dikkate alan entropi ağırlıklı TOPSIS yöntemi ile incelenmiş; organik polimerlerin çevresel kalıcılığı ise U.S. EPA tarafından geliştirilen BIOWIN yazılımından elde edilen biyobozunurluk tahminleriyle desteklenmiştir. Sonuçlar, hibrit koagülantların geleneksel koagülasyona göre teknik açıdan etkili ve çevresel olarak daha duyarlı bir alternatif olduğunu göstermektedir. Çalışma ayrıca, polimer sistemlerine yönelik yaşam döngüsü değerlendirmeleriyle desteklenen ileri araştırmaların önemini vurgulamaktadır. Bunun yanında, daha biyobozunur bileşenlerle geliştirilecek hibrit sistemlerin ve bu sistemlerin farklı endüstriyel atıksularda geniş kapsamlı olarak test edilmesinin benzer veya daha yüksek performans sağlayabileceği ortaya konmaktadır.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS iii
ABSTRACT iv
ÖZET v
TABLE OF CONTENTS vi
LIST OF FIGURES x
LIST OF TABLES xiii
LIST OF SYMBOLS/ABBREVIATIONS xv
1. INTRODUCTION 1
1.1. Research Objectives 2
2. LITERATURE REVIEW 4
2.1. Leather Industry 4
2.1.1. Beamhouse Operations 6
2.1.2. Tanyard Operation 6
2.1.3. Post Tanning Process 7
2.1.4. Finishing Process 7
2.2. Leather Industry Wastewater 8
2.2.1. Leather Industry Wastewater Characterization 8
2.2.2. Leather Industry Wastewater Treatment Stages 9
2.2.2.1 Preliminary Treatment 10
2.2.2.2 Primary Treatment 11
2.2.2.3 Secondary Treatment 12
2.2.2.4 Tertiary Treatment 12
2.2.2.5 Sludge Handling and Disposal 13
2.3. Coagulation and Flocculation Processes 13
2.3.1. Coagulant Classification 14
2.3.1.1 Hydrolyzing Metallic Salts 15
2.3.1.2 Inorganic Polymeric Coagulants 15
2.3.1.3 Organic Polymeric Coagulants 15
2.3.1.4 Natural Coagulants 16
2.3.2. Hybrid Materials in Coagulation and Flocculation 16
2.3.2.1 Structurally Hybridized Materials (Composites) 16
2.3.2.2 Chemically Bound Hybridized Materials 17

2.3.2.3 Functionally Hybridized Materials 17
2.3.3. Biodegradability of Hybrid Coagulants in Wastewater Treatment 17
3. MATERIALS AND METHODS 20
3.1. Process Overview at Çorlu Leather Industrial Zone 20
3.1.1. Physical Treatment Stage 22
3.1.2. Chemical Treatment Stage 22
3.1.3. Downstream Processes: Biological Treatment and Sludge Management 23
3.1.3.1 Biological Treatment Unit 23
3.1.3.2 Sludge Dewatering Unit and Drying Process 24
3.2. Experimental Design and Analytical Framework 26
3.2.1. Sampling Procedure 26
3.2.2. Preparation and Characterization of Polymer-Based Hybrid Coagulants 31
3.2.3. Experimental Treatment Scenarios and Workflow Design 37
3.2.3.1 Preliminary Screening Stage 38
3.2.3.2 Formulation Selection Stage 41
3.2.3.3 Dosage Optimization Stage 42
3.2.3.4 Optimized-Dose Jar Testing Stage 42
3.2.3.5 Phase Separation 46
3.2.3.6 Analytical Measurements 50
3.2.4. Data Evaluation and Comparison Approach 57
3.3. Mass Balance Calculations 58
3.3.1. COD Mass Balance 58
3.3.2. TOC Mass Balance 60
3.3.3. Heavy Metal Mass Balance (Al, Fe, Cr (Total)) 62
3.3.3.1 Mass Balance Analysis of Al, Fe and Cr in Raw Wastewater 63
3.3.3.2 Aluminum Mass Balance in Conventional Coagulant Scenarios ..... (M2 and M3) 63
3.3.3.3 Aluminum Mass Balance in Hybrid Coagulant Scenarios ..... (M5 and M6) 64
3.3.3.4 Chromium and Iron Mass Balance in Conventional Coagulant Scenarios (M2 and M3) 64
3.3.3.5 Chromium and Aluminum Mass Balance in Ferric Based Scenario (M4) 64
3.3.3.6 Chromium Mass Balance in Hybrid Coagulant Scenarios ..... (M5 and M6) 65

3.3.3.7 Iron Mass Balance in Ferric Based Coagulant Scenarios (M4, M5 and M6) 65
3.3.3.8 Calculation of Elemental Aluminum (Al) Contribution from Different Coagulants 66
3.3.3.9 Theoretical Iron (Fe) content in the commercial $FeCl_3$ coagulant 67
3.3.4. Fate of Polymers 68
3.3.4.1 Organic Polymers Estimation via TOC Difference 68
3.3.4.2 Inorganic Polymers Estimation via Aluminum Mass Balance 71
3.3.5. Total Suspended Solids (TSS) Mass Balance 74
3.3.6. Total Solids (TS) Mass Balance 76
3.3.6.1 Sludge Moisture Content 78
3.3.6.2 Dry Solid Yield 79
3.3.7. Estimation of Phase-Specific Total Dissolved Solids (TDS) 80
3.4. Theoretical Assessment of Biodegradability Using the BIOWIN Software 80
4. RESULTS AND DISCUSSION 82
4.1. Evaluation of Treatment Performance Based on Water Quality Parameters 82
4.1.1. Screening Tests and Dose Optimization 82
4.1.2. Comparative Performance of Selected Hybrids and the Conventional Treatment Method Under Optimized Conditions 88
4.1.2.1 COD Removal Performance 89
4.1.2.2 TSS Removal Performance 91
4.1.2.3 Sludge Characteristics and Solid Yield Evaluation 93
4.1.2.4 TOC Removal and Polymer Tracing via Differential Comparison 95
4.1.2.5 Aluminum Distribution Across Phases 98
4.1.2.6 Iron Distribution Across Phases 101
4.1.2.7 Chromium Removal Performance 103
4.1.3. Comprehensive Performance Evaluation of Coagulant Formulations 104
4.2. BIOWIN Modeling Results and Interpretation 111
4.2.1. Biodegradability Prediction of PolyDADMAC (Diallyldimethylammonium Chloride Monomer) 114
4.2.2. Biodegradability Prediction of Anionic PAM (Acrylamide and Acrylic Acid Monomers) 114
4.2.3. Biodegradability Prediction of Polyamine (Epichlorohydrin and Dimethylamine Monomers) 115
4.3. Environmental Evaluation and Impact Assessment 116

4.3.1. Comparison with Discharge Standards....116
4.3.2. Environmental Impact Matrix....119
4.3.2.1 Framework for Grouping Environmental Assessment Criteria....120
4.3.2.2 Determination of Sub-Criteria for the Sludge Management and Disposal Impact Group....123
4.3.2.3 Determination of Sub-Criteria for the Chemical Burden & Toxicity Group....124
4.3.2.4 Determination of Sub-Criteria for the Treatment Efficiency & Organic Load Management Group....127
4.3.2.5 Determination of Sub-Criteria for the Systemic & Long-term Environmental Robustness Group....129
4.3.2.6 Integrated Entropy–TOPSIS Approach for Environmental Performance Assessment....134
4.3.2.7 Environmental Performance Evaluation of Coagulant Formulations....141
4.3.2.8 Interpretation of Environmental Evaluation Results....147
5. CONCLUSION AND RECOMMENDATIONS....155
REFERENCES....157
APPENDIX A: SCREENING TESTS AND RESULTS....175
APPENDIX B: PERFORMANCE-BASED RANKING OF HYBRID COAGULANT FORMULATIONS....195
APPENDIX C: MASS BALANCE CALCULATIONS FOR COD....196
APPENDIX D: MASS BALANCE CALCULATIONS FOR TSS....202
APPENDIX E: MASS BALANCE CALCULATIONS FOR SLUDGE TOTAL SOLIDS....207
APPENDIX F: MASS BALANCE CALCULATIONS FOR TOC....213
APPENDIX G: MASS BALANCE CALCULATIONS FOR ALUMINUM (Al)....221
APPENDIX H: MASS BALANCE CALCULATIONS FOR IRON (Fe)....225
APPENDIX I: MASS BALANCE CALCULATIONS FOR CHROMIUM (Cr)....231
APPENDIX J: BIOWIN MODEL OUTPUTS FOR BIODEGRADABILITY ASSESSMENT....237
APPENDIX K: ENVIRONMENTAL IMPACT MATRIX COMPUTATIONAL RESULTS....242

LIST OF FIGURES

Figure 2.1. Leather production processes 5

Figure 2.2. Leather industry wastewater treatment processes 10

Figure 2.3. Coagulant classification 14

Figure 3.1. Visual representation of the treatment plant infrastructure 20

Figure 3.2. General layout of the wastewater treatment plant 21

Figure 3.3. Process flow diagram of biological treatment unit 24

Figure 3.4. Process flow diagram of sludge dewatering and drying units 25

Figure 3.5. Process flow diagram of physical and chemical treatment units 27

Figure 3.6. (a) Sample drums delivered to the treatment plant at the beginning of the study;.... (b) close-up of an individually labeled drum used to ensure traceability during the. 22-day composite sampling program 30

Figure 3.7. Mini laboratory refrigerator used for the short-term storage of phase-separated ..... samples during the experiments 30

Figure 3.8. Visual illustration of particulate agglomerates formed in a physically..... incompatible hybrid coagulant 32

Figure 3.9. Raw wastewater sample (M1) used as the baseline reference in the screening ..... experiments 38

Figure 3.10. Visual outcomes of the uniform-dose screening stage for one experimental day ... 39

Figure 3.11. Dose–response results example of a selected hybrid formulation 42

Figure 3.12. Experimental procedure for M2, M3, M4 and M5-coagulation with pH adjustment43

Figure 3.13. Experimental procedure for M6 – coagulation without pH adjustment.....44

Figure 3.14. Sequential images from the experimental procedure 45

Figure 3.15. Sequential representation of the phase-separation procedure 46

Figure 3.16. Representative images of analytical measurements.....55

Figure 3.17. Stepwise procedure for heavy metal analysis in sludge samples.....56

Figure 4.1. Comparison of average turbidity, COD, and TSS removal efficiencies .....
and sludge formation percentages for each treatment scenario and formulation .....
tested over 22 screening experiments.....84

Figure 4.2. Dose–response behavior of the five selected hybrid coagulant formulations .....
across four performance indicators 87

Figure 4.3. Average COD removal (%) for the conventional coagulant (P040102) and.....
selected hybrid formulations over a 22-day testing period.....89

Figure 4.4. Average TSS removal (%) achieved by the conventional coagulant .....
(P040102) and selected hybrid formulations over a 22-day testing period.....92

Figure 4.5. Average sludge volume and moisture content for all coagulant formulations 94

Figure 4.6. Average TOC removal efficiencies of all coagulant formulations 96

Figure 4.7. Mass-based distribution (%) of aluminum across supernatant (SUP), ...
central (CEN), and sludge (SLG) phases for each coagulant formulation.....99

Figure 4.8. Mass-based distribution (%) of iron across (SUP), (CEN), and (SLG) phases .....
for each coagulant formulation.....101

Figure 4.9. Average chromium removal efficiency (%) for each coagulant formulation.....103

Figure 4.10. Performance comparison of coagulant formulations 104

Figure 4.11. Comparative sludge images for selected formulations 106

Figure 4.12. Daily performance trends of coagulant formulations over a 22-day period.....
in terms of Cr, TOC, COD, TS, and TSS removal efficiencies. 107

Figure 4.13. Flowchart of the environmental impact matrix development process.....122

Figure 4.14. Computational flow of the entropy–TOPSIS method applied in this study.....140

Figure J.1. BIOWIN prediction results for N-methylmethanamine (Dimethylamine). 237

Figure J.2. BIOWIN prediction results for Oxirane, chloromethyl- (Epichlorohydrin). 238

Figure J.3. BIOWIN prediction results for 2-Propenamide (Acrylamide). 239

Figure J.4. BIOWIN prediction results for 2-Propenoic acid (Acrylic acid).....240

Figure J.5. BIOWIN prediction results for Diallyldimethylammonium chloride .....
(PolyDADMAC monomer unit). 241

LIST OF TABLES

Table 3.1. Composite sampling schedule for low and high production periods 28

Table 3.2. Overview of coagulants and flocculants used in hybrid formulation development 33

Table 3.3. Summary of all tested coagulant formulations 35

Table 3.4. Summary of experimental treatment methods and test distribution 48

Table 3.5. Measurement devices and analytical methods used for liquid-phase characterization 51

Table 3.6. Analytical methods and procedures for sludge-phase characterization 53

Table 3.7. Elemental aluminum content of applied coagulants 67

Table 4.1. Selected hybrid coagulant formulations from the M6 scenario 85

Table 4.2. Predicted biodegradability of target polymers using BIOWIN models 113

Table 4.3. Characteristics of industrial wastewaters eligible for deep marine discharge 117

Table 4.4. Discharge standards for leather industry wastewater 118

Table 4.5. Structure of the environmental impact matrix and evaluation domains 132

Table 4.6. Classification of environmental criteria and their environmental directions 146

Table 4.7. Calculation of the closeness coefficient and final ranking of coagulant alternatives . 147

Table A.1. Screening Test Results 175

Table B.1. Performance-based ranking of hybrid coagulant formulations 195

Table C.1. Mass balance calculations for COD.....196

Table D.1. Mass balance calculations for TSS.....202

Table E.1. Mass balance calculations for sludge total solids 207

Table F.1. Mass balance calculations for TOC 213

Table G.1. Mass balance calculations for Aluminum (Al) 221

Table H.1. Mass balance calculations for Iron (Fe) 225

Table I.1. Mass balance calculations for total Chromium (Cr) 231

Table K.1. Raw decision matrix prior to entropy weighting 242

Table K.2. Normalized decision matrix derived from raw criterion values.....243

Table K.3. Entropy values, divergence measures, and final criterion weights.....244

Table K.4. Aggregated entropy-based weights of thematic groups.....245

Table K.5. Normalized decision matrix for TOPSIS analysis – r_{ij} Calculation I 246

Table K.6. Normalized decision matrix for TOPSIS analysis– r_{ij} Calculation II.....247

Table K.7. Weighted normalized decision matrix 248

Table K.8. Determination of positive (A^+) and negative (A^-) ideal solutions for TOPSIS.....249

Table K.9. Distance of each alternative from the positive ideal solution (S^+) 250

Table K.10. Distance of each alternative from the negative ideal solution (S^-) 251

Table K.11. Calculation of the closeness coefficient (C_i) and final ranking of alternatives.....252

LIST OF SYMBOLS/ABBREVIATIONS

Symbol	Explanation
Al	Aluminum
$Al_2(SO_4)_3$	Aluminum Sulfate
$Al_2(SO_4)_3 \cdot 18H_2O$	Aluminum Sulfate Octa Decahydrate
$AlCl_3$	Aluminum Chloride
Ca	Calcium
$Ca(OH)_2$	Calcium Hydroxide
$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide
Cr	Chromium
Fe	Iron
$Fe_2(SO_4)_3$	Iron (III) Sulfate
$FeCl_3$	Iron Chloride
H_2S	Hydrogen Sulfide
Mg	Magnesium
Na_2CO_3	Sodium Carbonate
NaOH	Sodium Hydroxide
Na_2S	Sodium Sulfide
Na_2SiO_3	Sodium Silicate

Abbreviation	Explanation
BOD	Biochemical Oxygen Demand
CEN	Centrifuged Liquid Phase
COA	Certificate of Analysis
COD	Chemical Oxygen Demand
DMA	Dimethylamine
ECHA	European Chemicals Agency
FAU	Formazin Attenuation Unit
HDPE	High-Density Polyethylene
ICP-OES	Inductively Coupled Plasma Optical Emission Spectroscopy
IPC	Inorganic Polymeric Coagulant
LCA	Life Cycle Assessment

MCDA	Multi-Criteria Decision Analysis
MITI	Ministry of International Trade and Industry (Japan)
NDMA	N-Nitrosodimethylamine
NIS	Negative Ideal Solution
OECD	Organisation for Economic Co-operation and Development
OPC	Organic Polymeric Coagulants
PAC	Polyaluminum Chloride
PAC-17	Polyaluminum Chloride, 17% Al formulation
PAM	Polyacrylamide
PASiC	Poly aluminum silicate chloride
PDMDAAC / PolyDADMAC	Poly dimethyl diallyl ammonium chloride
PFC	Polyferric Chloride
PIS	Positive Ideal Solution
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SBR	Sequencing Batch Reactor
SDS	Safety Data Sheet
SKKY	Regulation on the Control of Water Pollution in Türkiye
SLG	Sludge Phase
SS	Suspended Solids
SUP	Supernatant Liquid Phase
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TS	Total Solids
TSS	Total Suspended Solids
UASB	Upflow Anaerobic Sludge Bed
U.S. EPA	United States Environmental Protection Agency
WWTP	Wastewater Treatment Plant

1. INTRODUCTION

The leather industry covers the processing of animal skins and hides with special methods and transforming them into a wide range of products suitable for human use. Products such as suitcases, bags, jackets, belts, shoes, fur and other garments are obtained by processing the leather. It is one of the oldest and well-established sectors in the world, but in recent years, due to the environmental pollution it causes, leather production has shifted to countries such as China, Indonesia and Vietnam. Despite the environmental problems caused by the leather industry, the world's demand continues to increase, and Türkiye has an important place in leather production in the world, especially in sheep leather processing (Balcı et al., 2016). Among the most important reasons that it poses a great threat to the environment are the large quantities and wide variety of toxic chemicals usage during the processing and the preference of chromium for the tanning process (Chowdhury et al., 2013).

Leather processing is an industry with a large amount of wastewater discharge and water consumption (Zhao et al., 2022). The major pollutants in leather industries effluents include high salinity, organics, suspended solids (SS), ammonia, sulfur, chromium, chloride, sodium, and heavy metals (Chowdhury et al., 2013). Since it has a high pollution load, the wastewater must be treated before discharge, otherwise the wastewater may reduce the amount of dissolved oxygen in the receiving water, adversely affecting the environment, causing eutrophication and ending aquatic life in the water (Shegani, 2014).

Since tannery wastewater characterization varies according to the type of tanning, chemicals used during processing, production stages and the desired final product to be obtained, the wastewater quality will not be the same in every plant. Depending on the specific characteristics of the wastewater, it is basically treated in physical, chemical, biological and advanced treatment systems (Ayoub et al., 2012). It is aimed to remove parameters such as chemical oxygen demand (COD), SS, turbidity, and metals in wastewater with coagulation and flocculation, which are physicochemical processes (Gungor et al., 2015).

Conventional coagulation processes are mostly carried out using aluminum (III) and iron (III) salts (Bajza et al., 2004). Although they are frequently preferred due to their ease of operation, low cost and wide usage area, they cause a high amount of sludge formation (El-taweel et al., 2023). The presence of components such as aluminum and iron which accumulate in the sludge due to the coagulation process and high amounts of organic and inorganic substances make sludge disposal

difficult. In addition, the residual aluminum remaining in the treated water is another problem, which can cause toxicity and Alzheimer's disease in humans and animals (Lee et al., 2012).

Hybrid materials are being developed instead of conventional coagulants to improve the treatment performance, reduce the toxicity, and decrease the dosage amount (Owodunni and Ismail, 2021). By combining different group coagulants with various techniques, more effective, high-performance and affordable options are created. For instance, while the coagulation efficiency of inorganic salts used alone is lower than inorganic polymeric coagulants (IPC) and organic flocculants; when they are combined with organic polymeric flocculants, improved results in treatment efficiency are achieved. High molecular weight and water-soluble organic polymeric coagulants such as polyacrylamide (PAM) and poly dimethyl diallyl ammonium chloride (PDMDAAC) can be recommended for this purpose (Lee et al., 2012). As a result, hybrid materials, which are a more effective, efficient and economical alternative, have become an important research topic due to the high potential in eliminating the problems related to toxic sludge formation.

1.1. Research Objectives

The objective of this thesis is to develop, evaluate, and environmentally contextualize advanced hybrid coagulant systems as viable alternatives to conventional metallic salts used in the coagulation–flocculation treatment of leather industry effluents. Leather wastewater is characterized by extremely high pollutant loads, including organic matter, suspended solids, heavy metals (particularly chromium, iron, and aluminum), high color intensity, and COD. Therefore, the treatment process requires not only high-performance removal technologies but also sustainable strategies that minimize chemical inputs and environmental burden.

This study seeks to address the limitations of conventional inorganic coagulants—such as high dosage requirements, sludge generation, poor biodegradability, and metal accumulation—by proposing hybrid formulations composed of inorganic coagulants (e.g., $Al_2(SO_4)_3$, PAC, $FeCl_3$) physically combined with organic polymers (e.g., polyDADMAC, polyamines, PAM). These hybrid systems are expected to enhance floc formation, reduce coagulant dosage, lower sludge volume, and consequently minimize sludge disposal costs, which remain one of the most significant operational challenges in full-scale leather wastewater treatment. In doing so, the formulations aim to deliver more efficient pollutant capture while improving overall process sustainability.

The research involves the design and testing of sixteen unique hybrid formulations across a six-method comparative experimental matrix (M1–M6), including pH-adjusted and non-adjusted conditions. Using 22 real wastewater samples collected from the Çorlu Leather Organized Industrial Zone, the treatment methods are systematically compared based on key performance metrics such as turbidity, color, COD, TOC, suspended solids, conductivity, and residual heavy metals. Phase-based analyses of both liquid fractions and solid sludge are conducted to assess the impact of treatment at each stage. Additionally, mass balance calculations for COD, TOC, Al, Fe, and Cr are performed to quantify the movement and fate of pollutants and coagulant residues across the process chain.

Furthermore, the thesis integrates a theoretical component using the U.S. EPA's BIOWIN software to predict the biodegradability of organic polymers used in hybrid formulations. This approach complements empirical findings with environmental screening insights and aligns the study with green chemistry principles. Through this dual-pronged methodology—combining experimental rigor with environmental modeling—the thesis aims to propose a technically and ecologically sound treatment approach for industrial-scale leather wastewater management.

Ultimately, this research aspires not only to optimize coagulation performance but also to provide a framework for selecting coagulants that balance efficiency, environmental safety, and operational feasibility. To systematically evaluate these dimensions, the study incorporates an objective multi-criteria decision analysis (MCDA) approach using entropy-based weighting and the TOPSIS method, allowing the technical and environmental performance of coagulant alternatives to be assessed in a comprehensive sustainability framework. The outcomes of this study are expected to contribute valuable guidance for process engineers, treatment plant operators, and policymakers working toward sustainable industrial wastewater solutions.

2. LITERATURE REVIEW

2.1. Leather Industry

Leather processing transforms hides and skins of animals into products for various uses (Kesarwani et al., 2015). The main raw materials in leather processing are raw and semi-finished leather. To obtain raw hide, animals such sheep, lamb, bovine, calf, or buffalo are frequently preferred (Kasal, 2000). The feature that makes rawhide-based products different from other materials is their unique complex physical structure, which varies depending on the type of animal that they obtained. As rawhide can be used in many different areas, the way it is processed may vary accordingly to its intended use. The leather industry is basically consisting of shoe, bag, garments and leather goods production industry, leather processing industry, and leather chemicals industry (Küçükpelvan et al., 2017).

Rawhide reaches its final leather form by going through certain mechanical and chemical processes (Ayoub et al., 2012). Although production processes may vary according to the type of rawhide and the structure of the facility, it can basically be handled in four main processes: beamhouse stage, tanning stage, post-tanning and finishing stage respectively (Figure 2.1.) (Küçükpelvan et al., 2017; Zhao et al., 2022).

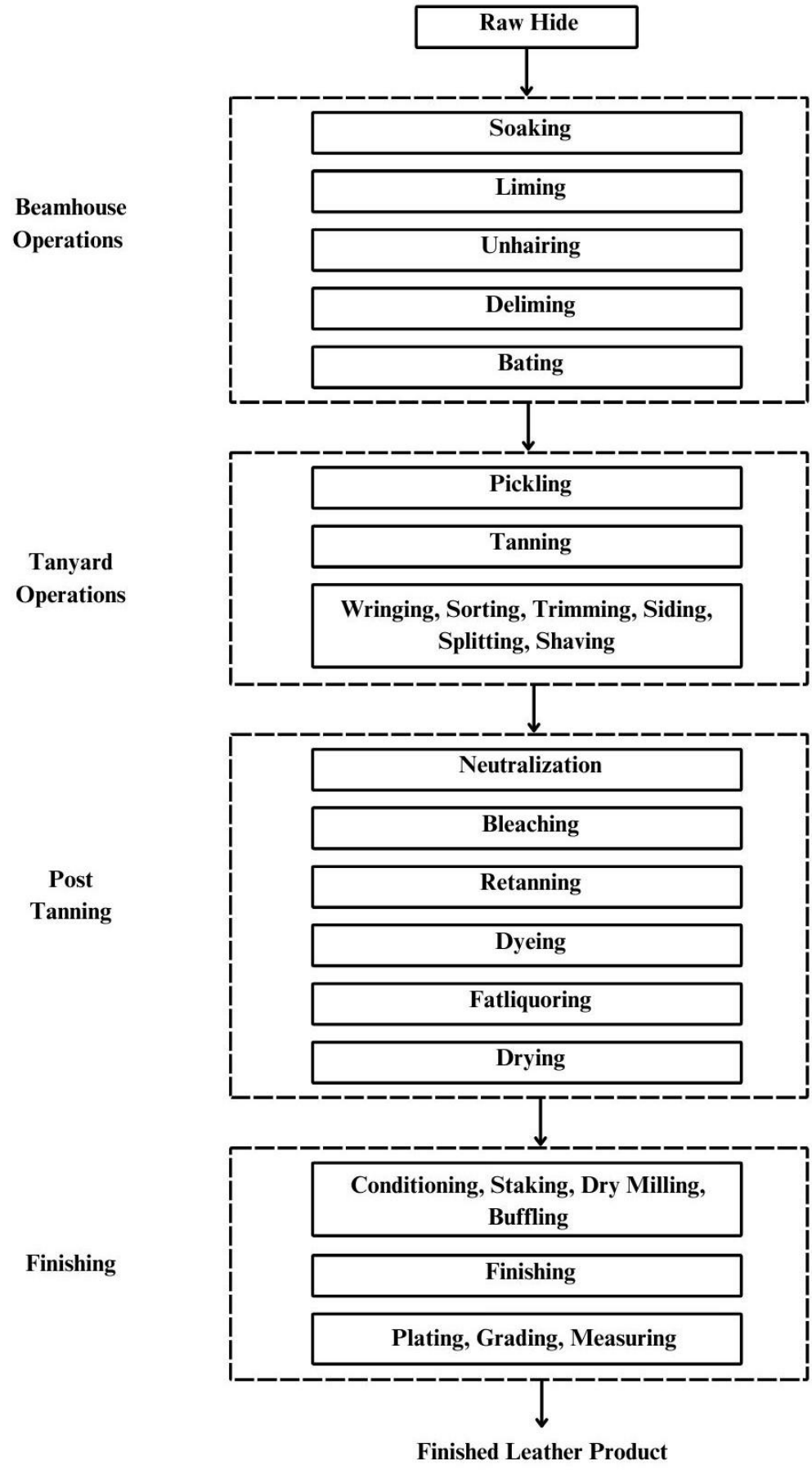


Figure 2.1. Leather production processes.

2.1.1. Beamhouse Operations

Beamhouse is a section where hides or skins are prepared for tanning. Raw materials are subjected to pre-processes such as soaking, liming, unhairing, deliming, bating and pickling. Thanks to these steps, unwanted parts of the skin are removed. Thus, it is ensured that the chemicals to be used in the next steps penetrate the skin better (Ahmed and Kotb, 1999; Guillén et al., 2011).

The skins of animals slaughtered for leather production are stored in cool, well-ventilated storage area with salting in order to protect them against possible bacteriological growth before proceeding to the process stage (Küçükpelvan et al., 2017; US EPA, 2000; Kesarwani et al., 2015). The soaking process takes place in two stages. First, the dirt, dung, blood and salt on the skin are removed, then it is ensured that the skin restores the moisture again and returns to its original raw state. A large amount of water and a small amount of preservatives like wetting agents and bactericides are used during this process (Küçükpelvan et al., 2017; US EPA, 2000). At the end of the soaking process, the salt that separated from the leather has become one of the main components of the leather industry wastewater (Ming-min, 2013).

In liming and unhairing processes, hair, fat, tissue and other residues are removed from the skin. Hair can be removed from the skin by melting with lime ($Ca(OH)_2$) and sodium sulfide (Na_2S) or another option is to weaken the hair with different chemicals and then remove it mechanically. This process requires a large amount of water. At the end of the process, the cleaned skin is immersed in a strong alkaline bath to reveal the collagen structure, and finally, it is separated into layers by the skin separation process (Küçükpelvan et al., 2017).

The next process is de-liming. pH level should be adjusted in order to prevent the skin from resisting the chemicals to be applied in further steps. Weak acid salts such as ammonium chloride and ammonium sulfate are generally used for this purpose (Küçükpelvan et al., 2017; Kesarwani et al., 2015). Unwanted proteins and short hairs are completely removed by another process called bating. It is an enzymatic process and at the end of it, degreasing is applied to remove excess oil from the skin and to ensure that the oil is distributed homogeneously (Küçükpelvan et al., 2017).

2.1.2. Tanyard Operations

Pickling process is applied before the tanning to make the leather ready for process. The pH of the leather is lowered to around 3 by the addition of acid solutions such as sulfuric acid, while sodium

chloride is added to prevent collagen damage and excessive swelling during the process. Thus, an environment where the hides can accept the chemicals to be applied more easily has been created (Küçükpelvan et al., 2017; US EPA, 2000).

Tanning is the process of transforming raw hide into a stable and non-putrescible material by applying various mineral, vegetable and synthetic organic materials. Thus, leather gains high hydro-thermal stability, resistance to bacterial growth and high temperature, and versatile application features. Today the most preferred method is chrome tanning due to its advantages such as obtaining pliable leather, not causing color fading or shape loss (Küçükpelvan et al., 2017; Kesarwani et al., 2015).

At low pH, chromium (III) salts are added, and the pH is raised in a controlled manner in order to fix the chromium. The main principle of this method is based on the cross-linking of chromium ions and free carboxyl groups in collagen tissue (Küçükpelvan et al., 2017). Besides chrome tanning other tanning methods include vegetable and aldehyde tanning (Kesarwani et al., 2015).

As the final step of the tanning process, excess moisture is removed, the surrounding areas are trimmed, and the desired size and thickness are adjusted (US EPA, 2000).

2.1.3. Post Tanning Process

Post tanning processes consist of neutralization, bleaching, retanning, dyeing and fatliquoring (US EPA, 2000). In the neutralization process, the skin pH is prepared for further processing by using weak alkaline substances. It is applied to lighten the skin color before bleaching, retanning and dyeing processes. The retanning process is done to improve the product properties by removing the structural differences in the leather, and several chemicals such as vegetable tanning extracts, aldehydes, resins and mineral tanning agents can combined to achieve a certain leather quality (Küçükpelvan et al., 2017). Then, the leather is dyed to the desired color. Finally, thanks to the fatliquoring process, collagen fibers are lubricated by using oil and wax to bring flexibility and softness to leather US EPA, 2000).

2.1.4. Finishing Process

In the finishing processes, the leather is made softer by mechanical softening and smoothing/buffing steps, so its minor faults are covered. Leather is processed with organic solvent or

water-based dyes and varnish to increase its resistance and enhance its appearance. After these processes, the leather is given its final shape and the process is completed with the garment stage (Küçükpelvan et al., 2017; US EPA, 2000).

2.2. Leather Industry Wastewater

Leather industry poses a threat to the environment by causing the generation of wastewater which contains high amounts of pollutants (Shegani, 2014). Mixing of chemicals used in production into wastewater causes toxic effects in the receiving environment, and this leads to adverse effects on the environment and human health (Küçükpelvan et al., 2017). During processing of leather, water is used in large quantities and almost the entire amount of consumed water turns into wastewater at the end of those processes. In addition, it has been observed that the water consumption and pollution load in facilities that use chromium as a tanner is relatively higher than others (Küçükpelvan et al., 2017; Ayoub et al., 2012). Processes where water is used most in leather production:

- In soaking of the rawhide,
- For creating a suitable environment for the chemical substances that are used in the processes,
- For carrying the chemicals used in the dyeing and fat liquoring stages,
- In order to remove unwanted products and residues from the leather during the process
- For the purpose of cleaning the production area and equipment (Kolçak, 1999).

2.2.1. Leather Industry Wastewater Characterization

Raw hide comes to the leather processing plants together with the wool, hair, oil, blood and meat particles on it, this causes an increase in the pollution load of industry and makes wastewater treatment difficult. During the production, different kinds of processes can be applied depending on the raw material and the desired final product type (Küçükpelvan et al., 2017). Therefore, the composition of tannery wastewater may vary depending on the type of tanning process, the chemicals used in production, general process line and final product. Consequently, a constant wastewater quality should not be expected from each facility (Ayoub et al., 2012).

Wastewater from the leather industry mainly contains hairs, proteins, acids, alkalis, trivalent chromium, arsenic, ammonia, sulfides, chloride, vegetable and/or synthetic tannins, sulfonated oils,

grease, solvents, dyes, and other auxiliary process chemicals used throughout tanning operations, as well as Ca, Mg, organics, and various toxic ingredients (Zhao et al., 2022; Ayoub et al., 2012; Mandal et al., 2010). Besides, tannery wastewaters are characterized by high concentrations of chemical oxygen demand (COD), suspended solids (SS), total Kjeldahl nitrogen (TKN), and have a widely fluctuating pH (Ayoub et al., 2012; Gungor et al., 2015). Uncontrolled discharge of tannery effluents into environment affects water quality as follows:

- Leather wastewater has high concentrations of biochemical oxygen demand (BOD) and its discharge into surface waters causes a significant decrease in the amount of dissolved oxygen.
- Macronutrients can lead to eutrophication in receiving water.
- Tannery wastewater may contain compounds toxic to aquatic life such as chromium and non-ionized ammonia (NH_3) (Shegani, 2014).

2.2.2. Leather Industry Wastewater Treatment Stages

Since wastewater treatment plants are designed according to the needs of wastewater quality, not all treatment plants are equal to each other (UNIDO, 2011). Depending on the wastewater characterization, tannery wastewater is treated by physical and/or chemical and/or biological methods (Ayoub et al., 2012). In tanneries, wastewater streams can be separated from each other as shown in Figure 2.2., or all wastewater lines can be collected and combined at a single point.

Nevertheless, since wastewater streams contain high concentrations of organic wastes and chromium compounds, it should be preferred to keep them separate (Swartz et al., 2017). It is recommended that the streams be separated from each other and subjected to pre-treatment according to their characteristics to prevent safety risks and sludge disposal problems. Otherwise, contamination of sludge with Cr (chromium) may lead to high sludge disposal costs and mixing of liming and tanning streams produces highly toxic gases such as hydrogen sulfide (H_2S) (UNIDO, 2011). As a result, separate collection and treatment of these wastewaters is very important in terms of treatment efficiency (Küçükpelvan et al., 2017).

This study mainly focused on coagulation and flocculation stages, which are physico-chemical processes of leather industry wastewater treatment. Therefore, the other main wastewater treatment parts will be discussed only in general terms in this section.

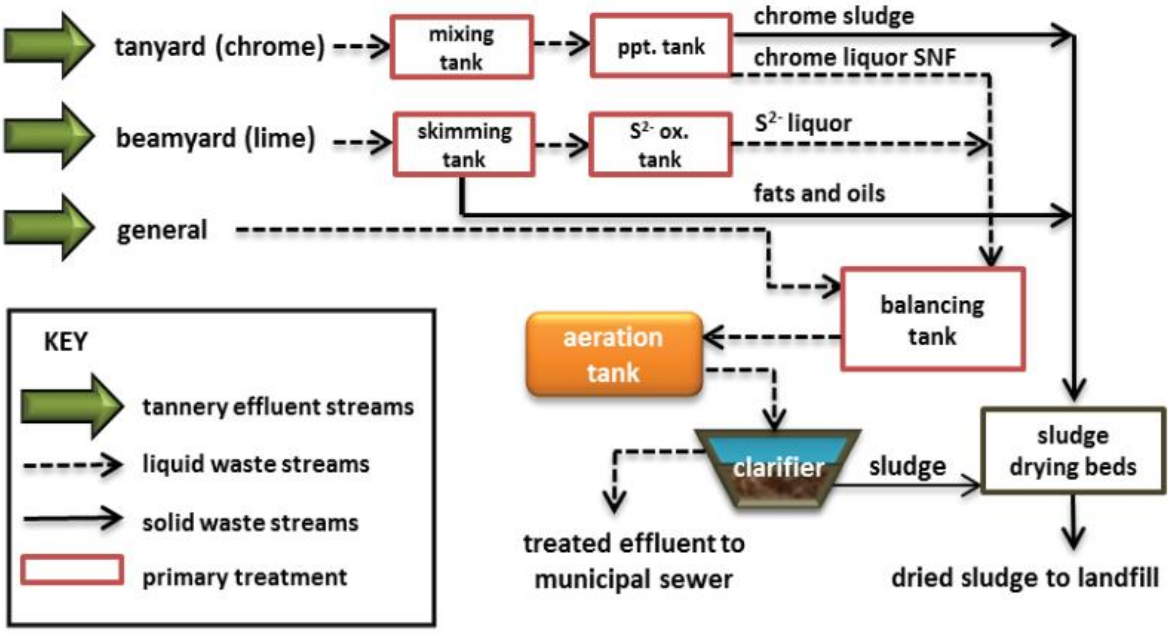


Figure 2.2. Leather industry wastewater treatment processes. (Swartz et al., 2017)

2.2.2.1. Preliminary treatment. In the preliminary treatment of leather industry wastewater; leather pieces, hair, wool and other insoluble suspended solids are physically separated (Küçükpelvan et al., 2017). Removing the chromium and sulfur content before being discharged into the wastewater collection network helps to reduce the inlet load (United Nations Industrial Development Organization, 2011). For sulfur removal, the catalytic air oxidation method has been recommended. In addition, toxic chromium can be treated through coagulation–flocculation and precipitation processes (Kasal, 2000).

Mechanical screens, grit removal systems, distribution wells and equalization tanks are used for this purpose. Hair and coarse materials, sand, grit and grease are removed physically at this stage. Moreover, in addition to sulfur and chromium removal, pre-precipitation was found to be effective in facilitating the precipitation of organic solids (Swartz et al., 2017).

The last important point is that various types of wastewater are generated during leather processing. Wastewater with high alkaline value originating from the liming process or high chromium concentration due to the tanning process may come to the facility. For this reason, equalization tank has an important place in wastewater treatment in the leather industry (Küçükpelvan et al., 2017).

2.2.2.2. Primary treatment. Physicochemical processes are applied in primary treatment. Settleable organic and inorganic solids are settled down by gravity or with the aid of chemical coagulants and/or flocculants. Other floating materials remaining on the surface are removed by stripping (Swartz et al., 2017; UNIDO, 2011). Thanks to the coagulation and flocculation process, in addition to chromium, parameters such as suspended solids, COD, BOD, sulfur and alkalinity are also removed (Kasal, 2000). Approximately 25-50% BOD, 50-70% total suspended solids and 65% oil and grease are removed at this stage (United Nations Industrial Development Organization, 2011). It is recommended to precipitate chromium- and sulfur-containing wastewater streams separately, because neutralization of alkaline wastewater causes the release of hydrogen sulfide in gaseous form (Swartz et al., 2017).

Chromium compounds cause high toxicity in leather wastewater. They are not biodegradable and have a potential to affect biological activities in the receiving environment and treatment plant. Furthermore, chromium has serious adverse effects on human health like carcinogenicity. In the leather industry, both Cr^{+3} and Cr^{+6} forms can be encountered due to the tanning process. Cr^{+6} is more toxic than Cr^{+3} and it can be found if dichromate is used in tanning (Kasal, 2000). The most common method for the removal of chromium from tannery wastewater is chemical precipitation (Küçükpelvan et al., 2017).

Coagulation is conventionally done by the application of Fe and Al salts after preliminary treatment (Naumczyk and Rusiniak, 2005). The most commonly used coagulants in tannery wastewater treatment are aluminum sulfate ($Al_2(SO_4)_3.18H_2O$), iron sulfate ($FeSO_4.7H_2O$), iron chloride ($FeCl_3.6H_2O$), polyaluminum chloride (PACl), calcium hydroxide ($Ca(OH)_2$) (Shegani, 2014). Small particles in the water are agglomerated by the help of these chemicals and converted into large flocs (Abujazar et al., 2022).

Flocculation is applied to promote the aggregation of small particles into larger flocs, which are subsequently removed by sedimentation, thereby improving water clarity. Filtration can then be applied as a subsequent step to remove residual fine particles (Abujazar et al., 2022). Common flocculants and coagulant aids used in water and wastewater treatment include synthetic or natural polyelectrolytes, and inorganic additives such as CaO, $CaCO_3$, and Na_2CO_3, which help adjust pH and improve coagulation efficiency. Additionally, polysilicates and silica-based compounds (e.g., Na_2SiO_3) have been incorporated into modern composite coagulants to enhance performance (Tzoupanos and Zouboulis, 2008), (Tolkou et al., 2014), (Oladoja, 2016).

In order for the effluent to reach the desired standard values, it is necessary to apply secondary (biological) treatment and advanced treatment steps after coagulation (Shegani, 2014). For technical requirements of coagulation and flocculation processes and coagulant classification, see section 2.3.

2.2.2.3. Secondary treatment. Leather industry wastewater contains high amounts of organic matter and this organic load is characterized by COD and BOD parameters. Biodegradable dissolved, and colloidal organic matter is removed by the help of biological treatment (United Nations Industrial Development Organization, 2011). Aerobic and anaerobic processes can be used to remove contaminants found in leather wastewater, including activated sludge, sequential anaerobic-aerobic aeration, oxidation ditch, sequencing batch reactor (SBR), batch biofilm reactor, fluidized bed and upflow anaerobic sludge bed (UASB) processes (Küçükpelvan et al., 2017).

Aerobic biological treatment is the process of metabolizing organic matter in wastewater with microbial action in the presence of oxygen with the help of aerobic microorganisms such as bacteria (UNIDO, 2011). Oxidation of organic matter causes an increase in biomass and sludge formation. Among the disadvantages of aerobic processes is the generation of a high amount of sludge, which demands considerable energy for handling and disposal (Küçükpelvan et al., 2017).

Anaerobic treatment is the process of decomposing organic and inorganic substances by anaerobic microorganisms in an oxygen-free environment. The most important advantages of anaerobic treatment are less energy requirement, high energy potential of methane, less equipment space requirement, and less sludge formation. However, the process also generates carbon dioxide and hydrogen sulphide, which are considered environmental and operational disadvantages (Küçükpelvan et al., 2017; Swartz et al., 2017). In particular, the use of anaerobic technology is limited because of the release of toxic and corrosive hydrogen sulfide in the tanning process (Swartz et al., 2017).

2.2.2.4. Tertiary treatment. Advanced treatment processes are applied to improve the quality of biological treatment effluent; however, these methods often require high cost and expert operation (Swartz et al., 2017). For this purpose, advanced purification methods such as activated carbon filters, advanced oxidation, membrane separations, reverse osmosis, ion exchange or stripping can be used (Küçükpelvan et al., 2017; Mella et al., 2017).

2.2.2.5. Sludge Handling and Disposal. Dried sludge from advanced treatment or solid waste from primary treatment is considered as hazardous and should be disposed of by sending it to appropriate municipal or private landfills (Swartz et al., 2017).

2.3. Coagulation and Flocculation Processes

Coagulation and flocculation are widely preferred processes in industrial wastewater treatment due to their relative simplicity and low cost (Swartz et al., 2017). The purpose of coagulation is to lower water consumption, improve chemical uptake, produce reusable or high-quality solid waste, and reduce specific impurities such as heavy metals and electrolytes from the wastewater (Shegani, 2014). This method provides reduction in chemical oxygen demand (COD), turbidity, color, suspended solids (SS), heavy metals, oil and organic matter (Abujazar et al., 2022).

Colloids which contain charged particles remain stable in water due to the repulsive force between charges of the same sign. The main purpose of coagulation is to destabilize these particles through charge neutralization (Freitas et al., 2017). Coagulants achieve this by neutralizing the negative charges on colloidal particles. Once destabilized, the particles aggregate during the flocculation stage, forming larger flocs that can be easily separated from water by settling (Owodunni and Ismail, 2021). The process usually begins with rapid mixing of the coagulant into the wastewater and the most common coagulants include aluminum (III) and iron (III) salts (Bajza et al., 2004). After the positively charged chemicals are added to the water, they neutralize the negatively charged colloids and form precipitates containing aluminum or iron (Owodunni and Ismail, 2021). Coagulant aids can also be used together with coagulants, the purpose of these materials is to prepare the water for the process, to give density and to add toughness to flocs (Ireland Environmental Protection Agency, 2002). In addition, where natural alkalinity is insufficient to react with coagulants, alkalinity can be added with alkaline chemicals such as lime or soda ash to maintain the optimum pH value (US EPA, 2000).

Coagulation and flocculation are interdependent processes (Owodunni and Ismail, 2021). Flocculation is the process that allows the small flocs formed during coagulation to be gathered into larger size so that they do not break down and can be removed in the clarification process easily (Ireland Environmental Protection Agency, 2002). Therefore, slow mixing is applied to obtain optimum performance from the flocculation (El-taweel et al., 2023). After coagulation and flocculation, the treatment process continues with sedimentation followed by filtration to remove any remaining impurities from the water (Abujazar et al., 2022).

Coagulation efficiency depends on the type of coagulation, mixing speed, settling time, its stability and lifetime, so the selection of appropriate coagulants for relevant wastewater characterization is important (Owodunni and Ismail, 2021). Furthermore, the other main factors affecting coagulation include pH, temperature, turbidity, colloid concentration, dosage, cations and anions in solution, colloid affinity to water and zeta potential (El-taweel et al., 2023; Dayarathne et al., 2021).

2.3.1. Coagulant Classification

Coagulants are classified into two types, mainly chemical and natural. As shown in Figure 2.3., chemical coagulants are divided into three subgroups as hydrolyzing metallic salts, prehydrolyzing metallic salts and synthetic cationic polymers. Natural coagulants are divided into three as plant based, animal based, and microorganism based natural coagulants (El-taweel et al., 2023; Gajbhiye, 2020).

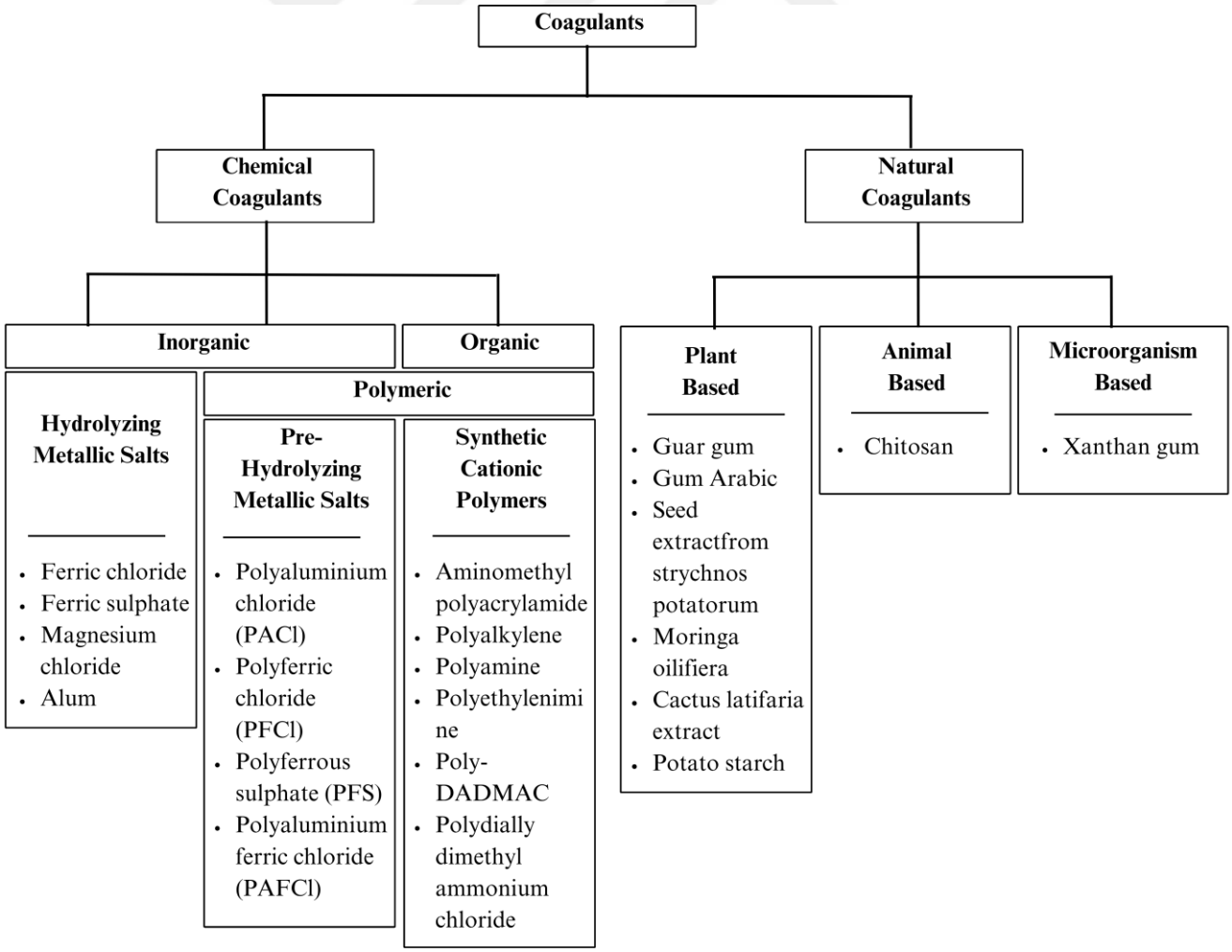


Figure 2.3. Coagulant classification. (El-taweel et al., 2023; Gajbhiye, 2020; Freitas et al., 2017)

2.3.1.1. Hydrolyzing metallic salts. The most preferred coagulants in wastewater treatment are aluminum and iron salts such as $AlCl_3$, $Al_2(SO_4)_3$, $FeCl_3$, and $Fe_2(SO_4)_3$, due to the advantages of metallic salts such as effectiveness, economical and easy operation, storage, handling and mixing features. The working principle is the hydrolysis of salts added to water by dissociating Al^{3+} and Fe^{3+} ions. The positively charged soluble complexes are easily adsorbed on the surfaces of negative colloids (Freitas et al., 2017).

However, besides the advantages and wide usage areas of hydrolyzing metallic salts, they have also important disadvantages like, high amount of sludge formation, adverse effects on environment caused by high residual metal concentrations in sludge, and brownish discoloration of iron salts on equipment (El-taweel et al., 2023; Freitas et al., 2017). In addition, since iron-based coagulants reduce alkalinity, the use of extra chemicals to balance the pH increases the total cost of treatment (Owodunni and Ismail, 2021). Aside from this, there is also a risk on human health, such as Alzheimer's disease, which occurs when aluminum residues enter the human body and accumulate in the brain (El-taweel et al., 2023). Consequently, the most important point is that the large amount of sludge and its high toxin content causes pollution problems and increase the disposal cost (Zhao et al., 2022).

2.3.1.2. Inorganic Polymeric Coagulants. Following hydrolyzing metallic salts, the second major group of inorganic coagulants is the pre-hydrolyzed metallic salts, such as PACI, PFCI, and PAFCI (see Figure 2.3). These are long-chain polymers with high molecular weight and are classified as inorganic polymeric coagulants (IPCs). They can be used alone as a primary coagulant or applied together with other inorganic coagulants. Their basicity and hydrophilic properties are among their characteristic features. In addition to being more environmentally friendly than metallic salts, they have also other advantages like low-dose applications are sufficient, their effects on pH are less, and they form cleaner and less sludge (Owodunni and Ismail, 2021). Moreover, pre-hydrolyzed metallic salts provide to remove color more effectively, cause less sludge production, and are effective even at lower temperatures compared to metallic salts (Gajbhiye, 2020). It has been proven that IPCs are more effective than conventional inorganic metallic salts, as they are more resistant to the temperature and the effect of the wastewater (Lee et al., 2012). However, they are more expensive, and the appropriate polymer must be selected correctly during application (Owodunni and Ismail, 2021).

2.3.1.3. Organic polymeric coagulants (OPCs). Long-chain, synthetic organic polymers are divided into two as polyelectrolyte and non-ionic. While polyelectrolytes contain ionizable groups such as sulfonic, carboxyl or amino groups; polymers which do not contain ionizable groups are defined as non-ionic. Polyelectrolytes can be anionic, cationic and ampholytic depending on whether they

contain positive or negative groups (El-taweel et al., 2023). They are highly effective at low doses and stand out as an economical and more environmentally friendly alternative because they cause less sludge formation. In addition, they do not create pH fluctuations, making them a safe option (Muniz et al., 2021).

2.3.1.4. Natural coagulants. Natural (green) coagulants are also used in wastewater treatment as a coagulant. Since they do not reduce alkalinity, pH is not affected. In addition, they do not cause high sludge formation unlike other chemical coagulants, so sludge disposal is not a problem like other options (Owodunni and Ismail, 2021). Since they are biodegradable, they stand out with their environmentally friendly features that do not harm the environment and human health (El-taweel et al., 2023).

2.3.2. Hybrid Materials in Coagulation and Flocculation

It has been reported that the treatment performance of coagulants in wastewater treatment is improved when they are combined with other natural or chemical coagulants (Owodunni and Ismail, 2021). Hybrid materials have arisen as an important potential in the wastewater treatment sector as they provide higher performance than conventional inorganic coagulants and are more affordable than organic flocculants (Lee et al., 2012).

Lee et al. (2012) classified hybrid materials as follows:

- Structurally hybridized materials (composites)
- Chemically bound hybridized materials
- Functionally hybridized materials

The selection of components for hybrid materials is based on the characterization of the wastewater to be treated (Lee et al., 2012).

2.3.2.1. Structurally hybridized materials (composites). Structural hybrid materials, which also known as composite materials, express mixing at the macroscopic level. Generally, inorganic, and organic hybrid materials prepared by physical mixing at ambient or high temperature are in this class. In other words, no new chemical species are formed, and the hybrid material feature obtained has been further developed by the combination of its components (Lee et al., 2012).

For example, inorganic coagulants have problems in removing low molecular weight pollutants. In order to overcome this problem, and to increase performance and removal efficiency, composite coagulant studies are carried out. Priority is given to combinations that reduce aluminum residues, prevent excess sludge formation, eliminate the need for pre-oxidation, being cost-effective. Olukowi et al. (2022) combined low-dose inorganic coagulant PAC and cationic organic coagulant poly-dimethyl-diallyl ammonium chloride (PDMDAAC). As a result of the study, it was seen that composite PAC/PDMDAAC offered improved water quality compared to PAC alone (Olukowi et al., 2022). Another example is PFC–PDMDAAC (Lee et al., 2012).

Composite coagulants are not only used in technical fields such as increasing the treatment performance, improving the weak floc problem, and floc recovery but also, they have increasing potential to offer economic advantages in industry and trade (Owodunni and Ismail, 2021).

2.3.2.2. Chemically bound hybridized materials. Chemically bound hybridized materials contain specific combinations and mixtures of atoms and molecules. They are obtained by adding a new chemical group to the molecular chain. They can be described as a kind of chemical modification. For this purpose, hydroxylation prepolymerization, copolymerization and chemical grafting/crosslinking methods can be applied (Lee et al., 2012).

For example, since the molecular weight of inorganic polymeric coagulants is lower, their aggregating capacity is also lower. Therefore, the performance of organic coagulants is better than PAC. In order to overcome this, polysilicic acid can be added to PAC and as a result the improved material PASiC is formed (Lee et al., 2012).

2.3.2.3. Functionally hybridized materials. Materials hybridized by combining the functions of structural hybrid materials and chemically bonded hybrid materials or using interface functions can be defined as functional hybridized materials, but it is still a new concept in terms of materials science and engineering (Lee et al., 2012).

2.3.3. Biodegradability of Hybrid Coagulants in Wastewater Treatment

Biodegradability refers to the ability of chemical substances to be biologically decomposed into simpler, non-toxic compounds such as carbon dioxide, water, and biomass by the action of microorganisms (Lavagnolo et al., 2023). This property has become a focal point in wastewater treatment, as the accumulation of non-degradable synthetic substances in aquatic environments can

lead to long-term ecological harm (Sarkar, 2023; Meles, 2014). Among the chemicals widely employed in wastewater coagulation processes, inorganic coagulants—such as alum, ferric chloride, and particularly polyaluminium chloride (PAC)—are known for their high removal efficiency but also for their environmental persistence and potential toxicity (Rizzo et al., 2005; Shirafkan et al., 2016). These compounds are not biodegradable. As a result, they increase sludge volume and may lead to residual metal concentrations in the effluent, which poses challenges for downstream biological treatment and complicates sludge disposal (Lees et al., 2001). Consequently, international regulations such as REACH and OECD biodegradability protocols increasingly emphasize the selection of readily biodegradable chemicals in line with green chemistry principles (OECD, 1992; ECHA, 2020; Vizade, 2025).

The limitations of conventional inorganic coagulants have spurred research into alternative systems that incorporate organic components. Inorganic coagulants, though cost-effective, exhibit critical flaws such as zero biodegradability and potential residual metal toxicity (Bhamidipati et al., 2021; Kweinor Tetteh and Rathilal, 2019). Moreover, studies have shown that the sludge produced from these coagulants often exhibits poor dewaterability and limited reuse potential (Lee et al., 2023). In contrast, organic and hybrid coagulants offer several advantages, such as effective performance at lower dosages and potential environmental compatibility—though their biodegradability must be rigorously assessed before widespread implementation (Kweinor Tetteh and Rathilal, 2019; Abujazar et al., 2022).

In the scope of this study, hybrid coagulants refer to chemical systems that combine an inorganic salt—commonly PAC—with one or more organic polymers such as polyDADMAC, polyacrylamide (PAM), or polyamines. While the inorganic portion is environmentally persistent, the environmental impact of the hybrid system depends heavily on the biodegradability of the organic fraction. Therefore, evaluating the fate of these organic polymers in natural or engineered aquatic systems is a vital component of sustainability-focused wastewater treatment design.

Among the focus polymers in hybrid systems, polyDADMAC is frequently cited for its high flocculation efficiency due to strong cationic charge but is poorly biodegradable and known to generate dimethylamine (DMA), a precursor to the carcinogenic compound NDMA during ozonation (Padhye et al., 2011). Polyamines, on the other hand, demonstrate superior biodegradability in certain configurations and have shown promising pollutant removal performance when applied as standalone or hybrid coagulants in wastewater treatment. In contrast, polyacrylamide (PAM) exhibits partial biodegradability that depends on factors such as molecular weight and environmental conditions;

however, its monomer, acrylamide, is toxic and strictly regulated due to its potential health risks (Cainglet et al., 2023; Cheng et al., 2024).

Although empirical biodegradation tests such as BOD, CO_2 evolution, and OECD guidelines are the gold standard, they are often costly and time-consuming (Strotmann et al., 1995). In this context, QSAR-based computational tools such as the EPA's BIOWIN model provide rapid, cost-effective estimations of a compound's aerobic and anaerobic degradation potential. BIOWIN operates via fragment-based molecular substructure recognition and includes seven submodels (BIOWIN 1–7), each addressing different aspects of biodegradability such as probability, speed, and environmental conditions (Lim, 2016).

BIOWIN has been successfully used to predict biodegradability outcomes that correlate well with OECD test results in various studies (Kılıç and Çeçen, 2023; Gül and Çeçen, 2021). Submodels 3 and 5 in particular are widely utilized in regulatory assessments for new polymeric materials, despite known limitations in accuracy for highly branched or ionized structures. Nonetheless, its utility for preliminary environmental screening remains significant.

In conclusion, evaluating the biodegradability of coagulant components—especially synthetic organic polymers—in hybrid systems is critical for designing wastewater treatment technologies that align with environmental sustainability goals. The results of BIOWIN-based predictions for the polymers under study will be presented and interpreted in detail in Section 4.2 of this thesis.

3. MATERIALS AND METHODS

3.1. Process Overview at Çorlu Leather Industrial Zone

Wastewater samples were collected from the Çorlu Leather Organized Industrial Zone (Çorlu Deri OSB), located in the Ergene district of Tekirdağ province. The region is a major hub for leather production in Türkiye, with an annual processing capacity of approximately 25 million small ruminant hides and 50,000 tons of bovine hides—corresponding to nearly 37% of the country's total leather output. The centralized wastewater treatment plant serving the zone is designed to manage complex industrial effluents, primarily from leather processing facilities. According to operational data, the plant has a design capacity of 35,000–40,000 m^3/day, although actual influent volumes fluctuate seasonally. Flow rates typically decrease to around 3,000–4,000 m^3/day in winter months (February–March) and rise significantly during peak production by May.

Wastewater generated by the industrial facilities within the Çorlu Leather Organized Industrial Zone is treated in a centralized plant equipped with advanced technologies to ensure maximum treatment efficiency, particularly for leather industry effluents. The treatment system is structured into four primary sections: physical, chemical, biological, and sludge dewatering units. Figure 3.1 presents an overall visual representation of the treatment plant infrastructure, while Figure 3.2 illustrates the general layout of the plant and the units employed in the process.



Figure 3.1. Visual representation of the treatment plant infrastructure. (Çorlu Deri ve Karma OSB, n.d.)

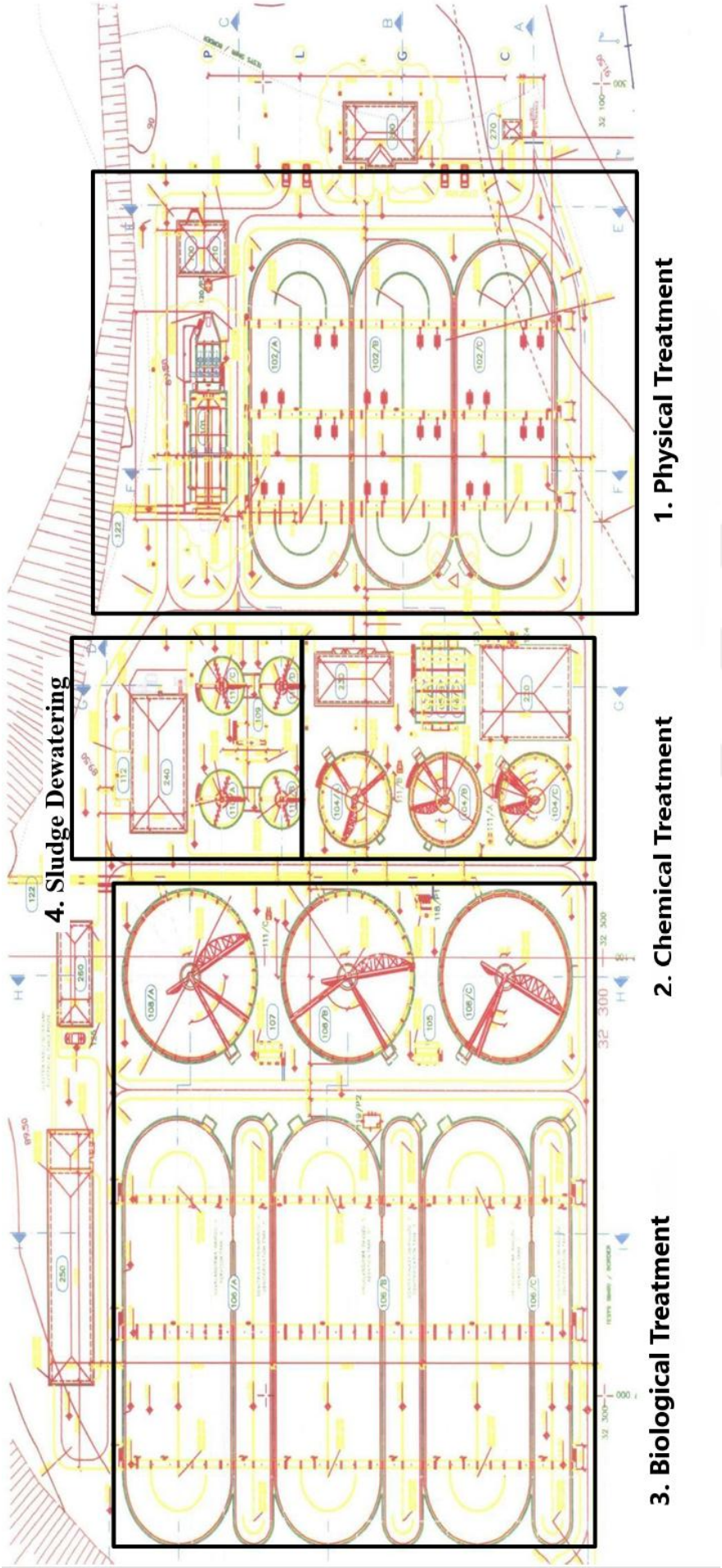


Figure 3.2. General layout of the wastewater treatment plant. (Çorlu Deri İhtisas ve Karma Organize Sanayi Bölge Müdürlüğü, n.d.)

3.1.1. Physical Treatment Stage

The physical treatment section of the Çorlu Leather Organized Industrial Zone Wastewater Treatment Plant is designed to eliminate coarse and fine solids, oil, and grit from the influent, thereby protecting downstream units and enhancing overall system performance. The process begins with preliminary screening, where the raw wastewater passes through two automatic and one manual coarse screen, each with a total capacity of 2,250 m^3/h, effectively removing large, suspended particles that may cause mechanical damage or operational issues in subsequent stages. The screened flow is then directed to a lifting station which elevates the wastewater to the fine screening stage.

Fine screening is achieved using three Huber Rotomat units, each with a design capacity of 2,250 m^3/h. These units retain smaller particulates that escape the coarse screens, ensuring a cleaner influent for subsequent treatment. The wastewater then enters two aerated grit and oil separators, each with a capacity of 4,500 m^3/h. Within these units, floating oils and grease are removed by mechanical scrapers and directed to collection tanks.

The final step in the physical treatment line is equalization, which plays a critical role in buffering hydraulic and pollutant fluctuations. This is achieved through three equalization tanks, each with a daily capacity of 12,000 m^3, where homogenization is ensured via 24 jet aerators (15 kW each). These tanks also function as neutralization basins, with lime dosing used to maintain pH levels within the range of 8.0 to 8.5. Following equalization, the preconditioned wastewater is pumped to the chemical treatment stage.

3.1.2. Chemical Treatment Stage

The chemical treatment stage constitutes a critical component of the overall treatment process, aiming to remove colloidal matter and fine suspended solids that are not adequately addressed during physical pretreatment. This phase begins in the coagulation tanks, where aluminum sulfate is dosed under controlled pH conditions to neutralize the electrostatic charges on suspended solids. The facility is equipped with three rapid mixing tanks, each designed to handle a flow rate of 500 m^3/h, to ensure effective dispersion of the coagulant throughout the wastewater.

The partially conditioned flow then enters six flocculation tanks, each designed to handle a flow rate of 500 m^3/h, where gentle mixing promotes the formation of larger, more settleable flocs. Anionic polyelectrolytes are automatically dosed at this stage to enhance floc cohesion and settling efficiency.

These flocs are subsequently removed in the chemical sedimentation units, which consist of three circular clarifiers. In these tanks, solid–liquid separation occurs: the settled sludge is extracted from the bottom via dedicated pumps and sent to the sludge handling line, while surface foam is removed through a scum collection system.

The clarified effluent from the sedimentation stage is then conveyed to the biological treatment units, where the remaining dissolved pollutants are removed. Following this, the flow continues through the sludge dewatering stages of the plant.

3.1.3. Downstream Processes: Biological Treatment and Sludge Management

A brief overview of the downstream biological and sludge management units is provided to contextualize their contribution to overall treatment performance and sludge formation.

3.1.3.1. Biological treatment unit. The biological treatment line operates through a sequence of denitrification, aeration, and clarification processes. Nitrogen removal is initiated in three anoxic denitrification tanks, where nitrates are biologically reduced to nitrogen gas. This is followed by aerobic degradation in three aeration tanks, where organic compounds are oxidized by microbial activity and ammonia is transformed to nitrate via nitrification. Internal circulation between these tanks allows for efficient conversion of nitrogen species under alternating redox conditions.

Subsequently, the flow proceeds to three secondary clarifiers, enabling the gravitational separation of biomass. Part of the settled sludge is recirculated to maintain biological activity, while excess sludge is directed to the sludge handling unit. Oxygen supply to the aeration tanks is maintained through nine blowers distributed across the system.

The final treated effluent, characterized by relatively high salinity is discharged into the Marmara Sea via an offshore outfall near Marmara Ereğlisi. During on-site evaluations, the potential for effluent reuse and water reclamation was discussed with facility personnel. Despite the growing emphasis on sustainable water management in industrial zones, officials indicated that the existing demand is currently met through groundwater abstraction, which remains both technically feasible and economically favorable under current conditions. As such, the development of advanced reuse infrastructure such as reverse osmosis or filtration systems has not been prioritized in the short term due to lack of immediate necessity and high associated capital costs. The process flow diagram of the biological treatment stage is presented in detail in Figure 3.3.

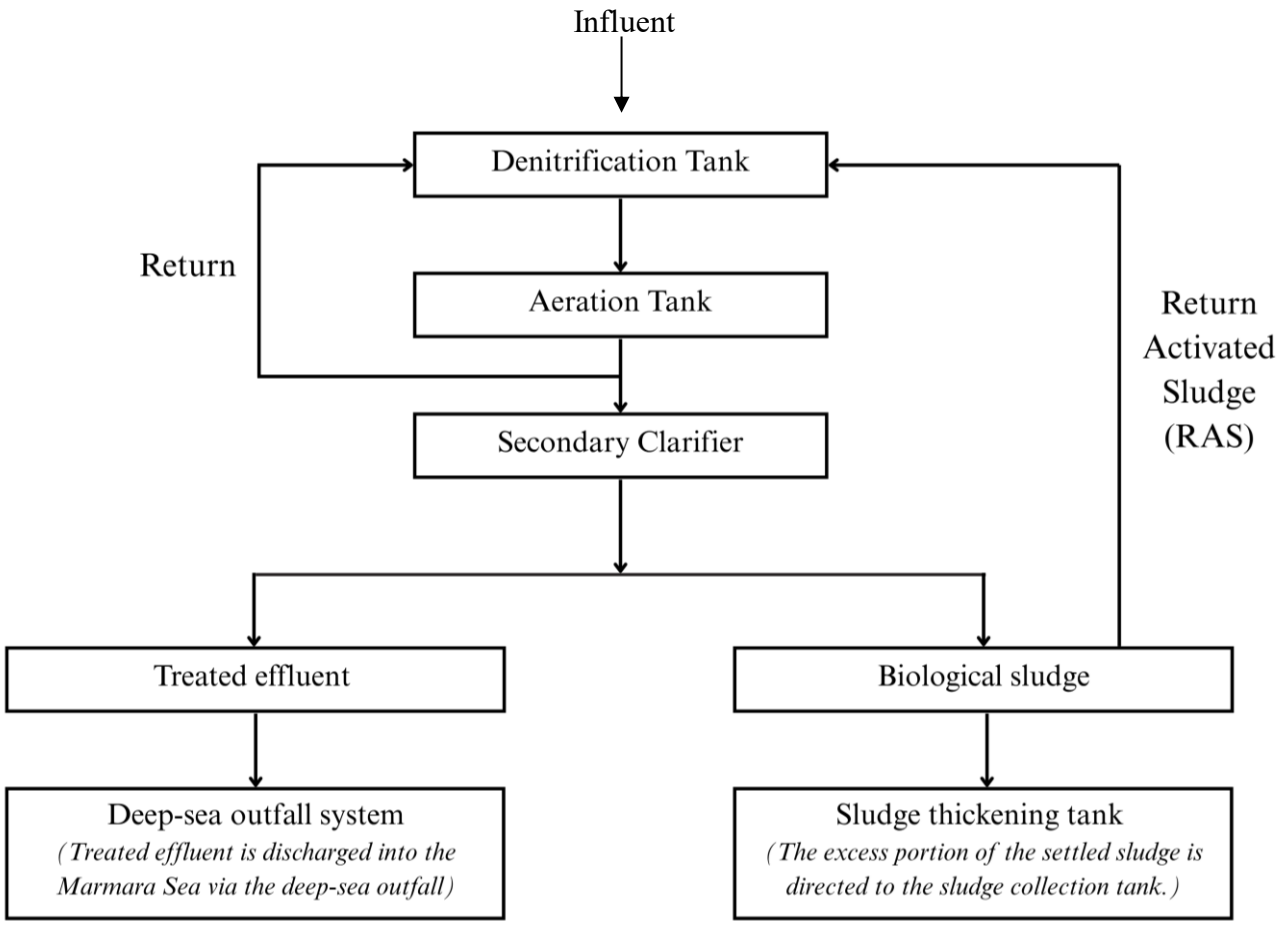


Figure 3.3. Process flow diagram of biological treatment unit.

3.1.3.2. Sludge dewatering unit and drying process. Sludge produced during chemical and biological sedimentation processes is initially directed to a central sludge collection tank, where homogenization is achieved using a mechanical paddle mixer. From this point, the sludge is conveyed to one of four gravity thickening tanks. The settled sludge is pumped to a distribution chamber and then sent to the decanter.

In the decanter units, automatic dosing of cationic polymer facilitates effective dewatering by enhancing the separation of water from solids. Each decanter is designed to process sludge at a flow rate of 1.5 tons per hour. The liquid phase extracted during this process is recycled to the equalization tank, while the dewatered sludge cake is transferred via enclosed conveyors to storage containers. At this stage, the dry solids content of the sludge typically reaches 18–25%.

The partially dewatered sludge is then subjected to drying. It is first directed through an intermediate storage silo and granulation unit, after which it enters the sludge drying unit. Here, moisture content is further reduced to approximately 5%, resulting in the production of stabilized dry sludge suitable for long-term storage or disposal. The dried sludge is conveyed to a dry sludge silo

through a discharge conveyor system. To control odor emissions associated with sludge processing and storage, biofilters are installed at key locations along the treatment line. An overview of the sludge dewatering and thermal drying stages is presented in Figure 3.4. This integrated dewatering and drying process significantly reduces sludge volume and weight, thereby improving manageability and minimizing final disposal costs.

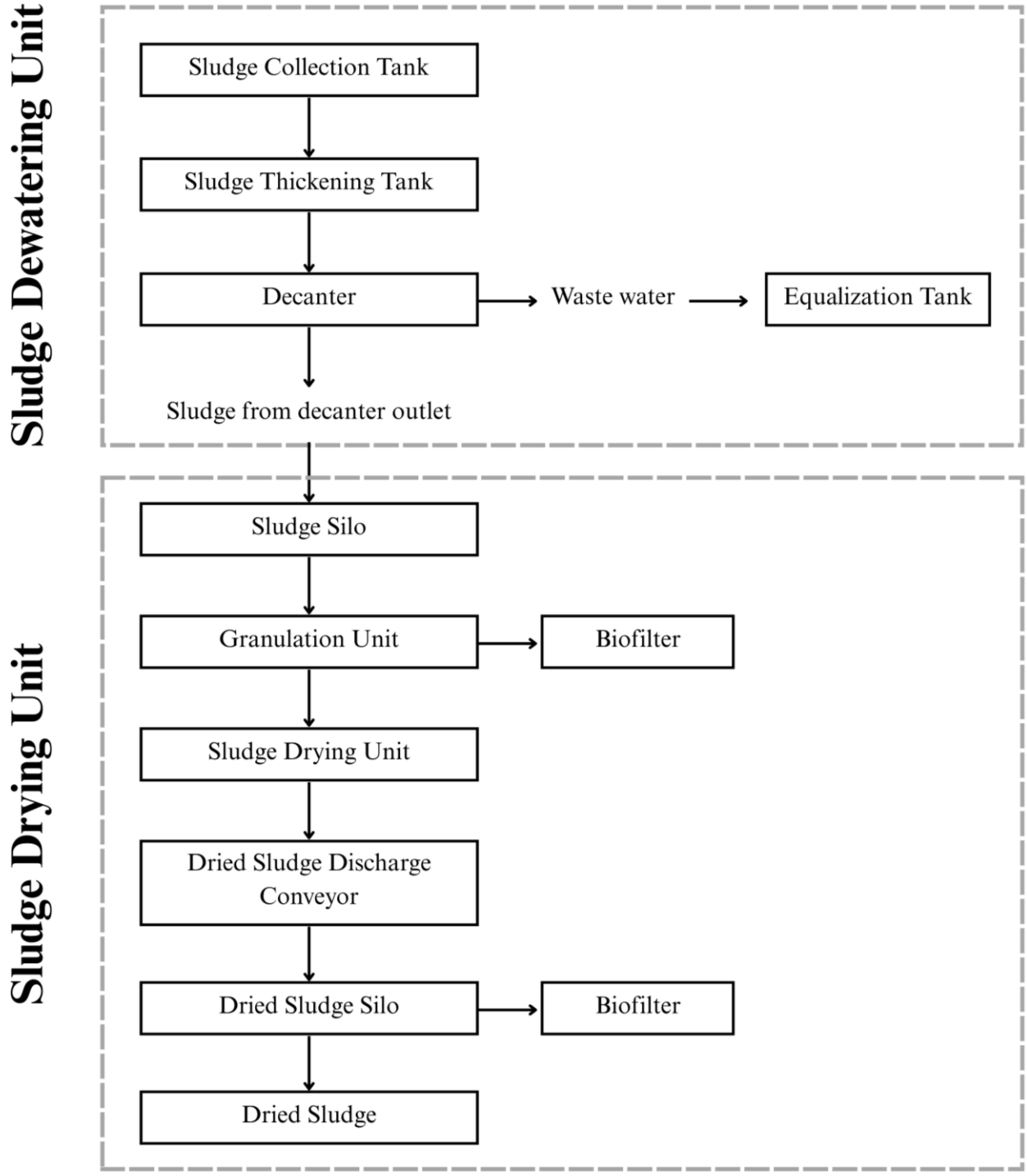


Figure 3.4. Process flow diagram of sludge dewatering and drying units.

According to technical insights obtained during site visits and operational briefings, the extensive use of aluminum sulfate, lime, and synthetic polyelectrolytes in the chemical treatment units has been identified as a major contributor to excessive sludge generation. These coagulants and flocculants, while effective in pollutant removal, promote the formation of dense flocs and residual solids, resulting in substantial sludge production. Consequently, the facility faces operational challenges related to the handling, thickening, and disposal of sludge, which not only requires extensive infrastructure (e.g., thickening tanks, decanters, drying units) but also imposes considerable economic burdens due to disposal costs and regulatory compliance. This issue has become increasingly critical as industrial zones strive to improve both environmental performance and cost efficiency. Within this context, the development of alternative treatment aids such as the hybrid coagulant–flocculant systems investigated in this study offers a promising solution. By reducing sludge generation while maintaining or enhancing treatment performance, such materials could potentially mitigate one of the most pressing limitations of conventional chemical treatment schemes.

3.2. Experimental Design and Analytical Framework

This study was designed to systematically evaluate the treatment performance of polymer-based hybrid coagulants in comparison with conventional chemical methods for leather industry wastewater. The experimental protocol followed a structured multi-phase approach that simulated full-scale operating conditions under controlled laboratory settings. The stepwise design of the study is described in detail in the subsequent sections.

3.2.1. Sampling Procedure

Based on preliminary consultations with plant engineers and subject-matter experts, composite samples were collected in consecutive months capturing low and high production (April and May 2025) to ensure reliable characterization of wastewater quality across operating regimes at project initiation. These periods correspond to times of reduced and intensified industrial activity within the facility, respectively, and therefore reflect contrasting influent loading rates. Specifically, April represents a transitional period with lower production volume following winter maintenance and reduced operational demand, while May coincides with a ramp-up in production due to increased orders and warmer weather, leading to higher wastewater flow and contaminant loads. These months were selected as representative operational extremes across seasonal regimes.

In order to obtain representative samples of the raw industrial wastewater, samples were collected from the inlet channel located immediately upstream of the equalization tanks. This point was selected because equalization involves substantial lime dosing for pH adjustment, which alters the wastewater's chemical composition—particularly its alkalinity—and would therefore compromise the characterization of the true influent. Sampling prior to lime addition ensures that the collected wastewater reflects the untreated composite load generated by the industrial facilities within the zone, providing a reliable basis for assessing pollutant characteristics and designing appropriate treatment strategies. The selected upstream channel, which allows direct grab sampling, is marked on the process flow diagram of the physical and chemical treatment units shown in Figure 3.5.

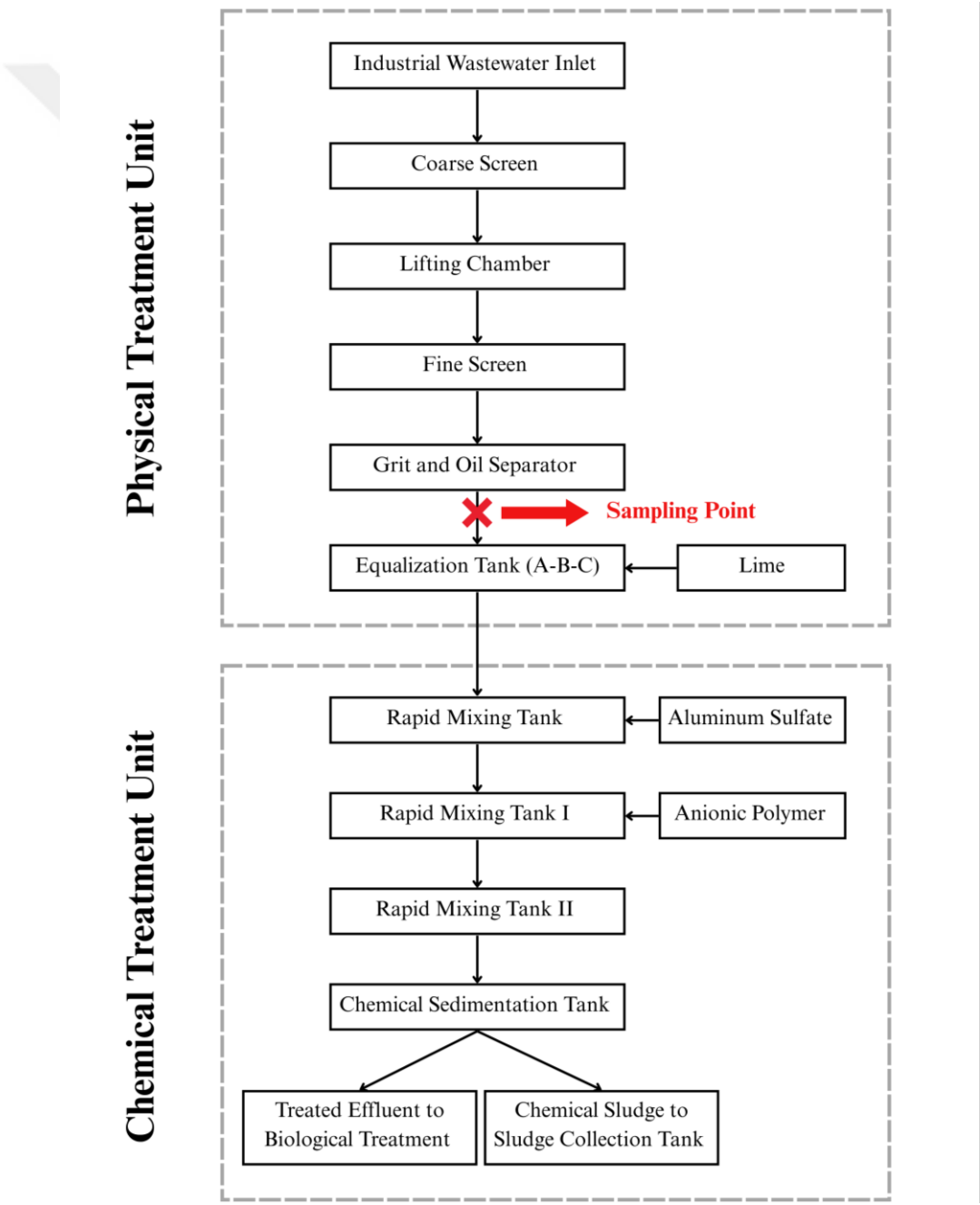


Figure 3.5. Process flow diagram of physical and chemical treatment units.

The treatment plant operates continuously on a 24/7 basis; therefore, 24-hour composite sampling was adopted to reflect diurnal variations in flow and pollutant concentrations. Each composite sample consisted of 20 liters of raw wastewater, collected from the same designated sampling. All samples were collected under consistent conditions to ensure comparability and reproducibility across sampling dates. The specific sampling days for each period are summarized in Table 3.1.

Table 3.1. Composite sampling schedule for low and high production periods.

Sampling Period	Date	Sample Code	Sample Type	Volume	Location
Low Production	April 3, 2025	YL-ATK-0401	24-hour composite	20 L	Upstream of Equalization Tank
Low Production	April 4, 2025	YL-ATK-0402	24-hour composite	20 L	Upstream of Equalization Tank
Low Production	April 8, 2025	YL-ATK-0403	24-hour composite	20 L	Upstream of Equalization Tank
Low Production	April 10, 2025	YL-ATK-0404	24-hour composite	20 L	Upstream of Equalization Tank
Low Production	April 14, 2025	YL-ATK-0405	24-hour composite	20 L	Upstream of Equalization Tank
Low Production	April 16, 2025	YL-ATK-0406	24-hour composite	20 L	Upstream of Equalization Tank
Low Production	April 18, 2025	YL-ATK-0407	24-hour composite	20 L	Upstream of Equalization Tank
Low Production	April 22, 2025	YL-ATK-0408	24-hour composite	20 L	Upstream of Equalization Tank
Low Production	April 24, 2025	YL-ATK-0409	24-hour composite	20 L	Upstream of Equalization Tank
Low Production	April 28, 2025	YL-ATK-0410	24-hour composite	20 L	Upstream of Equalization Tank
Low Production	April 30, 2025	YL-ATK-0411	24-hour composite	20 L	Upstream of Equalization Tank
High Production	May 02, 2025	YL-ATK-0501	24-hour composite	20 L	Upstream of Equalization Tank
High Production	May 05, 2025	YL-ATK-0502	24-hour composite	20 L	Upstream of Equalization Tank

Sampling Period	Date	Sample Code	Sample Type	Volume	Location
High Production	May 07, 2025	YL-ATK-0503	24-hour composite	20 L	Upstream of Equalization Tank
High Production	May 09, 2025	YL-ATK-0504	24-hour composite	20 L	Upstream of Equalization Tank
High Production	May 13, 2025	YL-ATK-0505	24-hour composite	20 L	Upstream of Equalization Tank
High Production	May 15, 2025	YL-ATK-0506	24-hour composite	20 L	Upstream of Equalization Tank
High Production	May 19, 2025	YL-ATK-0507	24-hour composite	20 L	Upstream of Equalization Tank
High Production	May 21, 2025	YL-ATK-0508	24-hour composite	20 L	Upstream of Equalization Tank
High Production	May 23, 2025	YL-ATK-0509	24-hour composite	20 L	Upstream of Equalization Tank
High Production	May 27, 2025	YL-ATK-0510	24-hour composite	20 L	Upstream of Equalization Tank
High Production	May 29, 2025	YL-ATK-0511	24-hour composite	20 L	Upstream of Equalization Tank

All collected wastewater samples were transferred into clean, labeled high-density polyethylene (HDPE) drums immediately after collection and stored under controlled conditions to preserve their physical and chemical integrity prior to analysis. The samples were kept in a cool, dry, and shaded environment to reduce microbial activity and chemical alterations until laboratory analysis. These handling procedures were designed to maintain representative sample quality in accordance with good laboratory practices for complex industrial effluents, particularly those originating from the leather industry (APHA, 2017).

As part of the sampling schedule, the filled drums were routinely collected by courier and promptly delivered to the experimental laboratory, where analyses were initiated without delay. This procedure ensured consistency, traceability, and representative sample quality throughout the study. An illustrative image of the sample drums delivered to the plant at the beginning of the study, along with a close-up view of an individually labeled drum, is presented in Figure 3.6.



(a)



(b)

Figure 3.6. (a) Sample drums delivered to the treatment plant at the beginning of the study; (b) close-up of an individually labeled drum used to ensure traceability during the 22-day composite sampling program.

The collected samples were stored in a refrigerator at 4 °C whenever extended holding times or additional analyses were required, thereby ensuring sample integrity throughout the study. A large laboratory refrigerator was used to store the bulk of daily collected samples. In addition, a mini refrigerator was employed for short-term storage during experimental procedures, particularly for phase-separated subsamples awaiting analysis. An illustrative image from the mini refrigerator, which was used for short-term storage during experimental work, is presented in Figure 3.7.



Figure 3.7. Mini laboratory refrigerator used for the short-term storage of phase-separated samples during the experiments.

3.2.2. Preparation and Characterization of Polymer-Based Hybrid Coagulants

Prior to the experimental phase of this study, a wide set of coagulant mixtures was prepared to assess the treatment performance of polymer-based hybrid coagulants relative to conventional agents. These hybrid materials were developed based on the structural hybridization strategy described in Section 2.3.2.1, which involves the physical combination of organic and inorganic coagulants without inducing chemical reactions or forming new compounds (Lee et al., 2012). The objective was to engineer synergistic blends that could improve coagulation efficiency, minimize sludge production, and reduce the overall chemical dosage required in the treatment process. These combinations were specifically designed for this study, rather than adapted from existing formulations, and were selected based on their expected compatibility and potential to generate synergistic coagulation effects under leather wastewater conditions.

Initially, a theoretical pool of potential coagulant combinations was defined to explore a broad range of possible synergistic interactions. Specifically, polyaluminum chloride (PAC 30, PAC 17), ferric chloride ($FeCl_3$), and aluminum sulfate ($Al_2(SO_4)_3$) were employed as inorganic coagulants, while polyDADMAC and polyamine were used as organic polymers. These materials were first weighed according to target dosage levels and then dissolved and homogenized in deionized water under controlled ambient conditions.

First, all candidate formulations were subjected to stability screening under standardized conditions. These mixtures were stored in sealed containers at room temperature and observed over a 24–48 hour period for signs of instability. Evaluation criteria included:

- Phase separation or stratification
- Precipitate formation or sedimentation
- Gelation or excessive foaming
- Handling issues such as abnormal viscosity or inadequate dispersion during mixing

Formulations displaying any of the above characteristics were considered physically incompatible or operationally impractical and were therefore excluded from further experimentation. Only those maintaining uniform, homogeneous, and stable physical properties throughout the observation period were retained. Second, practical applicability during dosing and mixing was also considered. Blends that presented challenges such as clogging, overly thick consistency, or poor mixing behavior were similarly ruled out to ensure that selected products would be feasible for real-world implementation.

Among the initial formulation candidates, the blend shown in Figure 3.6 was excluded due to insufficient physical stability. After a 24-hour resting period, the sample displayed distinct phase separation and visible particulate agglomerates, indicating poor miscibility between the organic and inorganic components. Since this formulation did not advance to the performance testing stage, its detailed composition is not reported; Figure 3.8. is included only to illustrate a typical case of physical instability observed during preliminary screening.

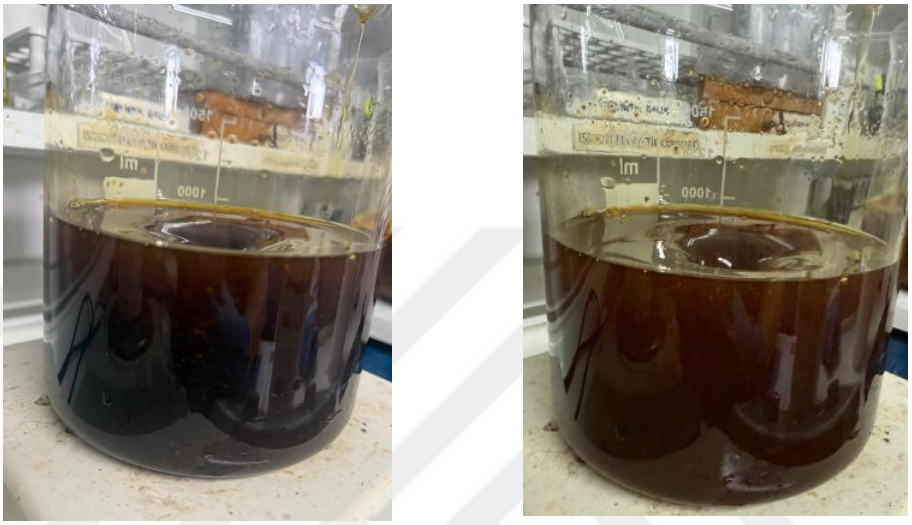


Figure 3.8. Visual illustration of particulate agglomerates formed in a physically incompatible hybrid coagulant.

To introduce the raw materials used in the hybrid coagulant formulations, Table 3.2 provides a comprehensive description of each inorganic and organic component included in this study. Each substance is described by its IUPAC name or common name, abbreviation used in the thesis, molecular or structural formula (where applicable), CAS number, molecular weight, manufacturer, and origin. For completeness, PAM is also listed in the table; however, it was used solely as a coagulant aid and was not incorporated into any of the hybrid formulations.

Building on this material inventory, the specific hybrid formulations created using these components are detailed in Table 3.3, which summarizes the 16 selected formulations developed for experimental testing. For benchmarking purposes, the table also includes the alum-based full-scale plant method and two widely used conventional coagulants (PAC 17 and $FeCl_3$) from the literature, allowing the performance of the hybrid formulations to be evaluated against established treatment practices.

Table 3.2. Overview of coagulants and flocculants used in hybrid formulation development.

Type	Abbreviation	Full Chemical Name	Chemical Formula	CAS Number	Origin	Molecular Weight (g/mol)
Inorganic Coagulant	PAC	Polyaluminum chloride *(Powder)*	$\{Al_2(OH)_nCl_{6-n}(H_2O)\}_m$	1327-41-9	China	*N/A**
Inorganic Coagulant	PAC 17	Polyaluminum chloride *(17% liquid)*	$Al(OH)_aCl_b(SO_4)_c$	1327-41-9	Türkiye	*Polymeric aluminum salt; no fixed molecular weight (polymeric mixture)*
Inorganic Coagulant	$FeCl_3$	Iron (III) chloride	$FeCl_3$	7705-08-0	Türkiye	162.2
Inorganic Coagulant	Alum	Aluminum sulfate	$Al_2(SO_4)_3 \cdot 18H_2O$	10043-01-3	Türkiye	594.4
Organic Cationic Polymer	PolyDADMAC / PDADMAC	Poly(diallyldimethylammonium chloride)	$(C_8H_{16}ClN)_n$	26062-79-3	China	20,000.00
Organic Cationic Polymer	Polyamine	Poly[(dimethylimino) (2-hydroxy-1,3-propanedily) chloride]	$[-CH_2CH(OH)CH_2N(CH_3)_2Cl-]_n$	25988-97-0	China	*Cationic polymer; broad molecular weight distribution (producer-specific)*

Type	Abbreviation	Full Chemical Name	Chemical Formula	CAS Number	Origin	Molecular Weight (g/mol)
Anionic Flocculant Aid	PAM	Poly(2-propenamide-co-sodium acrylate) / *(Anionic Polyacrylamide)*	[–CH_2–CH($CONH_2$)–]m / [–CH_2–CH(COONa)–]n	9003-05-8	France	*High molecular weight (>10^6 Da), polydisperse*

Notes:

- ✓ The CAS number for PAM (Polyacrylamide) is represented generically as 9003-05-8, which covers a wide range of copolymers based on acrylamide. Due to proprietary compositions, the specific CAS number was not provided by the manufacturer.
- ✓ *PAC has no fixed molecular weight due to its variable polymeric structure. Manufacturer reports key specifications such as basicity and Al content instead.
- ✓ Product specifications for all chemicals listed in Table 3.2 were obtained from the manufacturers' official websites, and the corresponding sources are cited in the reference list (AKKİM, n.d.-a; AKKİM, n.d.-b; May Asit, 2020; Shandong Jiahua Water Treatment Technology Co., Ltd, 2025; SNF Floerger Kimya San. ve Tic. Ltd. Şti., 2025; Wuxi Lansen Chemicals Co., Ltd, 2023a; Wuxi Lansen Chemicals Co., Ltd, 2023b).

Table 3.3. Summary of all tested coagulant formulations.

Type	Code	Inorganic Chemical Coagulant I	Amount of Inorganic Chemical Coagulant I (g)	Inorganic Chemical Coagulant II	Amount of Inorganic Chemical Coagulant II (g)	Organic Chemical Coagulant I	Amount of Organic Chemical Coagulant I (g)	Organic Chemical Coagulant II	Amount of Organic Chemical Coagulant II (g)	Amount of Deionized Water (g)
Hybrid Material Combinations Developed in This Study	**P010100**	%30 w/w solution of PAC powder	30	-	-	PolyDADMAC	5	-	-	65
	P010101	%30 w/w solution of PAC powder	30	-	-	Polyamine	5	-	-	65
	P010102	%30 w/w solution of PAC powder	30	-	-	-	-	-	-	70
	P020100	PAC 17	50	-	-	PolyDADMAC	5	-	-	45
	P020101	PAC 17	50	-	-	Polyamine	5	-	-	45
	P020102	PAC 17	50	-	-	-	-	-	-	50
	P010200	%30 w/w solution of PAC powder	30	$FeCl_3$	8	PolyDADMAC	5	-	-	57
	P010201	%30 w/w solution of PAC powder	30	$FeCl_3$	8	Polyamine	5	-	-	57
	P010202	%30 w/w solution of PAC powder	30	$FeCl_3$	8	-	-	-	-	62
	P020200	PAC 17	57	$FeCl_3$	0.8	PolyDADMAC	5	-	-	37.2
	P020201	PAC 17	57	$FeCl_3$	0.8	Polyamine	5	-	-	37.2
	P020202	PAC 17	57	$FeCl_3$	0.8	-	-	-	-	42.2
	P010300	%30 w/w solution of PAC powder	10	PAC 17	32	PolyDADMAC	5	-	-	53

Type	Code	Inorganic Chemical Coagulant I	Amount of Inorganic Chemical Coagulant I (g)	Inorganic Chemical Coagulant II	Amount of Inorganic Chemical Coagulant II (g)	Organic Chemical Coagulant I	Amount of Organic Chemical Coagulant I (g)	Organic Chemical Coagulant II	Amount of Organic Chemical Coagulant II (g)	Amount of Deionized Water (g)
	P010301	%30 w/w solution of PAC powder	10	PAC 17	32	PolyDADMAC	2.5	Polyamine	2.5	53
	P010302	%30 w/w solution of PAC powder	25	-	-	PolyDADMAC	2.5	Polyamine	2.5	70
	P010303	%30 w/w solution of PAC powder	10	PAC 17	32	Polyamine	5	-	-	53
Conventional Methods	**P040100**	PAC 17	100	-	-	-	-	-	-	-
	P040101	$FeCl_3$ (40%)	100	-	-	-	-	-	-	-
	P040102	$Al_2(SO_4)_3$ (40%)	100	-	-	-	-	-	-	-

Notes:

- ✓ All coagulant formulations were prepared in batches of approximately 100 g total mass.
- ✓ Mixing was performed at ambient temperature under continuous stirring to ensure full homogenization.
- ✓ Deionized water was used as the solvent in all mixtures.
- ✓ No additional pH adjustment or chemical modification was applied during preparation.
- ✓ PAC powder was pre-dissolved to prepare a 30% (w/w) stock solution (30 g PAC powder + 70 g deionized water), and this solution was used in all formulations.
- ✓ A medium-anionic polyacrylamide (PAM), prepared as a solution by dissolving 0.5 g of the polymer in 1 L of water, will be incorporated as a coagulant aid during the experimental performance tests.

3.2.3. Experimental Treatment Scenarios and Workflow Design

In order to evaluate the performance of both conventional and hybrid coagulants, a set of six treatment scenarios (M1–M6) was designed. These scenarios allowed comparison under both pH-adjusted and non-adjusted conditions. As part of the assessment, the conventional lime-based pH correction method was also compared with NaOH to explore alternative chemical options for plant optimization.

- M1: Untreated raw wastewater, analyzed directly without any chemical intervention.
- M2: The laboratory-scale replication of the conventional treatment method applied at the full-scale facility, which involves lime-based pH adjustment followed by aluminum sulfate ($Al_2(SO_4)_3$).
- M3: This method represents a modified version of the M2 scenario, in which the lime-based pH adjustment step is replaced with sodium hydroxide (NaOH).
- M4: Scenarios where other conventional methods, as described in the literature, were applied, with sodium hydroxide used for pH adjustment.
- M5: The scenario in which the hybrid materials developed in this study were applied with pH adjustment using sodium hydroxide, bringing the pH to the target range of 8.30–9.00.
- M6: The scenario in which the hybrid materials developed in this study were applied directly without any pH adjustment.

Overall, M1 served as the reference condition, while M2 and M3 represented plant-based conventional methods with different pH adjustment chemicals. M4 included additional literature-based conventional approaches, and M5–M6 evaluated the developed hybrid materials with and without pH control. In all scenarios, coagulant addition was followed by a medium-anionic PAM to ensure comparability across treatments.

The hybrid group consisted of 16 combinations of inorganic and organic agents, as presented in Table 3.3. Due to the large number of possible experimental evaluations, the study followed a structured and manageable workflow. This approach structured the experimental design into sequential stages of screening, selection, optimization, and advanced analyses, providing a clear framework for comparing the performance of all treatment scenarios.

3.2.3.1. Preliminary screening stage. In the preliminary screening stage, all six treatment scenarios (M1–M6) and all hybrid formulations were evaluated at a uniform coagulant dose using a standard jar test procedure (rapid mixing for 2–3 minutes, followed by 15 minutes of slow stirring and a settling phase). The aim of this stage was to obtain a comparable baseline for fundamental performance indicators, including pH, turbidity, COD, TSS, and sludge volume. A total of 36 parallel coagulation–flocculation tests were carried out in 250 mL beakers for each experimental day, and the screening experiments were repeated over a 22-day period.

For scenarios M2–M6, each treated sample was separated into three phases—supernatant, centrifuged liquid, and sludge solids. Routine analyses were performed primarily on the supernatant (SUP) to provide a practical and reliable measure of effluent quality after sedimentation. All experiments were conducted under identical conditions, using equal wastewater volumes and fixed chemical dosages of 0.6 g/L coagulant and 1.6 g/L anionic polyelectrolyte. This ensured a fair comparison of the performance of different coagulant systems and hybrid formulations.

In contrast, the M1 scenario (raw wastewater) was not subjected to phase separation. COD, TSS, pH, and turbidity were measured directly on the homogenized sample prior to settling. Removal efficiencies in all scenarios were calculated relative to the raw wastewater characteristics obtained in M1, which served as the baseline reference.

As an illustrative example, Figure 3.9 presents the raw wastewater control (M1), and Figure 3.10 shows the outcomes of the uniform-dose screening for the same experimental day, highlighting visual differences in turbidity reduction and sludge formation across scenarios.



Figure 3.9. Raw wastewater sample (M1) used as the baseline reference in the screening experiments.

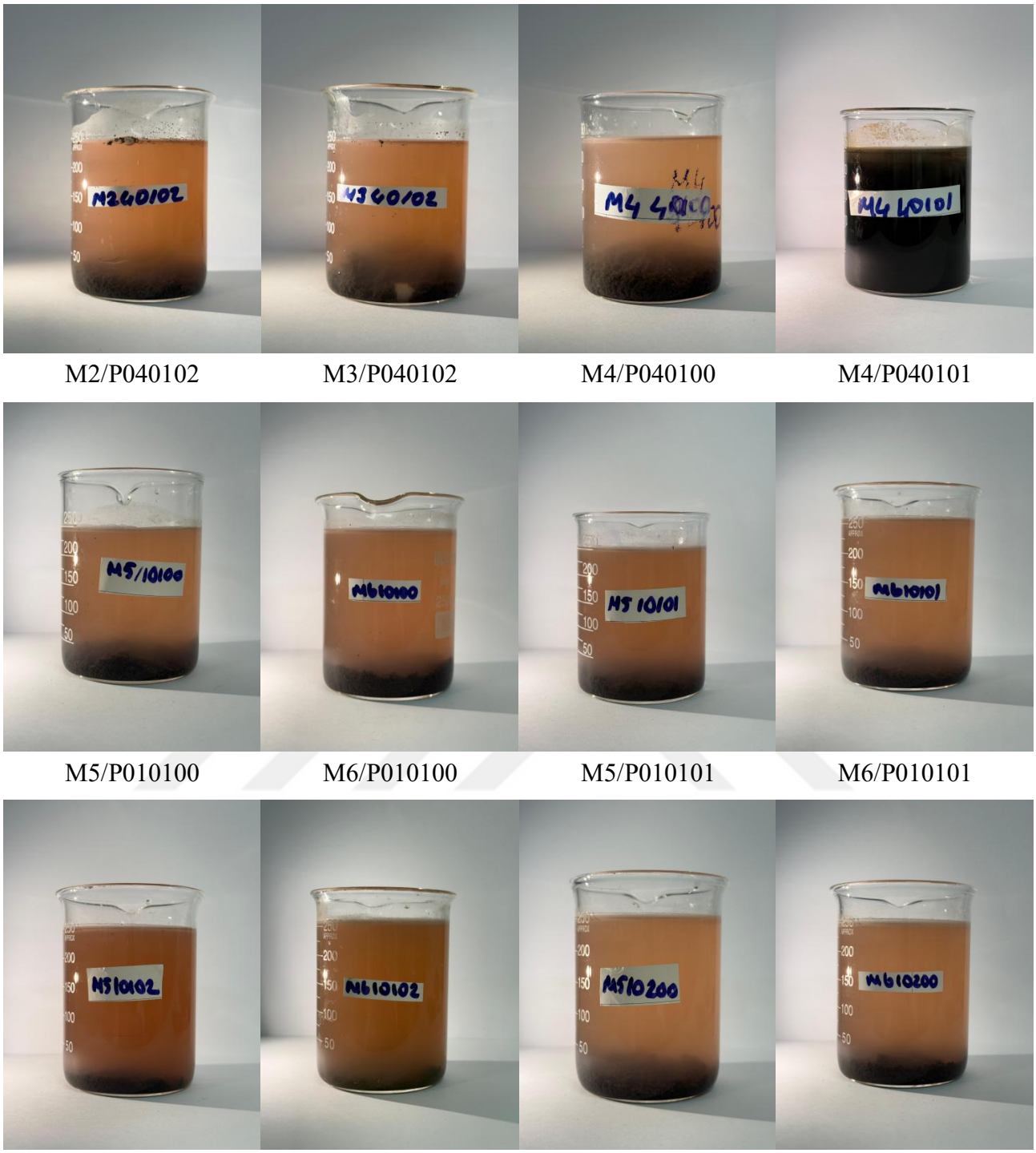


Figure 3.10. Visual outcomes of the uniform-dose screening stage for one experimental day.

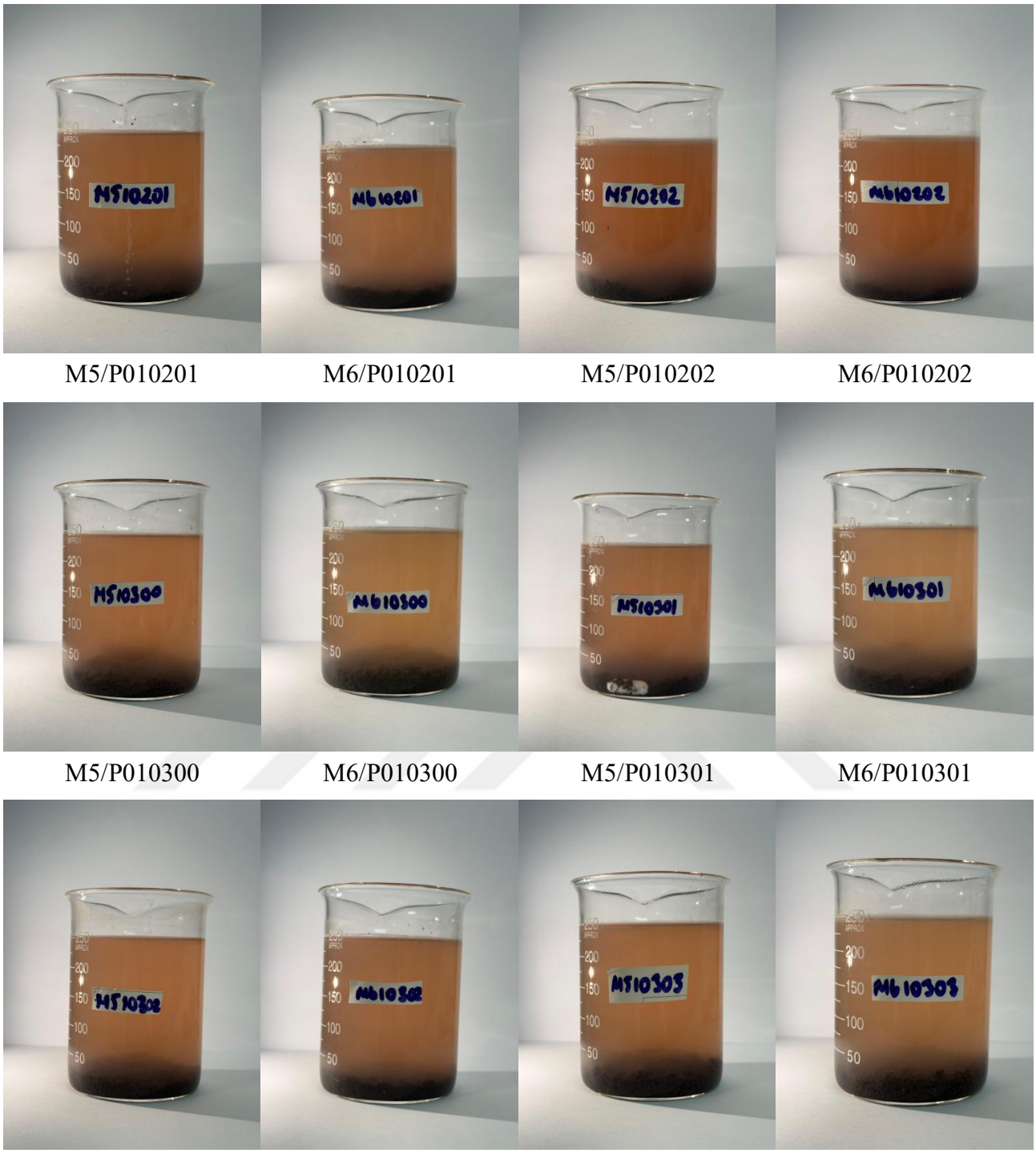
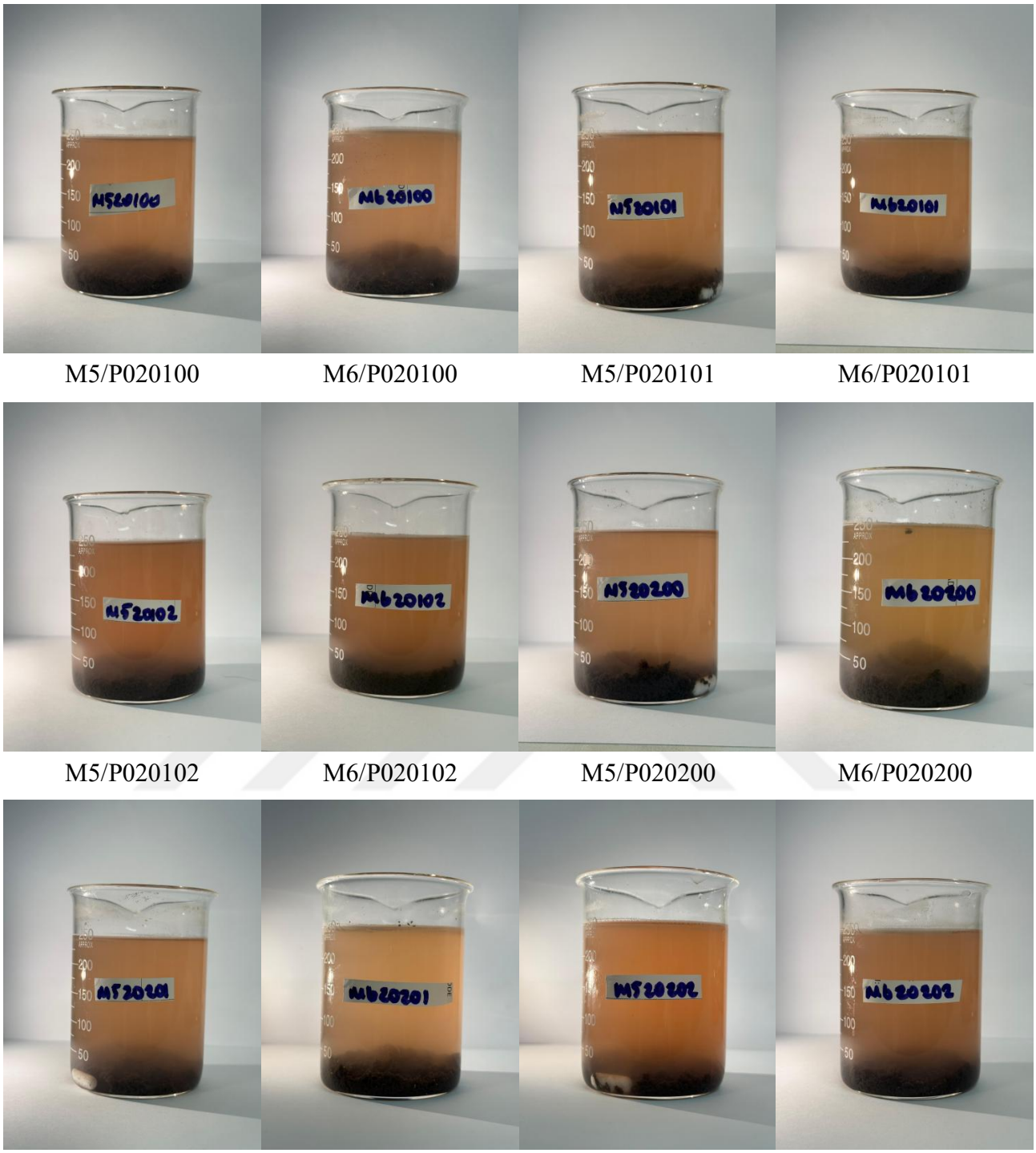


Figure 3.10. (continued)



M5/P020100 M6/P020100 M5/P020101 M6/P020101

M5/P020102 M6/P020102 M5/P020200 M6/P020200

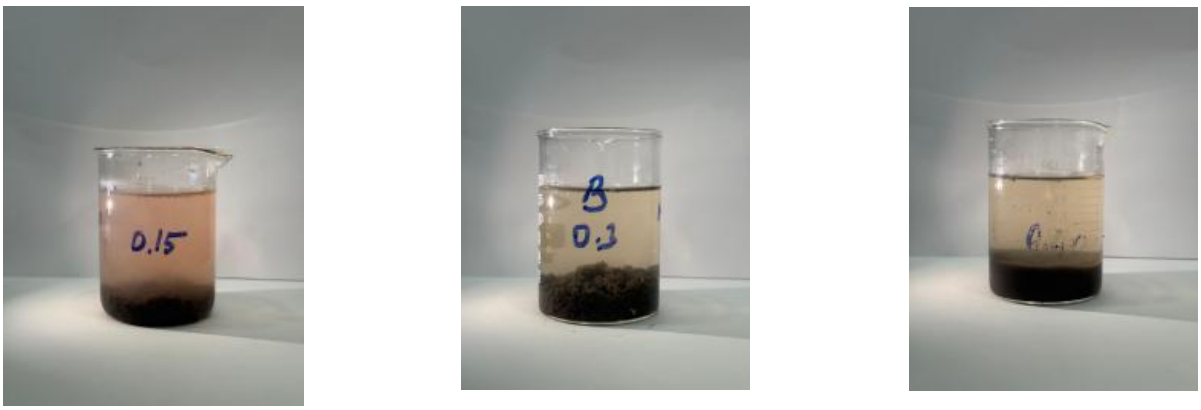
M5/P020201 M6/P020201 M5/P020202 M6/P020202

Figure 3.10. (continued)

3.2.3.2. Formulation selection stage. Following the screening stage, a structured selection procedure was applied in order to identify the most promising formulations. As an initial step of this process, the formulation coded M4/P040100, consisting of a 40% ferric chloride solution, was excluded due to its consistently inadequate performance; as shown in Figure 3.8, the sample exhibited neither a clear settling profile nor sufficient reductions in color and suspended solids.

For the remaining formulations, a comparative evaluation framework was developed in the form of an Excel-based calculation panel, which enabled the systematic ranking of products across the fundamental treatment parameters. While the detailed methodology and outcomes of this approach are presented in the Section 4, it is important to note here that the five top-performing formulations were selected as candidates for further study. These formulations were subsequently advanced to the dose optimization stage, where their treatment performance was re-evaluated under adjusted dosing conditions.

3.2.3.3. Dosage optimization stage. In optimization step, dose–response experiments were conducted to identify the minimum effective dosage for each of the five selected hybrid formulations. To determine the optimum operating range, six incremental dosages were tested per 250 mL wastewater sample: 600 mg/L, 1,200 mg/L, 2,000 mg/L, 2,400 mg/L, 2,800 mg/L, and 3,200 mg/L. This systematic approach enabled the determination of the lowest dose capable of achieving maximum treatment efficiency. The optimum dosage for each formulation was identified based on supernatant (SUP) measurements, including COD, TSS, sludge volume, and turbidity (see Section 4 for detailed results). Figure 3.11 provides representative images demonstrating the effect of dosage variation, comparing underdosing, optimum dosing, and overdosing conditions. The complete quantitative dose–response data for all formulations are reported in Section 4.



(a) (b) (c)

Figure 3.11. Dose–response results for one selected hybrid formulation: (a) showing insufficient removal; (b) showing effective turbidity and color removal with stable flocs; (c) showing increased sludge production and reduced floc stability.

3.2.3.4. Optimized-dose jar testing stage. After identifying the five selected formulations and determining their optimum dosages, the study progressed to its core analytical phase, in which the hybrid formulations were compared directly with the conventional treatment method used at the

facility. Under these optimized conditions, each formulation was subjected to a final jar-test procedure to generate the treated suspensions used in the subsequent analyses.

To contextualize this comparative assessment, Figures 3.12 and 3.13 present the procedural flow diagrams for the treatment scenarios M2–M6. These diagrams outline the stepwise operations specific to each method group, including the timing of pH adjustment, the coagulation–flocculation sequence, and the phases subjected to analysis. In contrast, the M1 scenario (raw wastewater) involved no treatment steps; the sample was analyzed directly after homogenization, with measurements limited to pH, COD, TSS, and turbidity. Accordingly, no flow diagram is provided for this case. Collectively, the diagrams establish the operational framework necessary for interpreting the phase-specific and comparative evaluations that follow.

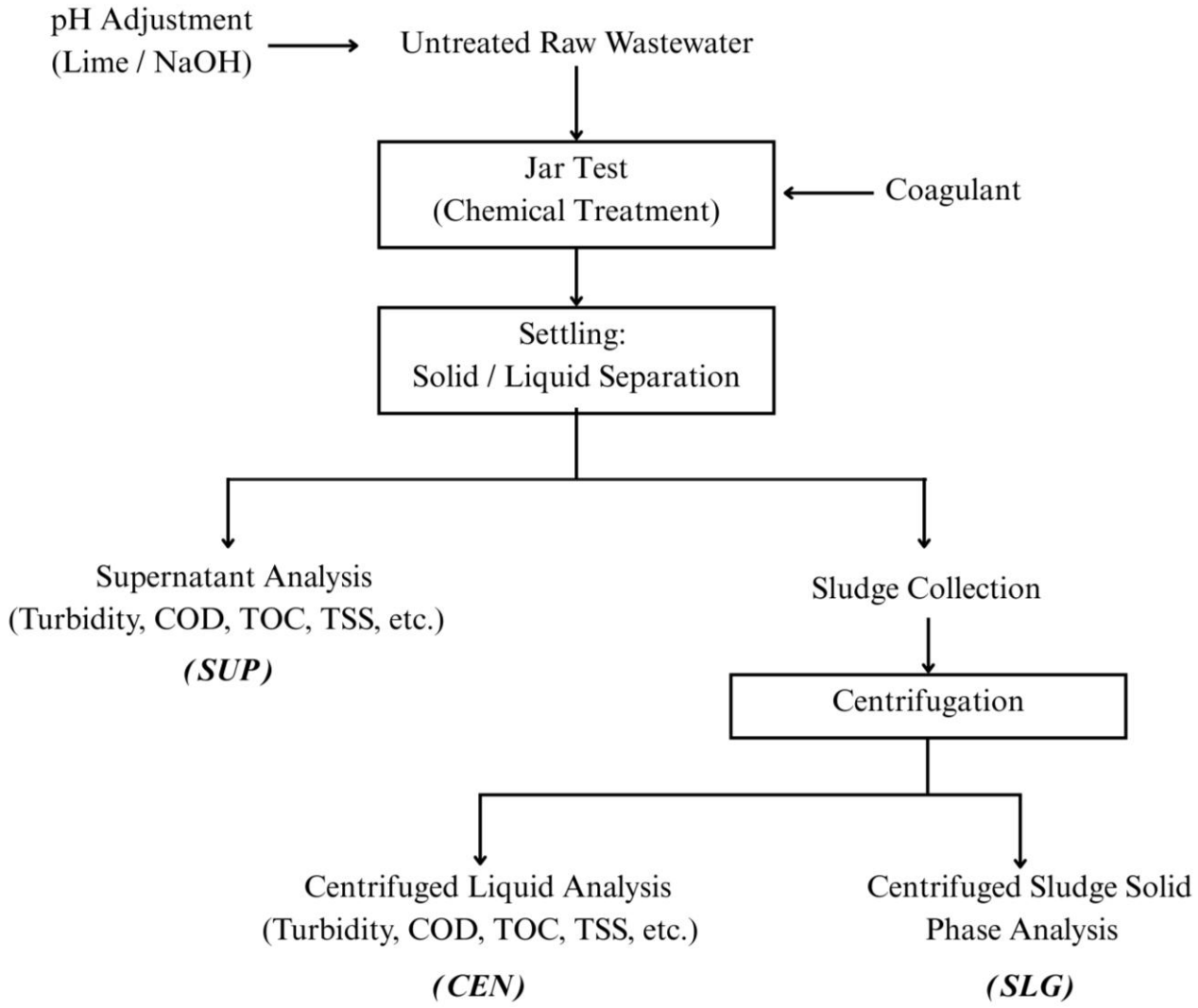


Figure 3.12. Experimental procedure for M2, M3, M4 and M5 – coagulation with pH adjustment.

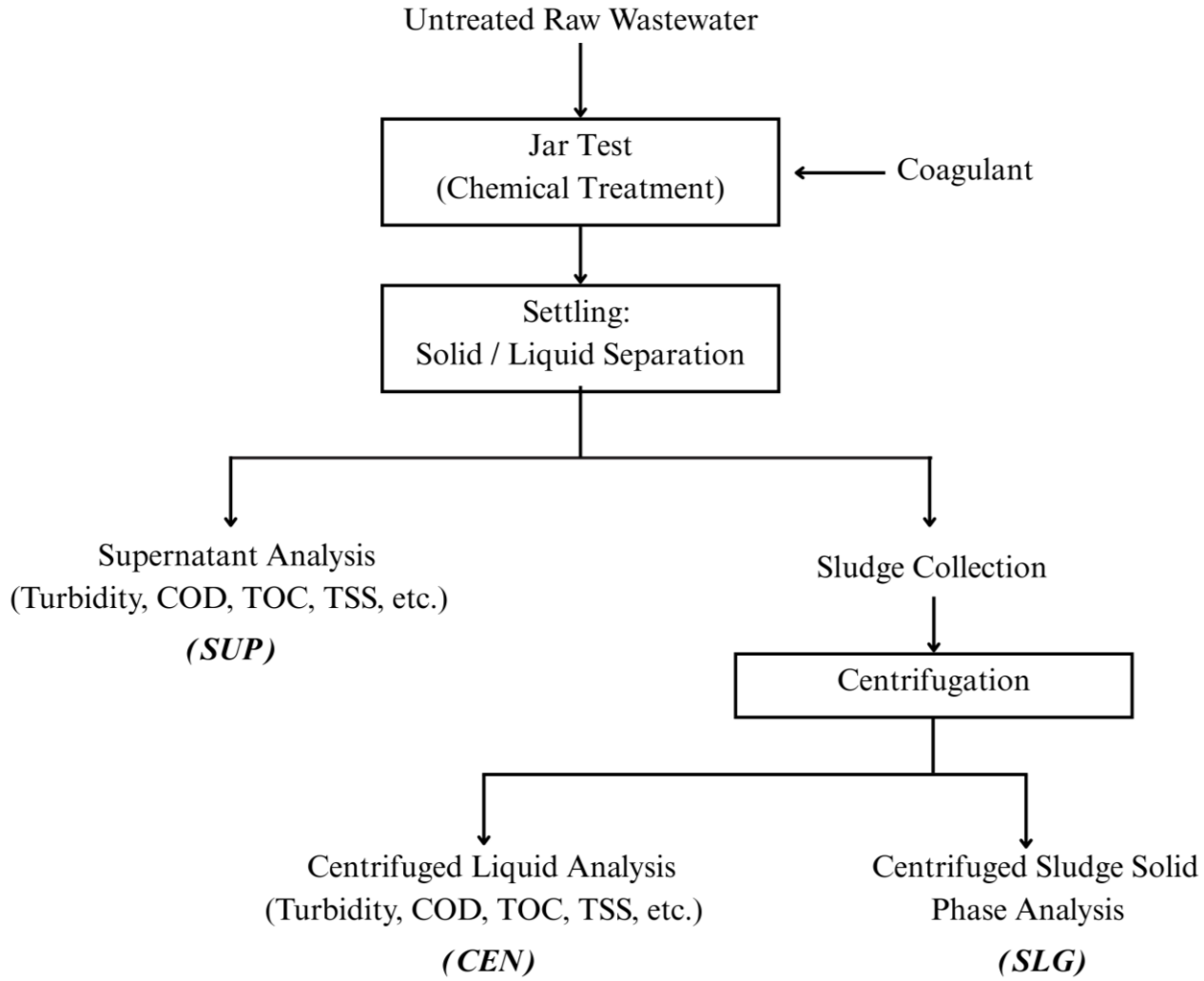


Figure 3.13. Experimental procedure for M6 – coagulation without pH adjustment.

Following the procedural workflows outlined in Figures 3.12 and 3.13, all jar-test operations were performed under standardized mixing conditions to ensure full comparability across the selected formulations. After the addition of the coagulant, rapid mixing was applied for 2–3 minutes, with a fixed dose of medium-anionic polyacrylamide (PAM) introduced during the final 30 seconds to support flocculation. This was followed by 15 minutes of slow mixing to promote floc growth, after which the suspensions were allowed to settle under quiescent conditions to simulate the sedimentation stage of full-scale treatment.

Representative images of the jar-test coagulation–flocculation procedure are shown in Figure 3.14. These photographs illustrate the key operational steps applied during the experiments—including pH monitoring, reagent dosing, floc development, and sedimentation—and provide visual context for the standardized jar-test protocol described above.



(a)



(b)



(c)



(d)



(e)

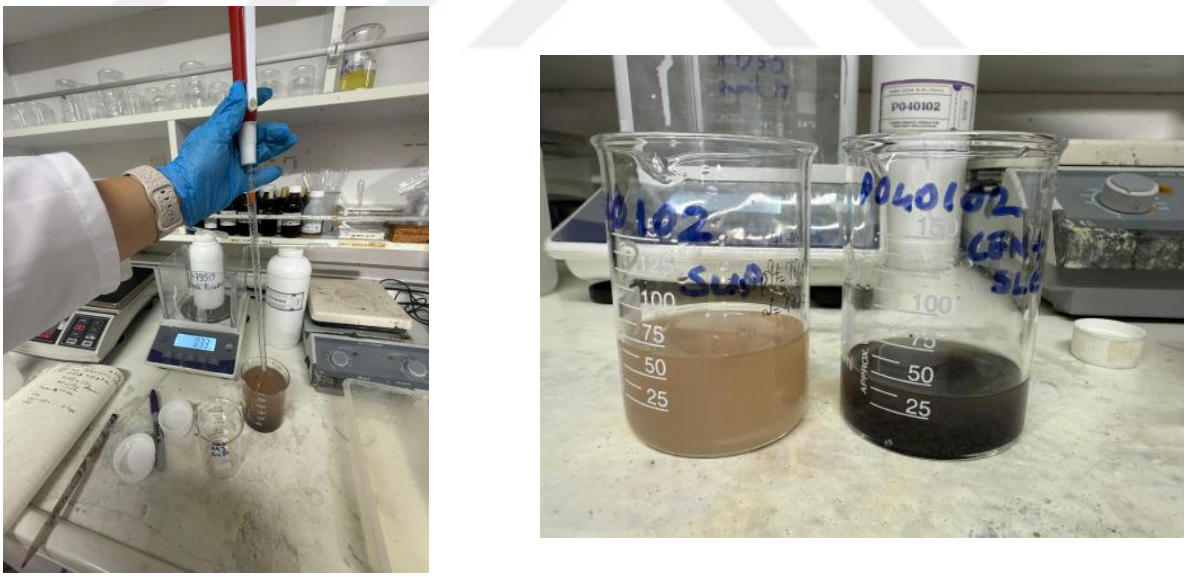


(f)

Figure 3.14. Sequential images from the experimental procedure: (a) pH monitoring prior to coagulant dosing, (b) close-up view pf pH measurement, (c) weighing of the anionic polyelectrolyte after coagulant addition, (d) dosing of the polyelectrolyte into the wastewater, (e) floc growth during slow mixing, and (f) clarified water after sedimentation.

The treated suspensions obtained from the final jar tests served as the input for the phase-separation stage, forming the basis for the detailed phase-specific and mass-balance analyses presented in the subsequent sections.

3.2.3.5. Phase separation. To enable a more detailed evaluation of treatment performance and to accurately quantify the distribution of pollutants between liquid and solid fractions, the treated suspensions were subjected to a systematic phase-separation procedure. After coagulation–flocculation and sedimentation, the mixtures were allowed to settle completely. The clarified supernatant was then withdrawn by pipette and designated as the SUP fraction. The remaining sludge was centrifuged to obtain the upper liquid layer, identified as the CEN fraction, while the residual solids constituted the sludge fraction (SLG). During each step, the volumes of all three fractions were measured using a graduated cylinder and recorded. During these steps, the volume of each fraction was also measured using a graduated cylinder and recorded. Representative images of the laboratory-scale phase-separation procedure are provided in Figure 3.15. These photographs illustrate the key steps of the separation workflow and complement the methodological description presented in this section.



(a) (b)

Figure 3.15. Sequential representation of the phase-separation procedure: (a) collection of the supernatant (SUP) using a pipette, (b) preparation of the remaining sludge–liquid mixture for volume measurement, (c) centrifugation of this mixture to separate the CEN and SLG fractions, and (d) final view of the three separated fractions.



(c)



(d)

Figure 3.15. (continued)

The resulting phase-separated samples enabled precise quantification of pollutant partitioning and supported reliable mass-balance calculations. By distinguishing these phases analytically, the study generated a clearer understanding of how each treatment method affected both effluent quality and sludge generation, providing a stronger basis for meaningful performance comparisons.

Overall, the experimental approach was designed to move systematically from broad screening to formulation selection, dosage optimization, and finally to detailed phase-specific analyses. This structure made it possible to focus analytical efforts on the most promising treatment systems while ensuring a fair and rigorous comparison between hybrid materials and the conventional plant-based method. To support this evaluation, Table 3.4 summarizes which phases (SUP, CEN, SLG) were analyzed at each stage of the study—screening, optimization, and advanced analyses—and lists the corresponding parameters measured.

This table provides a clear overview of how the analytical scope expanded as the experiments progressed from preliminary assessments to more detailed evaluations. For this reason, the methodological framework is presented here before the advanced analyses, providing the necessary context for understanding how the phase-based evaluations in the subsequent sections were structured.

Table 3.4. Summary of experimental scenarios and analyses conducted in each phase.

Scenario Code	Treatment Group	Treatment Phases (SUP, CEN, SLG)	Screening and Optimization Tests	Advanced Tests
M1	Untreated Wastewater	*N/A – untreated wastewater*	Turbidity, COD, TSS	Turbidity, COD, TSS
M2	Conventional Treatment 1 *(Lime + $Al_2(SO_4)_3$ + Polymer)*	SUP	Turbidity, COD, TSS	COD, TSS, TOC, Al, Fe, Total Cr
		CEN	-	COD, TSS, TOC, Al, Fe, Total Cr
		SLG	Sludge volume	Sludge volume, moisture content, dry solids concentration, dry solid yield, Al, Fe, total Cr, COD (calculated by mass balance), TSS (calculated by mass balance), and TOC (calculated by mass balance)
M3	Conventional Treatment 2 *(NaOH + $Al_2(SO_4)_3$ + Polymer)*	SUP	Turbidity, COD, TSS	COD, TSS, TOC, Al, Fe, Total Cr
		CEN	-	COD, TSS, TOC, Al, Fe, Total Cr
		SLG	Sludge volume	Sludge volume, moisture content, dry solids concentration, dry solid yield, Al, Fe, total Cr, COD (calculated by mass balance), TSS (calculated by mass balance), and TOC (calculated by mass balance)
M4	Conventional Treatment 3 *(Alternative Conventional Coagulants Referenced in Literature)*	SUP	Turbidity, COD, TSS	COD, TSS, TOC, Al, Fe, Total Cr
		CEN	-	COD, TSS, TOC, Al, Fe, Total Cr
		SLG	Sludge volume	Sludge volume, moisture content, dry solids concentration, dry solid yield, Al, Fe, total Cr, COD (calculated by mass balance), TSS (calculated by mass balance), and TOC (calculated by mass balance)

Scenario Code	Treatment Group	Treatment Phases (SUP, CEN, SLG)	Screening and Optimization Tests	Advanced Tests
M5	Hybrid Coagulant Treatments with pH adjustment	SUP	Turbidity, COD, TSS	COD, TSS, TOC, Al, Fe, Total Cr
		CEN	-	COD, TSS, TOC, Al, Fe, Total Cr
		SLG	Sludge volume	Sludge volume, moisture content, dry solids concentration, dry solid yield, Al, Fe, total Cr, COD (calculated by mass balance), TSS (calculated by mass balance), and TOC (calculated by mass balance)
M6	Hybrid Coagulant Treatments	SUP	Turbidity, COD, TSS	COD, TSS, TOC, Al, Fe, Total Cr
		CEN	-	COD, TSS, TOC, Al, Fe, Total Cr
		SLG	Sludge volume	Sludge volume, moisture content, dry solids concentration, dry solid yield, Al, Fe, total Cr, COD (calculated by mass balance), TSS (calculated by mass balance), and TOC (calculated by mass balance)

Notes:

- ✓ SUP means supernatant phase collected after sedimentation;
- ✓ CEN means clarified liquid obtained from the centrifuged sludge;
- ✓ SLG means solid fraction remaining after centrifugation

3.2.3.6. Analytical measurements. In the screening and optimization stages, the evaluation focused primarily on core performance indicators—turbidity, COD, and TSS measured in the supernatant (SUP) phase, and sludge volume assessed in the sludge (SLG) phase. These parameters provided the basis for identifying the five most effective hybrid formulations.

Once these formulations were tested at their optimum dosages and systematically separated into the SUP, CEN, and SLG phases, a more comprehensive comparison with the conventional benchmark method became necessary. Accordingly, the analytical scope was expanded in the advanced testing phase to evaluate treatment performance in greater depth.

In this stage, analyses were extended beyond the supernatant to include the centrifuged liquid and sludge fractions, enabling a more complete assessment of pollutant distribution and sludge behavior. Additional parameters were incorporated into the liquid-phase analyses (SUP and CEN), including TOC, Al, Fe, and total Cr, to capture both organic and inorganic constituents. For the sludge fraction (SLG), moisture content and dry solids concentration were measured to evaluate sludge characteristics and solids accumulation.

For parameters that could not be directly measured in the sludge phase, the corresponding values were derived mathematically to ensure that pollutant distribution across phases was fully accounted for and that mass-balance calculations remained complete. In addition to phase-specific measurements, the hybrid coagulant formulations themselves were analyzed for their inherent COD and TOC content. These baseline values were used to quantify the organic load introduced by each formulation and were incorporated into both treatment-performance interpretation and subsequent mass-balance calculations.

Within this analytical structure, the parameters measured in the liquid phases (SUP and CEN) are summarized in Table 3.5, while the parameters assessed in the sludge phase (SLG) are presented in Table 3.6.

Table 3.5. Measurement devices and analytical methods used for liquid-phase characterization.

Parameter	Measurement Device / Method
pH	pH measurement will be done with an automatic pH meter. Brand - Model: WTW inoLab pH 7110
Turbidity	Brand - Model: HACH DR/890 Colorimeter
Chemical Oxygen Demand (COD)	Brand - Model: HACH DRB 200 Thermoreactor Brand - Model: HACH DR/890 Colorimeter Chemical oxygen demand (COD) was determined by the reactor-digestion method in accordance with Hach Method 8000. The DRB 200 thermoreactor was pre-heated to 150 °C, and sealed COD digestion vials (range selected according to expected concentration; e.g., LR or HR) were prepared by adding 2.00 mL of well-mixed sample, tightly capping, and gently inverting to mix. Vials (including a reagent blank processed in parallel) were digested for 2 hours at 150 °C, then cooled (to ≤ ~120 °C, then to room temperature), inverted again to mix, and allowed to clarify. Measurements were taken on the DRB/890 using the instrument's programmed COD method for the selected vial range, following zeroing with the corresponding blank. This procedure and ranges follow Hach's reactor digestion instructions and instrument manuals. COD digestion vials were selected according to the expected concentration range of the samples. At the beginning of the study, High Range Plus vials (up to ~15,000 mg/L) were used, as higher COD levels were anticipated. As subsequent samples showed lower concentrations, High Range (~1,500 mg/L) and, where necessary, Low Range vials were applied. Dilution was performed whenever measured concentrations exceeded the selected range.
Total Suspended Solids (TSS)	The determination of total suspended solids (TSS) was performed gravimetrically in accordance with Standard Methods 2540 D (APHA, 2017). A well-mixed homogenized wastewater sample of known volume was filtered through a pre-weighed glass fiber filter to retain suspended matter. The filter and residue were then dried in a drying oven at 103–105 °C until constant weight was achieved, cooled in a desiccator, and reweighed. The increase in filter mass after drying corresponded to the TSS content of the sample. In cases where excessive solids led to clogging and prolonged filtration, either the sample volume was reduced or a larger filter was used. The TSS concentration was calculated using the following equation:

Parameter	Measurement Device / Method
	$$TSS\ \left(\frac{mg}{L}\right) = \frac{(W_f - W_i)x1000}{V} \qquad (3.1)$$ where W_f is the weight of the filter with residue (mg), W_i is the initial weight of the clean filter (mg), and V is the volume of the sample filtered (mL). The factor of 1000 is applied to convert the concentration from mg/mL to mg/L, as 1 mL corresponds to 0.001 L.
Heavy metal analysis	The quantification of heavy metals (Al, Fe, and total Cr) was conducted using inductively coupled plasma–optical emission spectroscopy (ICP-OES), following standard procedures (e.g., APHA, 2017). Prior to analysis, liquid samples acidified with ultrapure nitric acid to ensure preservation and stability. The samples were acidified to pH <2 by adding concentrated nitric acid (HNO_3), thereby preventing the precipitation of metal hydroxides and ensuring stability of dissolved aluminum in the solution. Then, liquid fractions were introduced into the ICP-OES system, where they were exposed to high-temperature argon plasma and element-specific optical emission signals were measured. For calibration, multi-element stock solutions (Periodic Table Mix 1 and 2, Merck, Germany) were used to prepare standards. This method provided reliable detection and quantification of trace metals across both liquid and solid phases of the wastewater treatment samples.
Total Organic Carbon (TOC)	The total organic carbon (TOC) content of the samples was determined using the high-temperature combustion method in accordance with Standard Methods 5310 B (APHA, 2017). Inorganic carbon was removed or accounted for separately to ensure that only organic carbon was measured. The prepared sample was then introduced into the analyzer, where it was combusted at approximately 700–1000 °C. During this process, organic matter was oxidized to carbon dioxide (CO_2), which was subsequently quantified by an infrared detector. The measured CO_2 was converted into TOC concentration based on calibration with standard solutions.

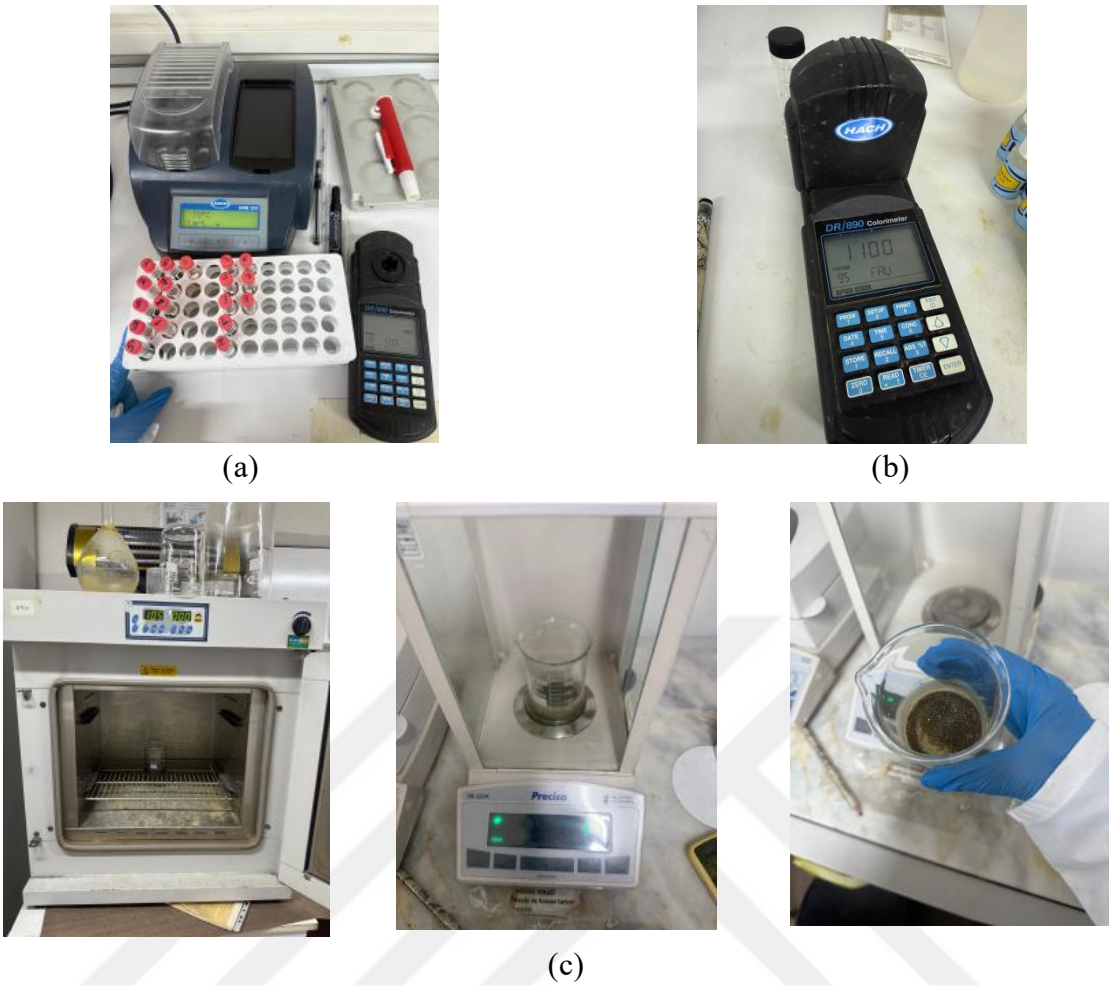
Table 3.6. Analytical methods and procedures for sludge-phase characterization.

Parameter	Measurement Device / Method
Sludge volume	The volume of sludge generated during treatment was determined through a stepwise volumetric approach. After the coagulation–flocculation and settling phases, the clarified supernatant was carefully withdrawn by pipette and its volume was measured using a graduated cylinder. The remaining mixture, consisting of water and wet sludge, was subsequently quantified in the same manner. This fraction was then centrifuged to enhance phase separation, after which the centrifuged liquid (CEN) was collected by pipette and measured volumetrically. The residual material remaining after centrifugation was defined as the sludge fraction (SLG), and its volume was calculated as the difference between the measured fractions. This procedure allowed for a more precise estimation of the sludge volume, while simultaneously quantifying the supernatant and centrifuged liquid volumes. In this way, the settleability and phase distribution of solids could be assessed consistently across all treatment scenarios.
Moisture content	A representative sample of centrifuged sludge was weighed to determine the wet mass. The sample was then dried at 105°C in a laboratory oven until a constant weight was achieved (typically over 24 hours). The dry mass was recorded, and moisture content was calculated using the following formula: $$Moisture\ Content\ (\%) = \frac{Wet\ Weight - Dry\ Weight}{Wet\ Weight} \times 100 \quad (3.2)$$
Dry solids concentration	Dry solids content was determined as the proportion of solid residue remaining after moisture removal. It was calculated by comparing the dry weight to the initial wet weight of the sludge using the formula: $$Dry\ Solids\ (\%) = \frac{Dry\ Weight}{Wet\ Weight} \times 100 \quad (3.3)$$ This metric quantifies the solids concentration in the dewatered sludge and is essential for assessing dewatering efficiency.

Parameter	Measurement Device / Method
Heavy metal content	For the sludge fraction (SLG), heavy metal analysis was carried out after sample preparation by microwave-assisted acid digestion. Approximately 0.1 g of dried and homogenized sludge sample was treated with 9 mL concentrated nitric acid (HNO_3, 67% v/v) and 3 mL concentrated hydrochloric acid (HCl, 67% v/v). The vessels were tightly sealed and subjected to controlled heating in a microwave digestion system (CEM MARS6) under an appropriate temperature program, ensuring complete decomposition of the solid matrix and transfer of metals into solution. After digestion, the samples were cooled to room temperature and diluted to 25 mL with ultrapure water in volumetric flasks. The digested samples were subsequently analyzed by ICP-OES using the same calibration standards and instrumental settings as described for the liquid fractions. This comprehensive approach enabled reliable quantification of Al, Fe, and total Cr in the sludge phase and supported the overall mass balance evaluation across all phases.

Together, these parameters provide a detailed and quantitative understanding of both pollutant removal performance and sludge management challenges, forming a reliable basis for evaluating the comparative advantages of hybrid versus conventional coagulant systems. In section 3.3, the calculation procedures for phase-specific mass balances are presented, while the detailed experimental results are provided in **Appendices A, C, D, E, F, G, H**, and I to support the interpretation of the main findings.

Representative examples of the analytical measurements are presented in Figure 3.16. These images illustrate some key components of the routine analyses performed throughout the study, including (a) the COD measurement setup using a thermoreactor and the Hach DR 890 device, (b) turbidity determination expressed in Formazin Attenuation Units (FAU), and (c) oven-drying and gravimetric determination of solids for sludge analysis. These examples are provided to visually support the standardized procedures summarized in Table 3.5 and Table 3.6, while the full set of analyses was systematically applied to all experimental samples.

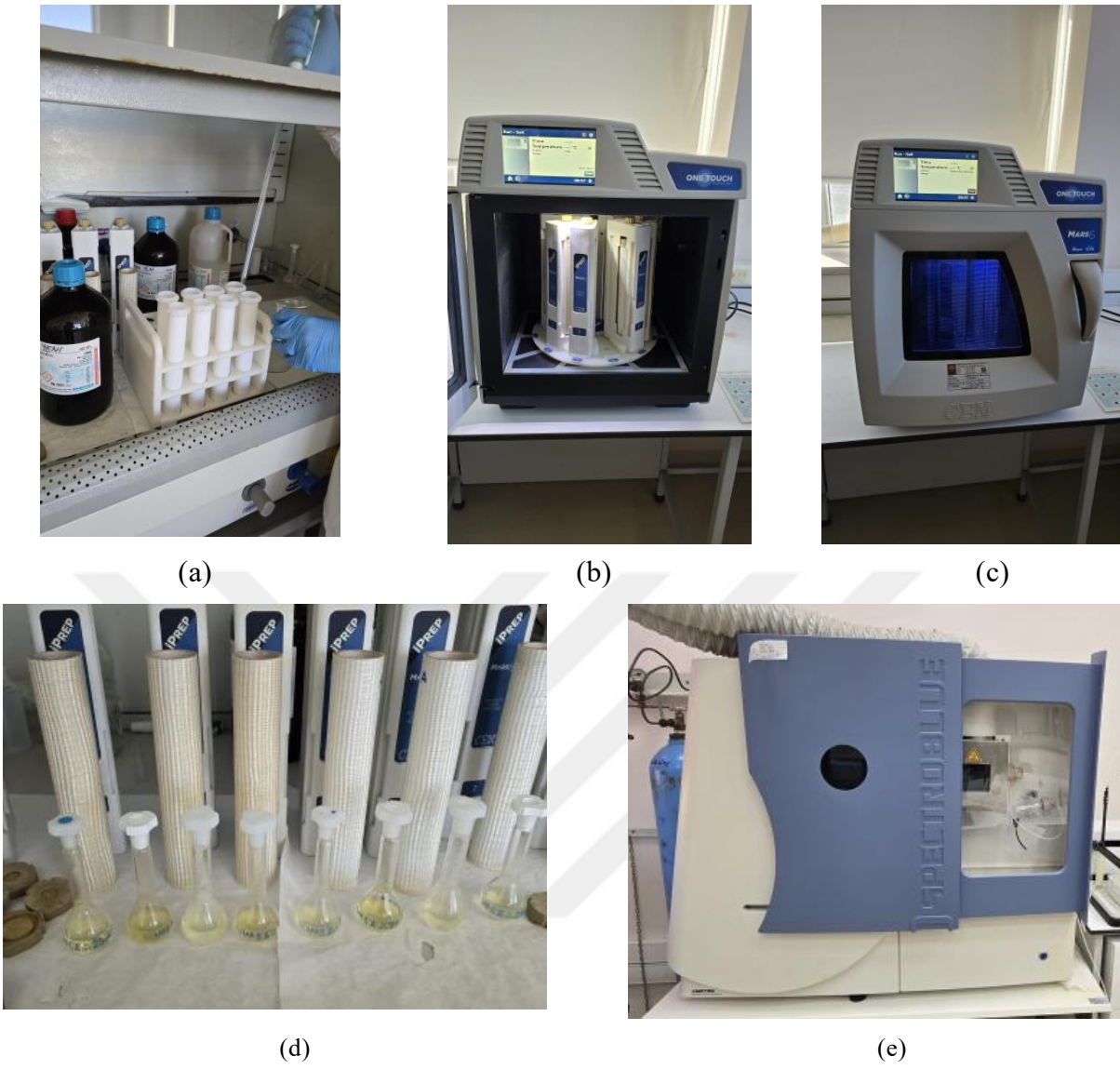


(a) (b)

(c)

Figure 3.16. Representative images of analytical measurements: (a) COD determination with a thermoreactor and Hach DR 890 device, (b) turbidity measurement in FAU with the Hach DR 890, (d) oven-drying and weighing of residues for sludge analysis.

For parameters assessed only after optimization—such as TOC and heavy metals (Al, Fe, and total Cr)—the analyses were performed on the separated phases (SUP, CEN, and SLG) following the final jar tests. To illustrate these advanced measurements, Figure 3.17 presents representative images from the heavy-metal determination workflow, including sample preparation, microwave-assisted acid digestion, and ICP-OES quantification. These images serve to demonstrate the analytical steps applied specifically to the optimized and phase-separated samples in the advanced testing stage.



(a) (b) (c)

(d) (e)

Figure 3.17. Stepwise procedure for heavy metal analysis in sludge samples: (a) sample preparation by acid addition prior to digestion, (b) placement of vessels into the microwave digestion system, (c) microwave-assisted acid digestion under controlled conditions (CEM MARS6), (d) post-digestion samples diluted to volume in volumetric flasks, (e) ICP-OES instrument used for quantification of Al, Fe, and total Cr.

3.2.4. Data Evaluation and Comparison Approach

Following the completion of the experimental procedures, all measurements were organized and processed to allow a clear and consistent comparison of the hybrid and conventional treatment methods. The data were recorded in structured Excel sheets, arranged by scenario (M1–M6), phase (SUP, CEN, SLG), and parameter, ensuring that removal efficiencies, sludge yields, and mass-balance calculations could be carried out reliably.

The evaluation followed the same stepwise logic as the experimental design. The first stage focused on the uniform-dose screening results, where pH, turbidity, COD, TSS, and sludge volume were examined under identical conditions. These results allowed all treatments to be compared on equal ground and helped identify the five hybrid formulations with the highest initial performance.

The second stage involved analyzing the dose–response results for these selected hybrids. By examining how removal performance and sludge volume changed with increasing coagulant dose, the minimum effective dosage—the optimum dose—for each formulation was determined.

In the final stage, attention shifted to the advanced analyses conducted after phase separation. At this point, the optimized hybrid formulations were compared directly with the conventional benchmark method (M2). Measurements obtained from the supernatant (SUP), the centrifuged liquid (CEN), and the sludge solids (SLG) were used to evaluate how pollutants were distributed across phases. Parameters such as COD, TOC, TSS, total solids, and selected heavy metals (Al, Fe, total Cr) were assessed. For parameters that could not be directly measured in the sludge, values were calculated mathematically to complete the pollutant mass balance. The raw wastewater (M1) served only as the influent baseline and was not separated into phases.

Beyond pollutant removal, the datasets were also used to examine operational considerations. The effect of different pH adjustment strategies was evaluated by comparing lime- and NaOH-based conditioning in the conventional scenarios (M2 vs. M3), as well as the performance of hybrid formulations with and without pH control (M5 vs. M6). In addition, the optimized hybrid dosages were compared with the full-scale plant dosage to assess how much treatment efficiency could be achieved per unit of chemical applied. Taken together, these analyses provided a clear and systematic framework for identifying the most effective hybrid formulations and understanding how they compare with the conventional plant method in terms of pollutant removal, sludge generation, and chemical demand. The detailed results and their interpretation are presented in Section 4.

3.3. Mass Balance Calculations

In this section, mass balance calculations were carried out to quantify the distribution and fate of pollutants across all three separated phases: specifically, the supernatant (SUP), centrifuged filtrate (CEN), and dewatered sludge (SLG). The analysis focused on key parameters, including COD, TOC, TSS, heavy metals (Al, Fe, Cr), and residual coagulant content. In addition to these core variables, sludge characteristics—namely moisture content and dry solid yield—were assessed to provide further insight into dewaterability and solid-liquid separation efficiency. Each balance was constructed using experimentally measured concentrations in conjunction with the corresponding phase-specific volumes or dry masses, thereby enabling a scenario-based comparison across all setups. The outputs of this multifaceted assessment serve to highlight phase-specific retention behavior and coagulant performance, and are further interpreted in the following discussion section (Section 4).

3.3.1. COD Mass Balance

COD mass balance was performed to evaluate the removal efficiency of organic pollutants and to determine their distribution across the supernatant, centrifuged filtrate, and dewatered sludge phases. For each treatment condition, COD concentrations measured in the three separated phases were multiplied by the corresponding phase volumes to calculate the total COD load in each fraction. These values were then compared to the initial COD of the raw wastewater to quantify the removal efficiency and to identify the phase in which the remaining organic load predominantly accumulated. This balance provided a clear view of how effectively each coagulant formulation reduced the overall chemical oxygen demand and supported comparisons between conventional and hybrid treatments in terms of organic pollutant control.

In the conventional treatment scenarios (M2, M3, and M4), where no significant COD input from coagulants was anticipated, the standard mass balance equation was directly applied without modification. COD loads in each phase were calculated from measured concentrations and volumes, assuming that all organic matter originated solely from the raw wastewater. This approach allowed for straightforward evaluation of removal performance and distribution behavior under traditional chemical treatment conditions:

$$M_{COD,in} = M_{COD,SUP} + M_{COD,CEN} + M_{COD,SLG} + \Delta M_{loss} \quad (3.4)$$

Where:

$M_{COD,in}$ = Total COD input (mg) from untreated wastewater

$M_{COD,SUP}$ = COD mass in the supernatant after settling (mg)

$M_{COD,CEN}$ = COD mass in the liquid fraction obtained after centrifugation (mg)

$M_{COD,SLG}$ = Extractable COD from dewatered sludge solids (mg)

ΔM_{loss} = Unaccounted COD losses due to experimental error, volatilization, adsorption, or sampling uncertainties (mg)

Each term in the above equation was further expressed as the concentration and volume as detailed below:

$$C_{COD,in} \times V_{total} = C_{COD,SUP} \times V_{SUP} + C_{COD,CEN} \times V_{CEN} + M_{COD,SLG} + \Delta M_{loss} \quad (3.5)$$

Where:

$C_{COD,in}$ = COD concentration in raw influent (mg/L)

V_{total} = Total volume of untreated wastewater processed (L)

$C_{COD,SUP}$ = COD concentration in the supernatant after settling (mg/L)

V_{SUP} = Volume of supernatant (L)

$C_{COD,CEN}$ = COD concentration in the centrifuged liquid phase (mg/L)

V_{CEN} = Volume of centrifuged liquid (L)

In cases where only the liquid phases (supernatant and centrifuged liquid) are analytically measured, the COD mass associated with the sludge phase can be estimated by subtracting the measured COD loads of the liquid fractions from the total COD input. Assuming negligible loss, the sludge-phase COD load was calculated as follows:

$$M_{COD,SLG} = C_{COD,in} \times V_{total} - (C_{COD,SUP} \times V_{SUP} + C_{COD,CEN} \times V_{CEN}) \quad (3.6)$$

This approach enables indirect estimation of organic matter retention in the solid phase and supports mass closure when direct sludge COD measurement is not performed.

For hybrid coagulant scenarios (M5 and M6), the intrinsic COD content of the coagulant formulations was taken into account. The COD content of hybrid coagulants was measured and recorded prior to application; therefore, their contribution as an additional organic load was

incorporated into the mass balance calculations. Accordingly, the mass balance equation was revised to include this additional input:

$$M_{COD,in} + M_{COD,hybrid\ coagulant} = M_{COD,SUP} + M_{COD,CEN} + M_{COD,SLG} + \Delta M_{loss} \quad (3.7)$$

Here, $M_{COD,hybrid\ coagulant}$ represents the pre-quantified COD load associated with the coagulant mixture itself. This term is particularly important for polymer-based formulations, which may introduce a non-negligible amount of organic matter into the system.

Accordingly, in hybrid treatment scenarios where direct sludge COD measurement was unavailable and ΔM_{loss} was considered negligible, the following revised equation was used to mathematically estimate the COD retained in the sludge phase:

$$M_{COD,SLG} = (C_{COD,in} \times V_{total} + M_{COD,hybrid\ coagulant}) - (C_{COD,SUP} \times V_{SUP} + C_{COD,CEN} \times V_{CEN}) \quad (3.8)$$

The influence of this additional input on total COD distribution and mass closure will be discussed comparatively in section 4.

In this study, COD removal efficiency was calculated based on the residual COD loads in the supernatant and centrifuged liquid phases. The dewatered sludge was considered as a successful retention phase, and therefore not included in the "residual" term. The following equation was used:

$$COD\ Removal\ Efficiency\ (\%) = \left(\frac{M_{COD,in} - (M_{COD,SUP} + M_{COD,CEN})}{M_{COD,in}}\right) \times 100 \quad (3.9)$$

The calculated COD removal efficiencies will be comparatively evaluated and discussed in Section 4, in relation to coagulant type, treatment condition, and phase-specific pollutant distribution.

3.3.2. TOC Mass Balance

TOC mass balance was conducted to assess the distribution and fate of organic carbon across the separated phases under different treatment conditions. TOC concentrations measured in the supernatant and centrifuged liquid were converted into mass loads using phase-specific volumes. As the TOC content of the dewatered sludge was not directly measured, the carbon load associated with the solid phase was estimated mathematically from the overall balance.

For conventional coagulant applications (M2, M3, and M4 scenarios), where no significant organic contribution from treatment chemicals was expected, the following standard mass balance equation was applied:

$$M_{TOC,in} = M_{TOC,SUP} + M_{TOC,CEN} + M_{TOC,SLG} + \Delta M_{loss} \quad (3.10)$$

Where:

$M_{TOC,in}$ = Total TOC input from untreated wastewater (mg)

$M_{TOC,SUP}$ = TOC mass in the supernatant after settling (mg)

$M_{TOC,CEN}$ = TOC mass in the centrifuged liquid phase (mg)

$M_{TOC,SLG}$ = Estimated TOC retained in the dewatered sludge phase (mg)

ΔM_{loss} = Unaccounted TOC losses due to experimental error, volatilization, adsorption, or sampling uncertainties (mg)

Each term was expressed based on concentration and volume:

$$C_{TOC,in} \times V_{total} = C_{TOC,SUP} \times V_{SUP} + C_{TOC,CEN} \times V_{CEN} + M_{TOC,SLG} + \Delta M_{loss} \quad (3.11)$$

Where:

$C_{TOC,in}$ = TOC concentration in raw wastewater (mg/L)

V_{total} = Total volume of untreated wastewater processed (L)

$C_{TOC,SUP}$ = TOC concentration in the supernatant (mg/L)

V_{SUP} = Volume of supernatant (L)

$C_{TOC,CEN}$ = TOC concentration in the centrifuged liquid (mg/L)

V_{CEN} = Volume of centrifuged liquid (L)

Where $M_{TOC,hybrid\ coagulant}$ refers to the pre-measured organic carbon introduced by the coagulant formulation. Accordingly, in hybrid scenarios (M5 and M6) where sludge TOC was not directly measured and losses were negligible, the solid-phase TOC load ($M^{total}_{TOC,sludge}$) was calculated as:

$$M^{total}_{TOC,sludge} = (C_{TOC,in} \times V_{total} + M_{TOC,hybrid\ coagulant}) - (C_{TOC,SUP} \times V_{SUP} + C_{TOC,CEN} \times V_{CEN}) \quad (3.12)$$

The influence of coagulant-originated carbon on TOC partitioning and mass closure will be comparatively evaluated in Section 4.

3.3.3. Heavy Metal Mass Balances (Al, Fe, Cr)

To evaluate the phase-specific behavior and removal performance of selected heavy metals, comprehensive mass balance analyses were conducted for aluminum (Al), iron (Fe), and chromium (Cr) under various treatment scenarios. Each metal's distribution was assessed across the supernatant, centrifuged liquid, and dewatered sludge phases by calculating the respective loads based on measured concentrations and corresponding phase volumes or dry sludge mass. Unlike the other parameters, the sludge-phase metal contents were determined directly through microwave-assisted acid digestion using concentrated nitric acid, followed by analysis with ICP-OES. This approach ensured that the metal loads bound to the solid phase were reliably quantified and incorporated into the mass balance calculations. Separate mass balance calculations were conducted for each metal species. The resulting values were compared with the total metal input originating from the raw wastewater, allowing for a detailed evaluation of removal performance and phase-specific distribution trends under different coagulant configurations. These findings are further discussed in Section 4. The general mass balance equation for heavy metals, introduced below, was then applied to all treatment scenarios (M2–M6), with M1 providing the influent reference values.

General Mass Balance Equation for Heavy Metals:

$$M_{(Al/Fe/Cr),in} = M_{(Al/Fe/Cr),SUP} + M_{(Al/Fe/Cr),CEN} + M_{(Al/Fe/Cr),SLG} + \Delta M_{loss} \quad (3.13)$$

Where:

$M_{(Al/Fe/Cr),in}$ = Metal load (Al or Fe or Cr) from untreated wastewater (mg)

$M_{(Al/Fe/Cr),SUP}$ = Metal load (Al or Fe or Cr) in the supernatant phase (mg)

$M_{(Al/Fe/Cr),CEN}$ = Metal load (Al or Fe or Cr) in centrifuged liquid phase (mg)

$M_{(Al/Fe/Cr),SLG}$ = Metal load (Al or Fe or Cr) in sludge phase (mg)

ΔM_{loss} = Unaccounted metal losses due to experimental error (mg)

Each term in the equation was further expressed as concentration and the corresponding phase volume or mass, as shown below:

$$C_{(Al/Fe/Cr),in} \times V_{total} = C_{(Al/Fe/Cr),SUP} \times V_{SUP} + C_{(Al/Fe/Cr),CEN} \times V_{CEN} + C_{(Al/Fe/Cr),SLG} \times M_{SLG} + \Delta M_{loss} \quad (3.14)$$

Where:

$C_{(Al/Fe/Cr),in}$ = Metal concentration (Al or Fe or Cr) in raw wastewater (mg/L)

V_{total} = Total volume of untreated wastewater processed (L)

$C_{(Al/Fe/Cr),SUP}$ = Metal concentration (Al or Fe or Cr) in the supernatant (mg/L)

V_{SUP} = Volume of supernatant (L)

$C_{(Al/Fe/Cr),CEN}$ = Metal concentration (Al or Fe or Cr) in centrifuged liquid (mg/L)

V_{CEN} = Volume of centrifuged liquid (L)

$C_{(Al/Fe/Cr),SLG}$ = Metal concentration (Al or Fe or Cr) in dewatered sludge (mg/g dry matter), measured after acidic digestion

$M_{SLG.}$ = Total dry mass of dewatered sludge (mg)

3.3.3.1. Mass balance analysis of Al, Fe, and Cr (Total) in raw wastewater. In the M1 scenario representing raw untreated wastewater, no phase separation was performed due to the highly heterogeneous nature of the influent. To determine the total influent concentrations of aluminum (Al), iron (Fe), and total chromium (Cr), well-mixed unfiltered samples were subjected to nitric acid digestion prior to analysis. This pretreatment step was necessary to solubilize particle-bound metals and to prevent potential interferences or clogging of the ICP-OES caused by the high suspended solids content of the raw wastewater. The digested solutions were then analyzed by ICP-OES, with each element (Al, Fe, Cr) quantified separately. The resulting concentrations represented the total metal input to the system, encompassing both dissolved and particulate fractions, and served as baseline reference values for subsequent mass balance calculations in the treated scenarios (M2–M6).

3.3.3.2. Aluminum mass balance in conventional coagulant scenarios (M2 and M3). In the conventional treatment scenarios (M2 and M3), aluminum sulfate ($Al_2(SO_4)_3$) was employed as the principal coagulant, serving as the dominant source of aluminum introduced into the system. Therefore, the total aluminum input in these scenarios consisted of both the naturally occurring aluminum content in the raw wastewater and the additional aluminum introduced via the coagulant.

The mass balance for aluminum was calculated by multiplying the measured concentrations in the supernatant, centrifuged liquid, and dewatered sludge phases by their respective volumes as described in Equation (3.14). The aluminum load introduced through $Al_2(SO_4)_3$ was taken into

account when evaluating the total system input. Accordingly, the balance equation was revised to reflect both sources of aluminum:

$$C_{Al,in} \times V_{total} + M_{Al_2(SO_4)_3} = C_{Al,SUP} \times V_{SUP} + C_{Al,CEN} \times V_{CEN} + C_{Al,SLG} \times M_{SLG} + \Delta M_{loss} \quad (3.15)$$

Where $M_{Al_2(SO_4)_3}$ denotes the aluminum contribution derived from the aluminum sulfate used in the treatment process. This approach allowed for an accurate representation of phase-specific aluminum distribution under conventional chemical coagulation conditions, enabling comparative evaluation with hybrid coagulant systems described in later sections.

3.3.3.3. Aluminum mass balance in hybrid coagulant scenarios (M5 and M6). In contrast to the conventional coagulant systems, Scenarios M5 and M6 employed hybrid formulations incorporating PAC-based inorganic polymers as the primary aluminum source. The revised mass balance equation was therefore expressed as:

$$C_{in} \times V_{total} + M_{Al,Coag.(M5/M6)} = C_{SUP} \times V_{SUP} + C_{CEN} \times V_{CEN} + C_{SLG} \times M_{SLG} + \Delta M_{loss} \quad (3.16)$$

Here, $M_{Al,Coag.(M5/M6)}$ represents the aluminum load introduced specifically through PAC-containing hybrid coagulants. The corresponding aluminum contribution will be directly calculated based on the product-specific aluminum content provided by the manufacturer and the applied coagulant dosage in each scenario.

3.3.3.4. Chromium and iron mass balance in conventional coagulant scenarios (M2 and M3). Although aluminum was externally introduced via aluminum sulfate in M2 and M3, chromium and iron originated solely from the raw wastewater. Therefore, their behavior was tracked to assess natural retention and removal under conventional treatment conditions. Using Equation (3.14), the phase-specific distributions of Fe and Cr were calculated without any coagulant-derived contributions. This allowed comparison of their fate relative to both raw wastewater conditions and to hybrid coagulant scenarios.

3.3.3.5. Chromium and aluminum mass balance in ferric chloride-based scenario (M4). In the M4 scenario, ferric chloride ($FeCl_3$) was the only coagulant applied, thus serving as the external source of iron. Chromium and aluminum loads in this scenario, however, derived exclusively from the raw wastewater. Consequently, their phase-specific behavior was evaluated using Equation (3.14),

without additional source terms. This analysis provided insight into the effectiveness of ferric chloride treatment in removing background Cr and Al present in the influent.

3.3.3.6. Chromium mass balance in hybrid coagulant scenarios (M5 and M6). In scenarios M5 and M6, no external chromium input was introduced through the coagulant formulations. However, chromium was originally present in the raw wastewater and may still undergo removal in hybrid treatment conditions. To evaluate its fate, a standard mass balance calculation was applied using Equation (3.14), based solely on measured chromium concentrations in the separated phases.This analysis served to assess the natural behavior and possible retention of chromium within hybrid systems despite the absence of chromium-based additives. Comparative insights are further discussed in Section 4.

3.3.3.7. Iron mass balance in ferric-based coagulant scenarios (M4, M5, and M6). In scenarios M4, M5, and M6, ferric chloride ($FeCl_3$) was employed either as a conventional coagulant (M4) or in combination with hybrid formulations (M5 and M6), contributing an external iron input to the system. These scenarios required a modified mass balance approach to account for the total iron load, which includes both the naturally occurring iron in the raw wastewater and the additional iron introduced via $FeCl_3$.

The mass of iron in each separated phase—supernatant, centrifuged liquid, and dewatered sludge—was quantified by multiplying the measured concentrations by the respective volumes or dry sludge mass, based on direct analytical results obtained via ICP-OES. The iron load contributed by $FeCl_3$ was incorporated into the total system input to ensure a comprehensive representation of metal partitioning behavior. Accordingly, the mass balance equation for iron in these scenarios was expressed as follows:

$$C_{in} \times V_{total} + M_{Fe\ coagulant} = C_{SUP} \times V_{SUP} + C_{CEN} \times V_{CEN} + C_{SLG} \times M_{SLG} + \Delta M_{loss} \quad (3.17)$$

Where:

$M_{Fe\ coagulant}$: Iron load introduced via ferric chloride ($FeCl_3$) used in M4, M5, and M6 scenarios, calculated based on product iron content and applied dosage.

This formulation enabled accurate assessment of phase-specific iron retention and supported comparative evaluations across treatment configurations with and without ferric-based additives. Detailed interpretation of iron distribution trends is provided in Section 4.

3.3.3.8. Calculation of elemental aluminum contribution from different coagulants. This subsection provides a methodological explanation regarding how the aluminum load introduced via chemical coagulants was calculated in the aluminum-specific mass balance analyses. To accurately estimate the aluminum load introduced through coagulant addition ($M_{Al\ coagulant}$), the elemental aluminum content of each coagulant product was calculated based on its composition as provided by the manufacturer (either from technical or safety data sheets). These coagulants and their compositional details are already defined in Table 3.3, which summarizes all tested products. Depending on their chemical nature, two different estimation approaches were applied:

- For aluminum sulfate ($Al_2(SO_4)_3 \cdot 18H_2O$), a salt-based aluminum compound, the elemental aluminum content was calculated using its full molecular formula and molar mass. The molar mass of $Al_2(SO_4)_3 \cdot 18H_2O$ is 666.4 g/mol, and it contains two moles of aluminum atoms (2 × 26.98 g/mol), which corresponds to an elemental aluminum fraction of 8.10% by weight in the pure salt. As the experiments were conducted using a 40% (w/w) aqueous solution prepared from the solid aluminum sulfate, the effective aluminum content introduced into the system was calculated as:

  $$\text{Al content (\%)} = 0.40 \times 8.10\% = 3.24\%$$

  This final value (3.24%) was used in the mass balance calculations to estimate the aluminum load contributed by the aluminum sulfate coagulant.

- For PAC (Powder) and PAC 17, which are oxide-based aluminum coagulants, the aluminum content was derived from their reported Al_2O_3 percentages. As elemental aluminum in these products is present in the form of Al_2O_3, a stoichiometric conversion was applied:

  Al_2O_3 contains approximately 52.92% elemental aluminum by mass. Based on this:
  - PAC (Powder) contains 30% Al_2O_3, thus the elemental aluminum content is 15.88%.
  - PAC 17 contains 17% Al_2O_3, resulting in an aluminum content of 8.997%.

These aluminum percentages were multiplied by the coagulant dose applied in each scenario, in order to calculate the total aluminum mass (mg) introduced into the system via coagulant addition. This value is represented in the dataset as $M_{Al\ coagulant}$ and was incorporated into the aluminum mass balance equations wherever applicable.

To accurately estimate the aluminum load contributed by each coagulant in mass balance calculations, the elemental aluminum percentage was determined based on the product's composition and chemical form. Table 3.7 summarizes the active compound, physical state, and applied conversion for each coagulant formulation. For aluminum sulfate, which was diluted to 40% solution prior to use, the elemental Al content was calculated based on theoretical molecular ratios. In contrast, for PAC-based coagulants (solid or liquid), the reported Al_2O_3 percentages were converted to elemental Al values using the stoichiometric factor (52.92%). This approach ensured consistency across coagulant types with different compositions and forms.

Table 3.7. Elemental aluminum (Al) content of applied coagulants.

Coagulant Type	Active Aluminum Compound	Physical Form	Reported Composition	Conversion Applied	Final Elemental Al (%)
$Al_2(SO_4)_3 \cdot 18H_2O$	Aluminum sulfate salt	Solid (diluted to 40% solution)	100% pure salt (8.10% Al)	40% × 8.10%	3.24%
PAC (Powder)	Al_2O_3	Solid (powder)	30% Al_2O_3	30% × 52.92%	15.88%
PAC 17 (Liquid)	Al_2O_3	Liquid	17% Al_2O_3	17% × 52.92%	9.00%

3.3.3.9. Theoretical iron (Fe) content in the commercial $FeCl_3$ coagulant. The ferric chloride ($FeCl_3$) coagulant used in this study was obtained as a commercial aqueous solution containing 41% (w/w) $FeCl_3$. To determine the theoretical iron (Fe) content in this solution, the molecular composition of $FeCl_3$ was considered.

- Molar mass of $FeCl_3$ = 162.2 g/mol
- Atomic mass of Fe = 55.85 g/mol

The weight fraction of Fe in pure $FeCl_3$ is calculated as:

$$\frac{55.85\ g/mol}{162.2\ g/mol} = 0.3445 \qquad \text{Fe content in pure } FeCl_3 \approx 34.45\%$$

Since the commercial solution contains 41% $FeCl_3$, the theoretical Fe content in the solution is:

$$41\% \times 0.3445 = 14.1345\ \%\ \text{Fe (w/w)}$$

Thus, the theoretical iron content of the $FeCl_3$ solution is 14.13% (w/w).

In summary, the theoretical aluminum and iron contents calculated for each coagulant were incorporated into the input term of the mass balance equations. Specifically, these values (expressed as % elemental Al or Fe by weight of the applied coagulant solution) were multiplied by the corresponding coagulant dosage used in each scenario to determine the external metal load introduced into the system. This load was then added to the naturally occurring metal concentrations measured in the raw wastewater, thereby defining the total influent metal input. By doing so, the mass balance calculations accounted not only for the background metals originally present in the wastewater but also for the additional contributions from coagulant dosing, ensuring a more accurate evaluation of phase-specific partitioning and overall removal performance. (Detailed information on the compositional calculations of aluminum- and iron-based coagulants has already been provided in the preceding sections. In this subsection, only the calculation steps are presented, as the primary purpose is to demonstrate how these theoretical values were incorporated into the mass balance framework.)

3.3.4. Fate of Polymers

Due to the analytical limitations associated with direct polymer quantification in complex wastewater matrices, an indirect evaluation of polymer distribution was conducted using a phase-based mass balance approach. The polymers employed in this study were classified into two categories based on their chemical nature: organic polymers (e.g., PolyDADMAC, polyamine, PAM) and inorganic, metal-based coagulants (e.g., PAC and PAC-17). Given their high molecular weight and diverse solubility profiles, especially in hybrid formulations, these polymeric substances are prone to differential partitioning across treatment phases. This behavior arises from their varying affinities toward aqueous and solid phases, driven by electrostatic interactions, bridging mechanisms, and solubility-dependent dispersion dynamics, as well as their reactivity and charge density (Bhamidipati et al., 2021).

To elucidate their fate within the system, different indirect indicators were employed depending on the polymer type. For organic polymers, TOC was used as surrogate parameter to estimate residual concentrations in the supernatant, centrifuged liquid, and dewatered sludge phases. For inorganic, aluminum-based coagulants, Al concentrations were used as a tracer to evaluate phase-specific accumulation patterns.

3.3.4.1. Organic polymers estimation via TOC difference. Direct quantification of polymer concentrations in treated water and sludge is analytically challenging due to their complex and often non-specific chemical structures. To address this limitation, a mass balance-based approach utilizing

total organic carbon (TOC) data was employed to indirectly estimate the contribution of organic polymers such as PolyDADMAC, polyamine, and PAM introduced through hybrid coagulant formulations. This method was specifically applied to scenarios which contain organic polymer-based hybrid coagulants, namely M5 and M6.

In this approach, it was assumed that any increase in total TOC load observed after treatment, relative to the TOC content of the untreated raw wastewater, was solely attributable to the organic components of the hybrid coagulants. This assumption is justified by the absence of any other external organic carbon sources in the experimental setup, and the fact that inorganic coagulant components (e.g., PAC) do not contribute to TOC.

In this study, the TOC content of the polymer solutions was measured directly using TOC instrumentation. Therefore, the total organic carbon input associated with hybrid coagulants was calculated based on the concentration and dosage volume of the polymer solutions, as shown in Equation (3.18):

$$M_{TOC,hybrid\ coagulant} = C_{TOC,hybrid\ coagulant} \times V_{hybrid\ coagulant\ dosage} \quad (3.18)$$

Where:

$M_{TOC,hybrid\ coagulant}$ = Total mass of organic carbon introduced into the system via the hybrid coagulant (mg)

$C_{TOC,hybrid\ coagulant}$ = Measured TOC concentration of the hybrid coagulants (mg/L)

$V_{hybrid\ coagulant\ dosage}$ = Volume of hybrid coagulant solution dosed into the system (L)

Once the total TOC contribution of the polymer additives was determined via direct measurement (Equation 3.18), the distribution of this load across the treatment phases was assessed by comparing TOC values between polymer-containing and polymer-free scenarios. Specifically, TOC increases observed in the supernatant and centrifuged liquid phases were attributed to polymer residues retained in the aqueous fractions. These increases, denoted as $\Delta M_{TOC,SUP}$ and $\Delta M_{TOC,CEN}$ were calculated as follows:

$$\Delta M_{TOC,SUP} = M_{TOC,\ SUP}^{with\ polymer} - M_{TOC,\ SUP}^{no\ polymer} \quad (3.19)$$

Where:

$\Delta M_{TOC,sup}$ = Incremental* TOC mass in the supernatant phase attributed to polymer addition (mg)

$M_{TOC,\ SUP}^{with\ polymer}$ = Measured TOC mass in the supernatant phase when polymer is added (mg)

$M_{TOC,\ SUP}^{no\ polymer}$ = Baseline TOC mass in the supernatant phase without polymer addition (mg)

$$\Delta M_{TOC,CEN} = M_{TOC,\ CEN}^{with\ polymer} - M_{TOC,\ CEN}^{no\ polymer} \quad (3.20)$$

Where:

$\Delta M_{TOC,CEN}$ = Incremental* TOC mass in the centrifuged liquid phase due to polymer addition (mg)

$M_{TOC,\ CEN}^{with\ polymer}$ = Measured TOC mass in the centrifuged liquid phase under polymer-containing condition (mg)

$M_{TOC,\ CEN}^{no\ polymer}$ = Baseline TOC mass in the centrifuged liquid phase without polymer addition (mg)

It should be noted that the term "incremental TOC" refers to the supplementary organic carbon load that arises specifically from the addition of polymers, relative to the baseline condition in which no such additives are present. In this context, incremental TOC does not represent the total organic carbon content of the system, but rather the differential contribution attributable to the polymeric component alone. This distinction is critical, as it allows for a more precise assessment of the extent to which polymer addition alters the overall carbon balance of the treatment process and provides insight into the potential environmental implications of introducing such materials.

To determine the residual fraction of polymer retained in the solid sludge phase, a differential mass balance was applied as shown in Equation (3.21), where $M_{TOC,SLG}^{polymer}$ represents the mass of organic carbon originating specifically from the hybrid coagulant that is estimated to remain in the sludge.

$$M_{TOC,SLG}^{polymer} = M_{TOC,\ SLG}^{with\ polymer} - M_{TOC,\ SLG}^{no\ polymer} \quad (3.21)$$

It should be noted that this expression estimates the polymer-specific TOC load retained in the sludge phase, based on a differential approach using polymer-only contributions.

This estimation is valid under the assumption that all unaccounted TOC is retained in the sludge phase, with negligible volatilization or biological loss. This approach provides a phase-resolved interpretation of polymer behavior in the system without requiring direct TOC measurements in the solid sludge fraction.

It is also important to note that TOC measurements encompass both dissolved organic carbon (DOC) and particulate organic carbon (POC) fractions. In this study, no filtration-based separation was applied to distinguish between these components; hence, the reported TOC values reflect a combined signal. While the phase-based sampling (supernatant, centrifuged liquid, sludge) provides macroscopic insight into polymer partitioning, it does not resolve the finer distinction between soluble and solid-bound fractions within each phase. This limitation is particularly relevant in the sludge phase, where high-molecular-weight cationic polymers are expected to adsorb onto solid surfaces. Such adsorption behavior is known to depend on factors like hydrophobicity and charge density, although parameters like $\log K_{ow}$ (the logarithm of the octanol–water partition coefficient, representing a compound's hydrophobicity), which quantify hydrophobic interactions, are rarely available for complex polymer mixtures.

3.3.4.2. Inorganic polymers estimation via aluminum mass balance. Unlike organic polymer-based coagulants, aluminum-based inorganic coagulants such as PAC and PAC-17 do not contribute to total organic carbon (TOC) and therefore require an alternative tracer for fate assessment. In this study, aluminum (Al), the active component of these formulations, was used as a representative indicator to track their distribution across treatment phases.

The total aluminum input into the system was first estimated using the Al concentration of the coagulant solution (obtained from the supplier) and the corresponding dosing volume, as shown in Equation (3.22):

$$M_{Al,input} = C_{Al,hybrid\ coagulant} \times V_{hybrid\ coagulant\ dosage} \quad (3.22)$$

Where:

$M_{Al,input}$ = Total aluminum mass introduced into the system via the coagulant (mg)

$C_{Al,hybrid\ coagulant}$ = Aluminum concentration in the coagulant solution (mg/L)

$V_{hybrid\ coagulant\ dosage}$ = Volume of hybrid coagulant solution dosed into the system (L)

Following treatment Al concentrations in all phases — including supernatant, centrifuged liquid, and sludge — were directly quantified using ICP-OES following appropriate sample preparation procedures. This comprehensive direct measurement approach allowed for a complete and accurate aluminum mass balance across the treatment system. The aluminum mass in each aqueous phase was calculated as:

$$M_{Al,phase} = C_{Al,phase} \times V_{phase} \tag{3.23}$$

Where:

$M_{Al,phase}$ = Total mass of aluminum in the respective treatment phase (mg)

$C_{Al,phase}$ = Measured aluminum concentration in the phase, obtained via ICP-OES (mg/L)

V_{phase} = Volume of the respective aqueous phase (L)

In the sludge phase, aluminum quantification was carried out by performing acidic digestion on the dewatered sludge samples, followed by elemental analysis using ICP-OES. The digestion process involved adding a known volume of acid solution to completely dissolve a pre-weighed portion of the sludge sample. The aluminum concentration in the resulting solution, expressed in mg/L, was used to calculate the total aluminum mass in the sludge phase as follows:

$$M_{Al,SLG} = C_{Al,digested} \times V_{digestion} \tag{3.24}$$

Where:

$M_{Al,sludge}$ = Total mass of aluminum in the sludge phase (mg)

$C_{Al,digested}$ = Aluminum concentration measured in the digestion solution via ICP-OES (mg/L)

$V_{digestion}$ = Volume of the digestion solution used for the sludge sample (L)

A complete mass balance was then established by summing the measured Al mass across all three phases:

$$M_{Al,input} \approx M_{Al,SUP} + M_{Al,CEN} + M_{Al,SLG} \quad (3.25)$$

Any discrepancies between input and output masses were considered negligible and attributed to minor sampling or analytical errors. Corresponding ΔM losses were calculated for completeness and are provided in **Appendix G**; however, these differences were considered insignificant and thus were not factored into the main mass balance calculations.

To distinguish aluminum introduced by the coagulant from the background aluminum content naturally present in the raw wastewater, a control scenario without any coagulant addition was used. In this study, the M1 scenario, which represents untreated raw wastewater, was selected as the baseline condition. Aluminum concentrations measured in M1 were subtracted from those measured in the coagulant-containing scenarios (such as M5 and M6) to calculate the net aluminum contribution originating solely from the coagulant.

$$\Delta M_{Al,phase} = M_{Al,phase}^{with\ PAC} - M_{Al,phase}^{no\ PAC} \quad (3.26)$$

This approach enabled clearer interpretation of coagulant-derived aluminum partitioning in the system, allowing phase-specific analysis while eliminating the influence of background aluminum.

Where:

$\Delta M_{Al,phase}$ = Net aluminum mass in the specified phase attributed solely to the coagulant (mg)

$M_{Al,phase}^{with\ PAC}$ = Measured aluminum mass in the phase after coagulant addition (mg)

$M_{Al,phase}^{no\ PAC}$ = Baseline aluminum mass in the same phase without coagulant addition (mg)

This differential calculation enables isolation of the aluminum fraction specifically introduced by the PAC-based coagulant, removing any contributions originating from background levels in the untreated wastewater.

In summary, the aluminum-based coagulants used in this study were quantitatively tracked across all treatment phases using a mass balance approach centered on directly measured aluminum concentrations. By incorporating background correction through a polymer-free control scenario (M1), the analysis provided a clearer understanding of the phase-specific distribution and retention behavior of aluminum introduced via PAC and PAC-17. This methodology enabled the differentiation of coagulant-derived aluminum from naturally occurring sources, offering a reliable framework for evaluating the fate and partitioning of inorganic polymer coagulants within the treatment system.

3.3.5. Total Suspended Solids (TSS) Mass Balance

Total suspended solids (TSS) represent the particulate matter retained on a filter during analysis and are widely used as an indicator of solid-phase removal efficiency in wastewater treatment. In this study, a mass balance approach was employed to quantify the fate and phase-specific distribution of TSS under different coagulant scenarios (M1–M6). The analysis aimed to evaluate the performance of both inorganic and hybrid coagulants in reducing particulate content and enhancing sludge formation. TSS concentrations were determined separately for each of the three treatment phases:

- Supernatant (SUP): After settling, the upper clarified liquid was sampled and filtered through pre-weighed glass fiber filters (0.45 µm pore size). The filters were dried at 105°C to constant weight, and TSS was calculated based on the mass retained.
- Centrifuged liquid (CEN): A portion of the settled suspension was centrifuged to remove fine particulates, and the supernatant was subjected to the same TSS measurement protocol as the supernatant phase.
- Sludge phase (SLG): In the sludge phase, direct filtration was not feasible due to high solids content. Therefore, a known volume of dewatered sludge was oven-dried at 105 °C until constant weight, and the resulting dry mass (g/L) was used as an approximate measure of suspended solids retained in this phase.

The total TSS input to the system was defined based on the concentration measured in the raw wastewater (M1) and the total volume treated:

$$M_{TSS,in} = C_{TSS,in} \times V_{Total} \tag{3.27}$$

Where:

$M_{TSS,in}$ = Total mass of TSS introduced into the system (mg)

$C_{TSS,in}$ = TSS concentration in raw wastewater (mg/L)

V_{Total} = Total volume of wastewater treated (L)

The TSS mass in each liquid phase was calculated using:

$$M_{TSS,phase} = C_{TSS,phase} \times V_{phase} \quad (3.28)$$

Where phase = supernatant or centrifuged liquid.

$C_{TSS,phase}$ = Measured TSS concentration (mg/L)

V_{phase} = Volume of the respective phase (L)

For the sludge phase, the total TSS was determined as the dry mass of sludge collected per scenario:

$$M_{TSS,SLG} = Dry\ sludge\ mass \quad (3.29)$$

Where:

$M_{TSS,SLG}$ = Mass of TSS retained in the sludge (mg)

A complete mass balance was established as follows:

$$M_{TSS,in} \approx M_{TSS,SUP} + M_{TSS,CEN} + M_{TSS,SLG} \quad (3.30)$$

Any small discrepancies were attributed to sample handling losses, drying inefficiencies, or instrument precision limitations. The above mass balance was repeated for each treatment scenario (M1–M6), enabling the quantitative comparison of key parameters using differential expressions:

TSS removal efficiencies for each treatment scenario (M2–M6) were calculated based on the difference between the total TSS mass entering the system and the cumulative TSS mass recovered in the liquid phases (SUP, CEN). The calculation was performed using the following expression:

$$TSS\ Removal\ (\%) = \left(\frac{M_{TSS,in} - \left(M_{TSS,SUP} + M_{TSS,CEN}\right)}{M_{TSS,in}}\right) x100 \quad (3.31)$$

Where:

$M_{TSS,SUP}$ = TSS mass measured in the supernatant phase (mg)

$M_{TSS,CEN}$ = TSS mass measured in the centrifuged liquid phase (mg)

In summary, the TSS mass balance analysis provided a comprehensive quantitative framework to evaluate particulate removal efficiency and solid-phase partitioning across all treatment scenarios (M1–M6). The total TSS input was calculated from the raw wastewater (M1) concentration and treated volume. Residual TSS in the supernatant and centrifuged liquid phases was quantified through filtration and gravimetric analysis. Due to the high solid content of the sludge phase, direct filtration was not feasible; therefore, oven-dried sludge mass was used as a proxy for retained solids.

TSS removal efficiencies were then calculated by subtracting the cumulative TSS mass in the liquid phases from the total input and expressing this difference as a percentage of the input load. Rather than isolating individual process parameters, this method captured the combined effect of coagulant formulation, dosage, and operational conditions on particulate retention. Overall, higher TSS retention in the sludge phase and lower residuals in the effluent indicated more efficient solid-liquid separation, providing a robust framework to compare treatment performance across all tested scenarios.

3.3.6. Total Solids (TS) Mass Balance

Total solids (TS) encompass all solid matter present in a wastewater sample, including both suspended (TSS) and dissolved (TDS) fractions. TS is an essential metric for evaluating the overall solid content of treated water and sludge and serves as a broader indicator of treatment performance beyond particulate removal alone.

In this study, a mass balance approach was used to quantify the distribution of total solids across three treatment phases—supernatant (SUP), centrifuged liquid (CEN), and sludge (SLG)—under different coagulant scenarios (M1–M6). This analysis complements the TSS-based evaluation by accounting for dissolved and colloidal solids retained in each phase.

TS concentrations were determined as follows:

- Supernatant (SUP): A representative portion of the clarified liquid was collected post-settling. TS was measured by evaporating a known volume of the sample at 105 °C to constant weight and calculating the retained mass.
- Centrifuged liquid (CEN): The same method was applied to the clarified supernatant obtained after centrifugation of the settled suspension.
- Sludge phase (SLG): The dewatered sludge samples were oven-dried at 105 °C until constant weight was achieved. The dry mass of the solid residue was recorded as the total solids retained in the sludge phase.

Equation (3.32) defines the total solids input to the system based on raw wastewater concentration and total treated volume. This serves as the starting point for the mass balance:

$$M_{TS,in} = C_{TS,in} \times V_{Total} \tag{3.32}$$

Where:

$M_{TS,in}$ = Total mass of TS introduced into the system (mg)

$C_{TS,in}$ = TS concentration in raw wastewater (mg/L)

V_{Total} = Total volume of wastewater treated (L)

The TS mass in each liquid phase was computed as:

$$M_{TS,phase} = C_{TS,phase} \times V_{phase} \tag{3.33}$$

Where phase = supernatant or centrifuged liquid.

$C_{TS,phase}$ = Measured TS concentration (mg/L)

V_{phase} = Volume of the respective phase (L)

In coagulation-based treatment systems, the total solids introduced into the system are expected to be distributed among the supernatant, centrifuged liquid, and sludge phases. However, under effective settling and separation conditions, the clarified liquid phases (SUP and CEN) are typically characterized by very low residual solids. As a result, the majority of the input TS is anticipated to accumulate in the sludge phase. Therefore, the overall mass balance of total solids can often be simplified as:

$$M_{TS,SLG} = Dry\ sludge\ mass \tag{3.34}$$

Where:

$M_{TS,SLG}$ = Mass of TS retained in the sludge (mg)

More broadly, total solids represent the sum of both suspended solids (TSS) and dissolved solids (TDS) across the system. While TSS is effectively removed through coagulation and settling, TDS is generally unaffected and remains in liquid phases. By integrating both TS and TSS measurements, it becomes possible to distinguish between particulate and dissolved fractions, and to better understand the phase-specific fate of different solid components. This integrated approach provides a more complete picture of coagulant performance and treatment efficiency.

In practice, the majority of total solids in the raw wastewater are expected to be retained in the sludge phase following coagulation and settling, especially under effective treatment conditions. Since the clarified liquid phases (SUP and CEN) contain minimal residual solids, their contribution to the total mass balance is typically negligible. As such, the mass of total solids introduced into the system $M_{TS,in}$ is approximately equal to the dry mass of solids retained in the sludge $M_{TS,sludge}$. This approximation provides a simplified yet valid representation of total solids distribution in well-performing coagulation systems.

This analysis enabled a holistic evaluation of coagulant performance by accounting for total solid-phase retention across all forms (suspended + dissolved). By comparing results from all scenarios to the control (M1), the method identified which treatments provided the greatest reductions in overall solid content and sludge production. Stronger solid-phase retention coupled with reduced residual solids in the liquid fractions indicated more efficient treatment behavior.

In addition to solids partitioning, the final sludge characteristics were also evaluated to assess the impact of coagulant formulations on sludge quality and handling properties. Two key parameters were calculated: sludge moisture content (%) and dry solid yield (g TS/L). These metrics provide further insight into the sludge quality and solid retention efficiency of each treatment scenario (M1–M6).

3.3.6.1. Sludge moisture content (%). Moisture content is a critical parameter in assessing sludge dewaterability, as high water content can increase handling and disposal costs. It was calculated based on the difference between the wet and dry masses of the collected sludge samples:

$$Moisture\ Content\ (\%) = \frac{(M_{wet} - M_{dry})}{M_{wet}} \times 100 \quad (3.35)$$

Where:

M_{wet} = Wet mass of the dewatered sludge sample (g)

M_{dry} = Dry mass of the same sludge sample after oven drying at 105°C (g)

This calculation was applied to each scenario to compare how different coagulant types influenced the final sludge moisture. In general, lower moisture percentages reflect more efficient water removal and enhanced dewaterability, which is desirable for downstream processing.

3.3.6.2. Dry solid yield (g TS/L). To evaluate the effectiveness of each treatment in generating solid biomass, the amount of dry solids produced per volume of treated wastewater was calculated as:

$$Dry\ Solid\ Yield = \frac{M_{dry}}{V_{treated}} \quad (3.36)$$

Where:

M_{dry} = Dry mass of the same sludge sample after oven drying at 105°C (g)

$V_{treated}$ = Total volume of wastewater treated in that scenario (L)

This value provides a normalized measure of solid retention, allowing comparison across scenarios with different influent characteristics or coagulant dosages. Higher dry solid yields indicate greater solids capture and better flocculation performance.

These sludge-related metrics complement the solids-based analyses by directly quantifying the physical outcome of solid-liquid separation. While parameters such as TSS removal reflect how effectively suspended particles are eliminated, metrics like sludge moisture content and dry solid yield provide insight into the quality and manageability of the resulting sludge. For instance, a treatment scenario that achieves high TSS removal but produces very wet sludge may still present challenges in terms of cost, dewatering, and handling. In contrast, scenarios yielding drier and denser sludge offer significant operational advantages and improved process efficiency.

By evaluating moisture content and dry solid yield together, this section provides a holistic perspective on sludge quality. Combined with the results presented in previous sections, it supports the overall assessment of which coagulant formulations performed best not only in pollutant removal

but also in producing manageable and compact sludge. The results obtained from the sludge moisture and dry solid yield analyses are further interpreted and discussed in detail in Section 4.

3.3.7. Estimation of Phase-Specific Total Dissolved Solids (TDS)

Total Dissolved Solids (TDS), representing the soluble and non-particulate fraction of total solids, were not directly measured in this study. Unlike total suspended solids (TSS), TDS cannot be removed by physical filtration methods and is considered a key parameter for evaluating the impact of treatment processes on dissolved pollutant removal.

Although, in theory, TDS concentrations can be estimated by subtracting TSS from total solids (TS) within the same phase (i.e., TDS = TS − TSS), this approach was not implemented here. This decision was primarily due to the fact that TS concentrations in the liquid phases (SUP and CEN) were extremely low. Additionally, TSS measurements could not be performed in the sludge phase due to its high solid content and the limitations of filtration-based analysis.

These phase-specific measurement constraints hindered the consistent and accurate application of the TS − TSS relationship across the three-phase framework used in this study. As such, TDS was acknowledged solely as a theoretical component within the total solids balance and was not quantified numerically. This approach ensures the integrity of the analysis by avoiding speculative estimates and focusing on parameters that were reliably measured under the experimental conditions.

3.4. Theoretical Assessment of Biodegradability Using BIOWIN Software

In this study, the biodegradation potential of selected synthetic organic polymers used in hybrid coagulant systems was evaluated using the U.S. Environmental Protection Agency's (EPA) BIOWIN predictive software. The modeling was conducted as a cost-effective and rapid preliminary assessment tool to estimate the aerobic and anaerobic biodegradability of the polymers under consideration. BIOWIN operates through quantitative structure–activity relationships (QSAR) and estimates degradation behavior based on molecular substructure fragments.

The polymers evaluated in this analysis included:

- PolyDADMAC (polydiallyldimethylammonium chloride)
- PAM (polyacrylamide)
- Polyamine (specific structure referenced via CAS/SMILES identifiers)

The molecular structures of these compounds were entered into the BIOWIN platform in SMILES (Simplified Molecular Input Line Entry System) format, retrieved from the PubChem database. For each compound, the predictions from the following submodels were recorded:

- BIOWIN 3: Ultimate biodegradation timeframe (in weeks/months)
- BIOWIN 5 & 6: Probability of ready biodegradability (OECD 301 alignment)
- BIOWIN 7: Anaerobic biodegradation potential (presence/absence)

BIOWIN provides several submodels with varying levels of reliability. In this study, priority was given to the most widely accepted models (BIOWIN 3–6), which have shown the best overall performance in predicting biodegradability (Boethling et al., 2003). Other submodels were considered only as supporting information and were not emphasized due to their limited applicability to large polymeric structures. It should be noted that BIOWIN predictions are primarily validated for low-molecular-weight, non-ionic organic chemicals. Therefore, the results for high-molecular-weight or ionized polymers should be interpreted as indicative rather than definitive.

All predictions were performed using BIOWIN v4.10, with results interpreted in line with standard threshold values recommended in the literature and regulatory frameworks (e.g., REACH, OECD). A compound was classified as “readily biodegradable” if its BIOWIN 5 value exceeded 0.5 and BIOWIN 3 indicated degradation within weeks rather than months. Such theoretical assessments provide valuable insight into the potential persistence of polymers in sludge and effluent streams, and the detailed outcomes and interpretations from BIOWIN are presented in Section 4.2, complementing the experimental mass balance results.

4. RESULTS AND DISCUSSION

4.1. Evaluation of Treatment Performance Based on Water Quality Parameters

The results are presented in a structured progression that reflects the experimental logic established in the previous chapter. Initial screening tests provide an overview of the general treatment behavior and guide the subsequent dose-optimization stage, where the most promising hybrid formulations are refined under controlled conditions. Building on these outcomes, the comparative performance of the selected hybrids and the conventional treatment method is evaluated under optimized conditions across multiple dimensions, including COD and TSS removal, sludge characteristics and solid yield, TOC removal together with polymer tracing, and the phase-specific distribution of aluminum, iron, and chromium. Together, these layers of analysis provide a well-rounded basis for evaluating how each coagulant formulation performs as a whole, making it possible to understand their treatment capabilities in a clear, connected, and scientifically grounded way.

4.1.1. Screening Tests and Dose Optimization

All raw data generated during the screening stage are provided in **Appendix A**, including the experimental date, treatment scenario, formulation code, pH adjustment agent (when applicable), initial and final pH values, working volumes, and the amounts of coagulant and anionic polyelectrolyte applied. As described in Section 3.2.3.1, the screening tests were performed under standardized laboratory conditions using fixed coagulant and coagulant aid (PAM) dosages to ensure comparability among formulations. This standardization allowed each product to be evaluated under identical chemical and environmental conditions, enabling intrinsic differences in treatment performance to be distinguished without the influence of external variables. During this phase, turbidity, COD, and TSS were measured in the supernatant (SUP), while sludge volumes and both influent and adjusted pH values were systematically recorded. These measurements formed the basis for assessing the preliminary treatment behavior of the M2–M6 scenarios and guided the subsequent dose optimization stage.

Among all scenarios evaluated, M2 and M3 exhibited the lowest overall treatment performance. COD removal was limited to 8.16% (M2) and 6.26% (M3), with TSS removal only 17.29% and 16.74%, respectively. These scenarios also produced the highest sludge volumes (SLG): 4.88% for

M2 and 4.02% for M3, likely due to the high chemical input required—especially in M2, where lime's reactive and bulky nature contributes significantly to sludge formation.

In contrast, Scenario M4, based on liquid PAC 17, achieved the highest TSS removal efficiency (27.28%) among the conventional treatment scenarios (M2–M4). COD removal reached 18.21%, closely aligning with hybrid scenarios. The SLG volume was moderate at 3.19%. These results demonstrate PAC 17's effectiveness as a standalone coagulant. However, the absence of additional organic coagulants or metal salts suggests that M4 lacked the synergistic benefits observed in hybrid systems.

Scenario M5, featuring pH-adjusted hybrid coagulants, showed consistently high performance, with COD removal ranging from 13.42% to 20.81%, TSS removal between 25.44% and 26.26%, and SLG volumes from 2.26% to 3.84%. The most successful formulation in this scenario, M5 – P020200, delivered top results in both COD and TSS removal. The controlled pH conditions likely enhanced coagulant reactivity, particularly improving COD removal due to more efficient destabilization of organic compounds and improved floc formation.

Despite the absence of pH control, Scenario M6 performed similarly well to M5, especially in TSS and turbidity removal. For instance, M6 – P020200 reached 20.66% COD removal, 26.43% TSS removal, and 3.86% SLG, ranking among the top-performing formulations. Other notable formulations include M6 – P020100, M6 – P020201, and M6 – P010300, all of which exhibited high removal efficiencies. M6 also produced generally lower sludge volumes, consistent with literature noting that the exclusion of pH adjustment chemicals reduces overall sludge yield.

This observation is consistent with previous studies suggesting that omitting pH adjustment can help reduce sludge production, as pH control—especially when combined with coagulants—can significantly alter sludge characteristics. Zhang et al. (2023) specifically showed that pH changes during coagulation influence sludge morphology and structure, which may result in increased sludge yield.

Furthermore, some M6 formulations outperformed M5 in turbidity removal, suggesting that operating within the natural pH of the system may support more stable and effective coagulation. In certain cases, aggressive pH adjustment can lead to colloid restabilization rather than effective flocculation. A summary of average removal efficiencies and sludge generation percentages for all scenario–formulation pairs is illustrated in Figure 4.1 below. The chart provides a comparative visual

overview of turbidity, COD, and TSS removal performances, as well as sludge formation trends across the all-tested formulations.

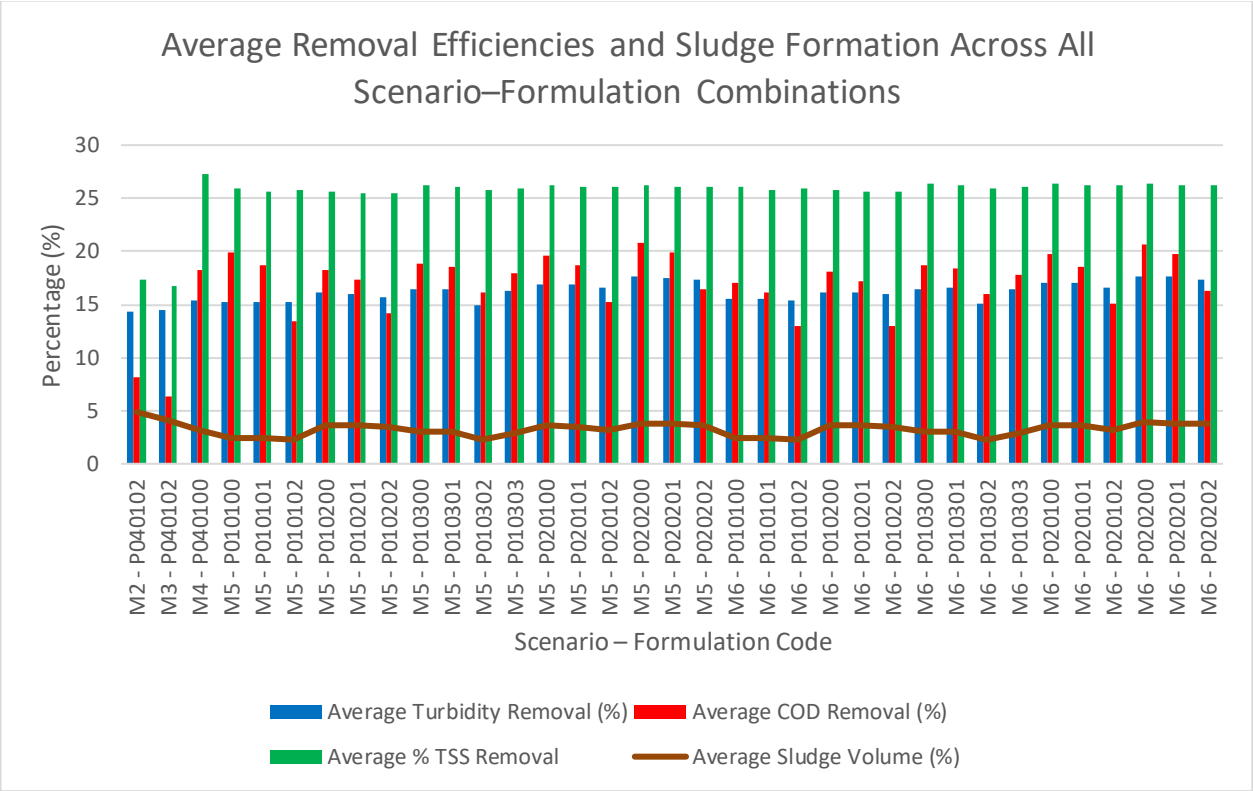


Figure 4.1. Comparison of average turbidity, COD, and TSS removal efficiencies and sludge formation percentages for each treatment scenario and formulation tested over 22 screening experiments.

In summary, both M5 and M6 scenarios significantly outperformed the conventional approaches (M2, M3, and M4). While M5 benefited from optimized laboratory conditions and achieved slightly higher removal rates, M6 matched or closely followed its performance and offered operational advantages. The elimination of pH adjustment steps, reduced chemical usage, and minimized sludge generation position M6 as a more sustainable, operationally simplified and cost-effective alternative. As such, five of the best-performing M6 formulations were selected for further evaluation in the optimization and advanced testing phases of this study.

To further support the selection of the M6 scenario for advanced testing, a performance-based scoring matrix was constructed to evaluate and rank all formulations within this scenario. While the bar chart provided above (Figure 4.1) visually reflects general removal trends, a multi-criteria decision-making (MCDM) approach was employed to ensure a more structured and justified selection.

The scoring system was designed to reflect both regulatory compliance priorities and environmental considerations. In accordance with national wastewater guidelines, COD and TSS removal were assigned the highest importance, as these parameters are directly associated with pollutant load reduction and legal discharge limits. However, due to the specific scope and environmental relevance of this study, sludge formation (SLG) was also treated as a critical parameter. Since one of the main objectives of hybrid coagulant development is to minimize chemical input and subsequent sludge production, SLG was weighted accordingly.

All four parameters (SLG, turbidity, COD, and TSS removal) were normalized using min–max scaling. The scoring model rewarded lower values for sludge formation and higher values for removal efficiencies. Final composite scores were calculated using a weighted formula that prioritized COD and TSS, followed by SLG, and finally turbidity. The full details of the normalization and scoring calculations are provided in **Appendix B**. The top-ranked M6 formulations identified through this matrix are summarized in Table 4.1 below and were selected for further optimization and advanced testing.

Table 4.1. Selected hybrid coagulant formulations from the M6 scenario (based on a 100-gram total formulation weight).

Code	Inorganic Chemical Coagulant I	Amount of Inorganic Chemical Coagulant I (g)	Inorganic Chemical Coagulant II	Amount of Inorganic Chemical Coagulant II (g)	Organic Chemical Coagulant I	Amount of Organic Chemical Coagulant I (g)	Organic Chemical Coagulant II	Amount of Organic Chemical Coagulant II (g)	Amount of Deionized Water (g)
P020100	PAC 17	50	-	-	PolyDADMAC	5	-	-	45
P020200	PAC 17	57	$FeCl_3$	0.8	PolyDADMAC	5	-	-	37.2
P020201	PAC 17	57	$FeCl_3$	0.8	Polyamine	5	-	-	37.2
P010300	PAC (Powder)	10	PAC 17	32	PolyDADMAC	5	-	-	53
P010301	PAC (Powder)	10	PAC 17	32	PolyDADMAC	2.5	Polyamine	2.5	53

Following the screening phase, the five top-performing formulations were selected and carried forward to the optimization stage, where the primary objective was to optimize the coagulant dosage for each formulation. At the same time, the effectiveness of PAM dosage was also evaluated within the applied dose ranges. This allowed for the identification of the specific dosage combinations under which each product achieved its maximum performance, in alignment with its intrinsic composition.

It was observed that hybrid formulations could maintain high treatment efficiency even at lower PAM dosages, whereas traditional coagulant, aluminum sulfate (alum), required substantially higher PAM input to perform effectively.

The ability of hybrid formulations to achieve high performance with lower PAM dosages is considered to be a result of their built-in polymeric structures, which may enhance their capacity to drive coagulation and flocculation processes more effectively. This offers a notable advantage in terms of chemical efficiency and process economics. Consequently, while alum's high PAM demand implies increased chemical consumption and elevated operational costs, hybrid formulations stand out as a more sustainable and cost-effective alternative.

As part of the dose optimization studies, a detailed evaluation was conducted for the five top-performing hybrid formulations under representative conditions. To ensure consistency, test days with relatively stable influent quality were selected, and Day 14—characterized by raw wastewater values close to the study average—was used as the reference point. On this day, four key performance indicators—sludge production, TSS removal, turbidity removal, and COD removal—were assessed for each formulation based on the supernatant phase. The results are summarized in Figure 4.2.

Sludge generation exhibited a generally linear increase across the entire coagulant dose range for all formulations. Between 0.60 and 2.40 g/L, the increase in sludge was moderate and proportional, indicating controlled floc formation. However, from 2.80 to 3.20 g/L, the slope of the curve became steeper, suggesting the onset of overdosing, where excess coagulant or flocculant resulted in denser or excessive sludge production.

COD removal showed a steep improvement between 1.20 and 2.40 g/L, indicating effective removal of organic pollutants within this range. Most formulations achieved their peak performance near 2.80 g/L. At 3.20 g/L, a slight decline in efficiency was observed for some formulations, consistent with common overdosing effects such as residual organics or destabilization from excessive chemical input.

Turbidity removal demonstrated a saturation-type curve, with sharp improvements between 0.60 and 2.00 g/L, followed by a slower but continued increase up to 2.80 g/L. Beyond this point, turbidity removal either plateaued or slightly declined, indicating that further increases in chemical dosage did not yield significant performance gains.

Lastly, TSS removal demonstrated a classic coagulation profile: low removal at 0.60 g/L, rapid increase up to 2.00–2.40 g/L, and a plateau near 2.80 g/L. At 3.20 g/L, a slight leveling off or minor decrease was observed, again indicative of mild overdosing. The overall dose–response behavior across all parameters confirms the consistency and robustness of the selected formulations and supports the use of a 2.80 g/L operational dose for subsequent evaluations.

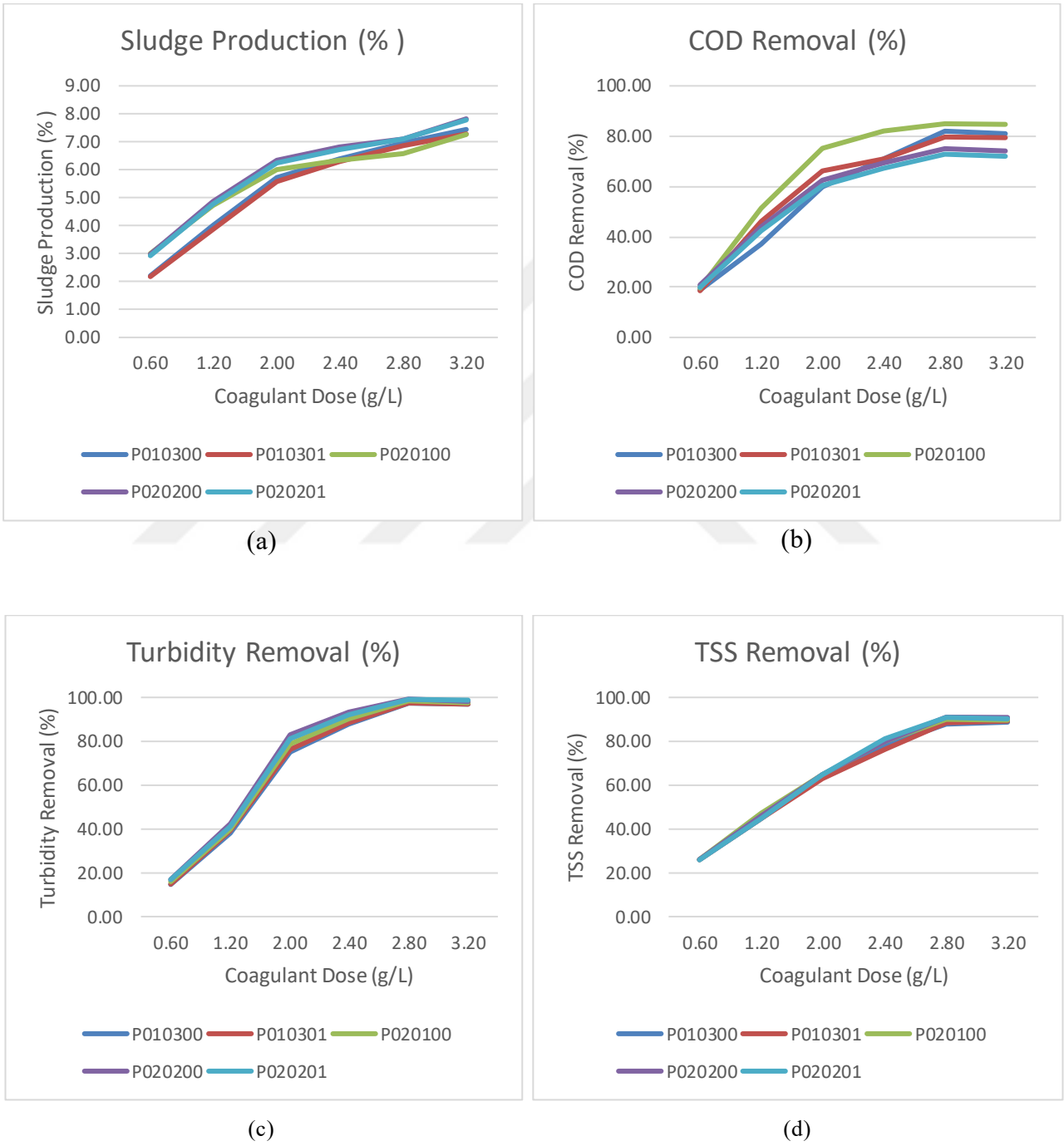


Figure 4.2. Dose–response behavior of the five selected hybrid coagulant formulations across four performance indicators: (a) Sludge generation (SLG%), (b) COD removal efficiency (%), (c) Turbidity removal efficiency (%), and (d) TSS removal efficiency (%), as a function of coagulant dose (g/L).

With increasing coagulant dosage, removal efficiencies for TSS, turbidity, and COD showed a marked and rapid increase particularly in the 0.60–2.00 g/L range, indicating effective destabilization of colloidal and suspended solids and the onset of efficient coagulation–flocculation mechanisms. In the 2.40–2.80 g/L range, the system approached its saturation point, with maximum removal efficiencies being recorded, albeit with a noticeable decline in the rate of improvement. At 3.20 g/L, a slight decrease in COD removal was observed in certain formulations, suggesting the onset of overdosing effects, as frequently reported in the literature. This observation is consistent with the findings of Joaquin and Nirmala (2019), who reported that increasing coagulant dosage beyond the optimal range led to a decline in COD and turbidity removal efficiency during municipal wastewater treatment, highlighting the negative impact of coagulant overdose.

Similarly, turbidity and TSS removals also displayed marginal stagnation or very slight decline, although these effects may not be clearly visible in the plotted curves, they are noticeable upon closer statistical examination. Overdosing can lead to particle restabilization, weakening of floc structure, or increased chemical residues in the treated water. In this context, the dose–response profiles allow not only the identification of an optimum dose, but also the recognition of a critical upper limit beyond which performance may deteriorate. Furthermore, although each formulation followed its own characteristic response curve due to minor compositional differences, their optimum regions nevertheless converged within the same upper dosage interval.

In summary, the evidence supports the adoption of a uniform 2.8 g/L operational dose and frames the basis for subsequent comparative evaluation. Although the selected formulations differed slightly in composition, they shared a common structural basis of an aluminum salt combined with a polymeric additive, and their dose–response profiles were broadly comparable. A uniform operational dose of 2.8 g/L was therefore adopted for comparative testing. For optimum dosage of aluminum sulfate ($Al_2(SO_4)_3$)-based formulations prepared as a 40% stock solution, this corresponds to an application volume of 8 mL per liter of wastewater. In the following section, the results of all advanced analyses that performed based on the selected optimum dosages will be discussed in detail.

4.1.2. Comparative Performance of Selected Hybrids and the Conventional Treatment Method Under Optimized Conditions

As a result of the optimization studies, the hybrid coagulant dosage was determined as 2.8 g per 1 L of raw water. In the conventional method, a 40% aluminum sulfate solution was applied at 8.0 mL per 1 L. Under these optimized and standardized conditions, the advanced stage focuses on

detailed comparisons between the selected hybrid formulations and the conventional method. Performance is evaluated across the three phases (SUP, CEN, and SLG), with phase-specific mass balances employed to resolve unmeasured quantities.

The remainder of this section presents a direct comparison between the selected hybrid formulations (P020100, P010300, P010301, P020200, P020201) and the conventional coagulant (M2/P040102) in terms of pollutant removal and sludge management across 22 days of extended testing.

4.1.2.1. COD removal performance. The comparative evaluation of COD removal efficiency clearly highlights the superior performance of the hybrid coagulants over the conventional aluminum sulfate formulation (P040102). Based on the 22-day testing period, the average COD removal achieved with P040102 was 68.1%, while all hybrid formulations outperformed this benchmark. Notably, formulations such as P020100 (84.7%), P010300 (81.6%), and P020200 (74.7%) demonstrated substantial improvements in organic matter removal. As shown in Figure 4.3., the PAC-based formulation P020100 consistently achieved the highest COD removal, with other hybrid coagulants also outperforming the conventional alum-based formulation.

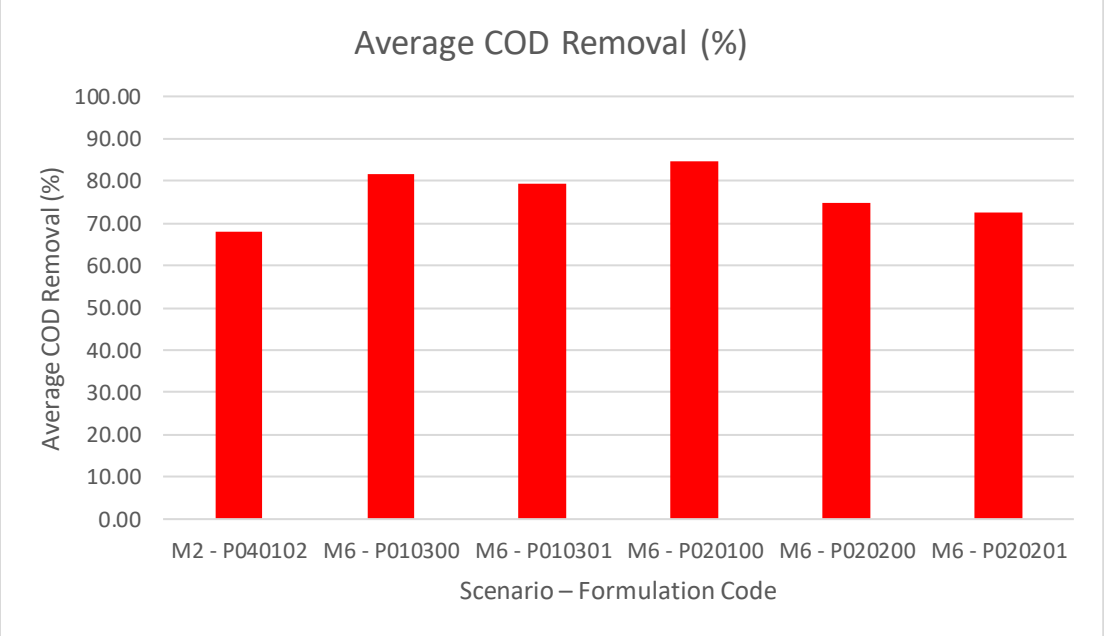


Figure 4.3. Average COD removal (%) for the conventional coagulant (P040102) and selected hybrid formulations over a 22-day testing period.

The distribution of COD across the treatment phases revealed a clear concentration of organic matter in the sludge phase, with lower values observed in the supernatant (SUP) and centrifuged

liquid (CEN) phases. Notably, the COD content in the centrifuged phase occasionally exceeded that of the supernatant. This can be explained by the fact that the centrifuged phase is derived directly from the sludge and may therefore contain dissolved organics that are not present in the initial supernatant. As it represents a secondary liquid fraction separated from the sludge matrix, slightly elevated COD levels in this phase are consistent with expectations.

Meanwhile, the calculated COD content in the SLG phase appeared disproportionately high relative to its small volumetric fraction. This can be attributed to the dense nature of the sludge flocs formed during coagulation, which tend to concentrate residual organics. This trend is not uncommon in coagulation–flocculation systems and reflects the strong affinity of dense flocs for entrapping both particulate and soluble organic fractions. Since the sludge volume is relatively compact, even modest organic mass accumulation can result in high COD concentrations on a per-volume basis.

Such behavior highlights the importance of interpreting COD not only through effluent clarity or removal percentages, but also in terms of phase-specific distribution. A high-performing coagulation system may yield clear effluents with low COD levels in the liquid phases, while concentrating the majority of the organic load into the sludge matrix. This reinforces the value of phase-resolved mass balance analyses in fully characterizing treatment efficiency and understanding the fate of organic pollutants in wastewater treatment.

Among the tested hybrids, P020100, a formulation based on PAC, PolyDADMAC, and deionized water, delivered the highest COD removal. This enhanced performance can be attributed to the synergistic effect between pre-hydrolyzed aluminum species in PAC and the strong cationic charge density of PolyDADMAC, which promotes efficient destabilization and bridging of dissolved organic compounds. The use of $FeCl_3$ in the P020200 and P020201 formulations also contributed to effective removal, albeit with slightly lower COD performance compared to other hybrids.

Despite differences in composition, the hybrid coagulants tested in this study demonstrated broadly comparable performance across key water quality indicators. A comprehensive dataset presenting all COD-related measurements—including phase-specific concentrations, removal efficiencies, and mass balance calculations across the 22-day testing period—is provided in **Appendix C** to support the findings discussed in this section.

Importantly, all COD removal values reported in this study were calculated on a mass basis (mg), rather than as simple influent–effluent concentration differences. In each scenario, the measured COD

concentrations in SUP, CEN, and SLG phases were multiplied by their respective volumes, allowing for a phase-specific quantification of organic pollutant loads. The sum of these values was used in the mass balance framework to determine removal efficiency, providing a more representative picture of pollutant fate across all treatment phases.

Beyond average removal efficiencies, further insights were gained from the detailed phase-based mass balance analysis. COD concentrations in SUP and CEN phases were directly measured, while COD levels in the SLG phase were derived from mass balance equations, allowing a full accounting of organic pollutant distribution. No external organic load was introduced by the conventional coagulant (P040102), as aluminum sulfate solutions are inorganic and free of carbon-based additives. In contrast, for the hybrid formulations, the COD contribution of the coagulant stock solutions was experimentally measured and incorporated into the total COD input, since these coagulants contained organic constituents such as PolyDADMAC and/or polyamines, which can introduce a measurable background COD load independent of the raw wastewater.

On the other hand, the anionic polyelectrolyte (PAM) used as a flocculant was excluded from the COD input calculations. Since only a small volume of a 1.60 g/L PAM stock solution was added during each hybrid trial, the actual PAM dose introduced into the system was extremely low—rendering its contribution to the overall organic load negligible. Therefore, for the purposes of mass balance modeling and comparative evaluation, the PAM-related COD was considered insignificant and thus omitted from the calculation of total COD input.

In summary, COD removal performance among hybrid coagulants was consistently superior to the conventional benchmark, driven by enhanced charge neutralization and bridging mechanisms. The mass balance assessment further underscored the importance of interpreting COD distribution holistically across all phases, rather than relying solely on supernatant-based measurements.

4.1.2.2. TSS removal performance. The comparative analysis of TSS removal demonstrates that all hybrid formulations outperformed the conventional aluminum sulfate-based coagulant (P040102). As shown in **Appendix D**, the 22-day dataset reveals consistent advantages in suspended solids removal for the hybrid coagulants across all treatment scenarios. Figure 4.4 presents the average TSS removal (%) observed for each formulation, illustrating the performance gap between the conventional and hybrid coagulants.

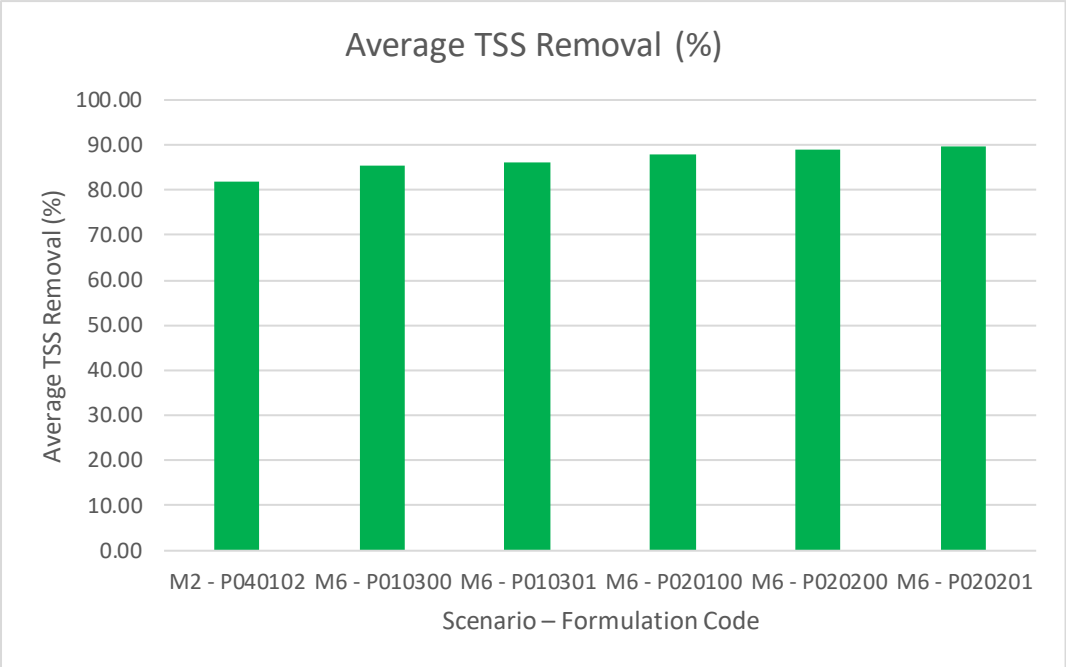


Figure 4.4. Average TSS removal (%) achieved by the conventional coagulant (P040102) and selected hybrid formulations over a 22-day testing period.

A minor but recurring observation was that the TSS concentration in the centrifuged liquid (CEN) phase occasionally exceeded that of the supernatant (SUP) phase. This is likely because the CEN phase represents the second liquid fraction separated from sludge under higher mechanical force, and sampling was performed using pipettes. As a result, entrained particles from the sludge matrix may have contributed to slightly elevated TSS values in this phase. This may reflect a phenomenon occasionally observed in coagulation–flocculation systems, where fine particles loosely associated with sludge flocs are potentially released into the liquid phase during centrifugation.

Among the hybrid coagulants, the highest average TSS removal efficiencies were observed in P020201 (89.73%) and P020200 (89.13%), both of which integrate PAC, Polyamine or PolyDADMAC, and a small fraction of $FeCl_3$. This suggests that the inclusion of ferric ions may enhance particle destabilization and floc structure formation in hybrid systems, particularly under stable pH conditions. Formulations P020100, P010301, and P010300 also achieved strong TSS removal rates (ranging between 85.5% and 87.8%), further validating the contribution of PAC–polymer synergies to particulate removal performance.

In contrast, the conventional alum formulation (M2/P040102) exhibited a comparatively lower TSS removal of 81.77%. This performance gap can be attributed to the less efficient hydrolysis

products of aluminum sulfate, which form weaker flocs compared to pre-polymerized aluminum species (PAC) and cationic polymers used in hybrid blends.

In addition to superior TSS removal, the hybrid coagulants also demonstrated a clear advantage in terms of sludge generation. While the conventional aluminum sulfate formulation (P040102) produced an average sludge volume of 10.22%, the hybrid formulations generated significantly lower volumes, ranging from 7.18% to 7.84%. This reduction indicates that hybrid coagulants promoted the formation of denser and more compact flocs, which settled more efficiently during sedimentation.

The lower sludge volume, despite high TSS removal efficiencies, suggests improved solid–liquid separation and more efficient particle capture by the hybrid systems. This outcome is especially advantageous for downstream processes, since producing less sludge means that smaller volumes must be dewatered and ultimately disposed of, easing both operational burdens and the associated environmental footprint. Overall, the results demonstrate the practical advantages of hybrid coagulants, offering stronger pollutant removal together with more efficient sludge management.

These findings align with literature reporting that PAC and organic polymer-based hybrid coagulants not only improve particle capture efficiency but also produce denser, more settleable sludge with lower overall volume (Ahmad et al., 2008). Additionally, the small amount of $FeCl_3$ present in some formulations may further contribute to sludge densification through increased interparticle bonding.

In conclusion, the hybrid coagulants demonstrated robust and efficient performance in removing suspended solids, with reduced sludge generation compared to the conventional approach. These advantages underline the potential of tailored hybrid systems in enhancing coagulation–flocculation efficiency while minimizing operational burdens in wastewater treatment.

4.1.2.3. Sludge characteristics and solid yield evaluation. In addition to pollutant removal, the evaluation of sludge properties provides critical insight into the overall effectiveness of the treatment process. In this section, sludge volume, moisture content, and dry solid yield obtained under different scenarios are examined to highlight their implications for process efficiency and downstream sludge management.

In this study, the sludge characteristics of the tested formulations varied significantly depending on their chemical composition. The conventional aluminum sulfate-based formulation (P040102)

exhibited a high average moisture content of 70.27% and the highest sludge volume (10.22%), indicating the formation of loose and poorly consolidated flocs. This is consistent with literature findings suggesting that hydrolysis products of aluminum sulfate tend to form weaker flocs, leading to lower sludge density and more challenging dewatering (Cao et al., 2016).

In contrast, the hybrid formulations containing PAC and cationic polymers (e.g., PolyDADMAC or polyamine) demonstrated improved sludge quality, with moisture contents in the range of 54–58% and significantly lower sludge volumes. For instance, P020100 produced sludge with 45.37% dry solids, the lowest average sludge volume (7.18%), and a dry solids yield of 3.14 g TS/L—indicating a compact floc structure with reduced water content. Similarly, P020200 and P020201, both containing a small dose of $FeCl_3$ in addition to PAC and polymers, showed strong performance, with sludge volumes below 7.85% and high dry solids concentrations. The presence of ferric ions may have enhanced interparticle bonding, contributing to denser floc formation.

Figure 4.5 illustrates the inverse relationship between sludge volume and moisture content. As shown, formulations producing lower-moisture sludge also generated lower sludge volumes, suggesting the formation of more compact and efficiently settled flocs. These results indicate that hybrid coagulants improve not only pollutant removal but also downstream sludge handling.

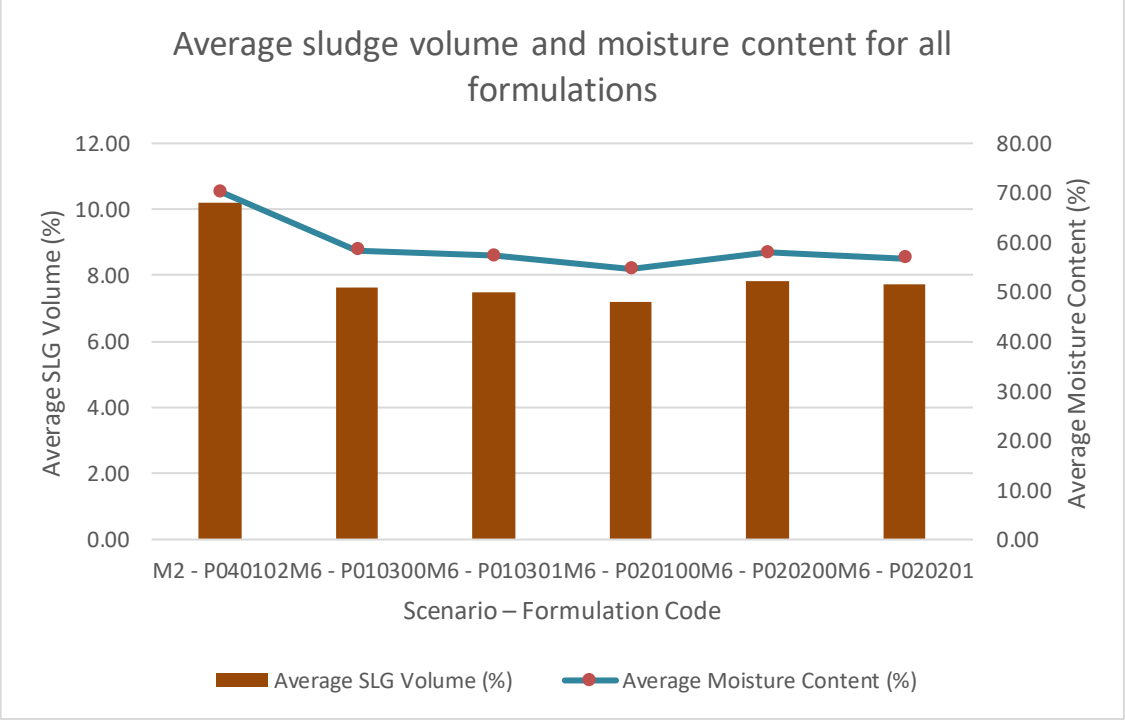


Figure 4.5. Average sludge volume and moisture content for all coagulant formulations.

From an environmental perspective, producing sludge with lower moisture content and smaller volume significantly reduces the energy required for dewatering, transportation needs, and the carbon footprint of the treatment process. Moist sludge is more energy-intensive to process and occupies more space during storage and transport. In this context, hybrid coagulants offer advantages not only in operational efficiency but also in minimizing environmental impact across the sludge management chain.

In conclusion, sludge characterization results indicate that hybrid coagulants produce denser, lower-moisture, and smaller-volume sludge, offering clear benefits for both cost reduction and environmental sustainability. The conventional aluminum sulfate formulation, by contrast, results in voluminous and water-rich sludge, limiting the overall process efficiency. These findings further support the potential of hybrid formulations as effective alternatives not only for pollutant removal but also for improved post-treatment sludge management. A complete set of sludge-related measurements is presented in **Appendix E.**

4.1.2.4. TOC removal and polymer tracing via differential comparison. The evaluation of TOC removal in this study involved both conventional and hybrid coagulant formulations, with particular emphasis on assessing the contribution and fate of organic polymer additives. A total of eight formulations were examined, expanding beyond the standard five hybrid formulations and one conventional coagulant used in earlier analyses. This extension was necessary to accommodate a set of polymer-free reference formulations (P020102, P020202), which were developed specifically to isolate the TOC impact of the organic components in the hybrid coagulants.

The measured average TOC removal efficiencies across all formulations were calculated based on mass (mg) before and after treatment, in line with the standard removal efficiency formula and it is found that the results are ranged from 65.46% (P040102) to 84.12% (P020100), following a trend that closely mirrored the COD removal results and underscoring the correlation between TOC and COD in evaluating the removal of organic pollutants. Hybrid coagulants generally outperformed the conventional aluminum sulfate formulation (P040102), with TOC removal efficiencies reaching over 80% in polymer-based blends such as P010300 and P020100. To provide a clearer understanding of the formulation-specific performances, the average TOC removal values for each tested coagulant system are summarized in Figure 4.6 below.

It should be noted that, in this evaluation, the TOC concentration associated with the sludge phase was determined mathematically, as direct measurement was not feasible. Detailed numerical

results are provided in **Appendix F.** The relatively higher concentration observed in the sludge phase is further justified by the considerably lower volume of the sludge compared to the aqueous phases, which leads to a denser accumulation of organic residues per unit volume.

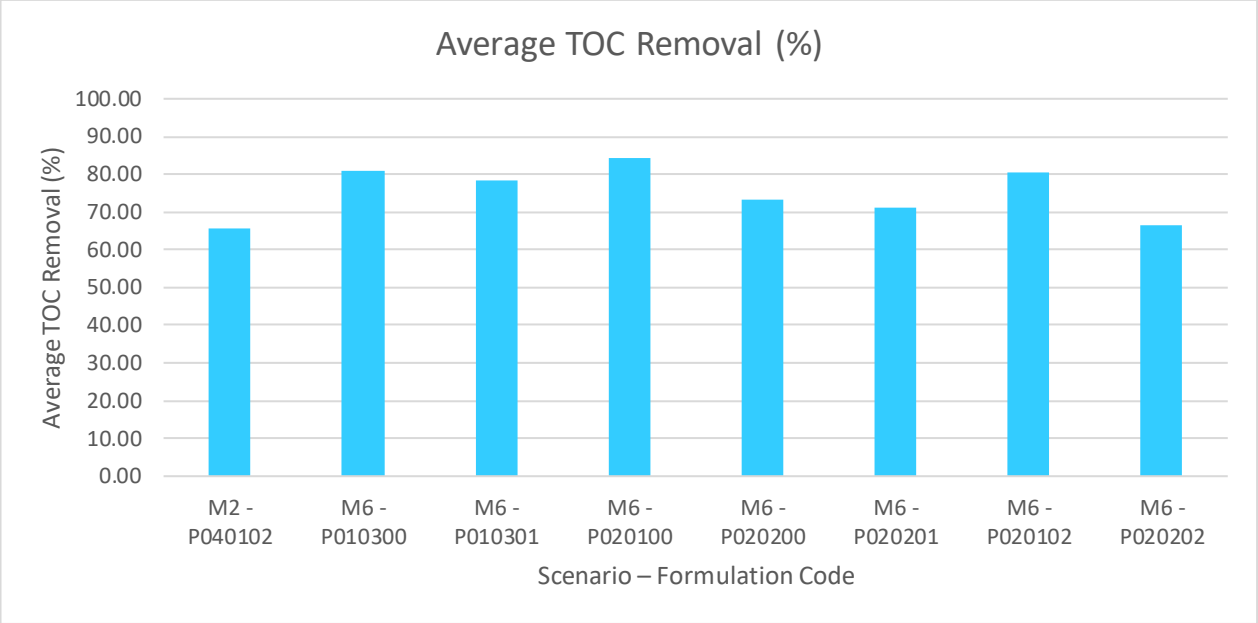


Figure 4.6. Average TOC removal efficiencies of all coagulant formulations.

Among the hybrid formulations, M6–P020100 achieved the highest average TOC removal with 84.12%, followed by M6–P010300 (80.83%), M6–P010301 (78.47%), and M6–P020102 (80.38%). These results clearly demonstrate that polymer-containing hybrid coagulants significantly outperform the conventional aluminum sulfate formulation M2–P040102 (65.46%) in terms of organic carbon removal.

The polymer-free hybrid formulations, namely M6–P020102 (80.38%) and M6–P020202 (66.42%), showed noticeably lower TOC removal compared to their polymer-based counterparts. This contrast further confirms the critical role of organic polymer additives in enhancing TOC removal efficiency. Notably, the performance gap between P020100 and its polymer-free version P020102 highlights an approximate 3.74% increase in efficiency due solely to the presence of PolyDADMAC.

Analysis of formulation contents underscores the importance of both the presence and type of polymer. For example, P020100, which contains PolyDADMAC, achieved the highest TOC removal. The relatively high performance of P020102, despite lacking any polymer additive, suggests that PAC alone has a strong intrinsic capacity for carbon removal. The slightly reduced efficiency of P010301

compared to P010300 indicates that minor variations in polymer composition can influence TOC removal performance.

Overall, the results suggest that the presence of organic polymers in hybrid coagulants substantially improves TOC removal, likely through enhanced flocculation, greater adsorption surface area, and more effective capture of colloidal and dissolved organic matter. These findings are also consistent with COD removal trends, emphasizing the complementary nature of TOC and COD as key parameters for evaluating treatment efficiency.

In parallel, TOC concentrations in the CEN phase were consistently found to be slightly higher than those in the SUP phase, supporting the hypothesis that organic matter is being effectively transferred to the floc matrix. Since the CEN phase was collected by pipetting the liquid trapped between settled sludge particles, it likely contains floc-bound or adsorbed organic residues that do not appear in the clear supernatant. To further clarify the origin of these organic residues and quantify the specific contribution of polymer additives to this distribution pattern, a differential comparison approach was applied.

To further distinguish the portion of TOC associated specifically with polymer additives, three hybrid formulations (P020100, P020200, and P020201) were paired with their corresponding polymer-free counterparts (P020102 and P020202). These comparisons allowed the identification of additional TOC loads introduced by organic additives and enabled a mass balance-based estimation of polymer distribution across the treatment phases (supernatant, centrifuged liquid, and sludge).

For example, the P020100 vs. P020102 comparison isolated the TOC effect of PolyDADMAC, while P020201 vs. P020202 provided insights into the contribution of polyamine. Since the added inorganic polymers themselves do not contribute to COD, their influence was best tracked through TOC analysis. It is noteworthy that, during TOC mass balance calculations, most ΔM values in the supernatant and centrifuged liquid phases were negative, whereas those in the sludge phase were consistently positive. This pattern suggests that the polymeric organics added via hybrid coagulants were predominantly retained in the solid phase rather than remaining dissolved. Such behavior is consistent with the known tendency of high molecular weight cationic polymers to adsorb onto solid flocs. Detailed ΔM values for each formulation and phase are provided in **Appendix F** for reference.

Furthermore, the negative ΔM values observed in the liquid phases may also reflect the superior TOC removal performance of polymer-containing formulations, resulting in minimal residual organic

load in the aqueous compartments. This reinforces the hypothesis that these organics were successfully transferred to the sludge phase, consistent with the positive ΔM values found in SLG. While the TOC mass balance approach does not identify the exact molecular species present in each phase, the distribution pattern is clear. Negative ΔM values in the supernatant and centrifuged liquid, together with positive ΔM values in the sludge, indicate that the organic polymers added through hybrid coagulants were largely retained in the solid phase. This inference is further supported by the known adsorption behavior of high-molecular-weight cationic polymers, which tend to bind to suspended solids and settle into the sludge during coagulation-flocculation processes.

Therefore, TOC analysis not only confirmed the pollutant removal effectiveness of hybrid formulations but also served as a powerful tool for tracking polymer fate in the system. The combination of direct measurement and indirect calculation provides a comprehensive picture of organic carbon dynamics in coagulation–flocculation treatment of tannery wastewater. Detailed numerical values and phase-specific comparisons are provided in **Appendix F.**

4.1.2.5. Aluminum distribution across phases. In this study, the effects of different coagulant systems, ranging from conventional inorganic coagulants to hybrid formulations, on the distribution of aluminum across distinct physical phases (supernatant, centrifuged liquid, and sludge) were comprehensively analyzed. While the initial evaluation relied on measured aluminum concentrations in each phase, a more meaningful understanding was achieved by examining mass-based elemental distribution, which better reflects how aluminum actually moves through the treatment system.

Importantly, in this section, the evaluation of aluminum distribution was not based on removal efficiency, as the raw water used in the experiments was not heavily loaded with aluminum—this is also evident in the **Appendix G,** where raw water aluminum concentration levels are reported. Therefore, the majority of the aluminum present in the system originated from the coagulants themselves. As such, the analysis focuses on how this coagulant-derived aluminum partitioned into different physical phases during the coagulation process. The goal was to establish a best balance between phases, rather than to assess removal from raw water. All detailed quantitative results and supporting data are provided in the **Appendix G.**

Additionally, in order to validate the internal consistency of the experimental data, a ΔM loss parameter was introduced. This represents the discrepancy between the theoretically dosed aluminum and the sum of aluminum recovered from all three measured phases, accounting for potential losses or analytical uncertainties inherent to sample processing. ΔM_{loss} values remained within acceptable

limits and are fully documented in the **Appendix G**, alongside raw measurement data and additional validation metrics.

The coagulant systems employed in this study revealed notable differences in the phase distribution of aluminum, which were primarily governed by the types and quantities of active ingredients within each formulation. However, these differences should not be interpreted solely based on mass-derived percentages; a comprehensive evaluation must also consider the actual aluminum-bearing composition and coagulant dose of each formulation.

Among the systems studied, formulation P040102, which consists solely of 100 g of 40% aluminum sulfate ($Al_2(SO_4)_3$), serves as a benchmark representing conventional coagulation. In this system, the proportion of aluminum remaining in the supernatant phase reached 4.89%, significantly higher than that observed in hybrid formulations, where SUP levels frequently fell below 4%. This elevated SUP proportion is attributed to the highly soluble and monomeric nature of aluminum in alum-based systems, which lack the structural capacity to effectively bind and immobilize Al in solid phases. As illustrated in the following figure (Figure 4.7.), the mass-based percentage distribution of aluminum across the SUP, CEN, and SLG phases is presented for each coagulant formulation evaluated in this study.

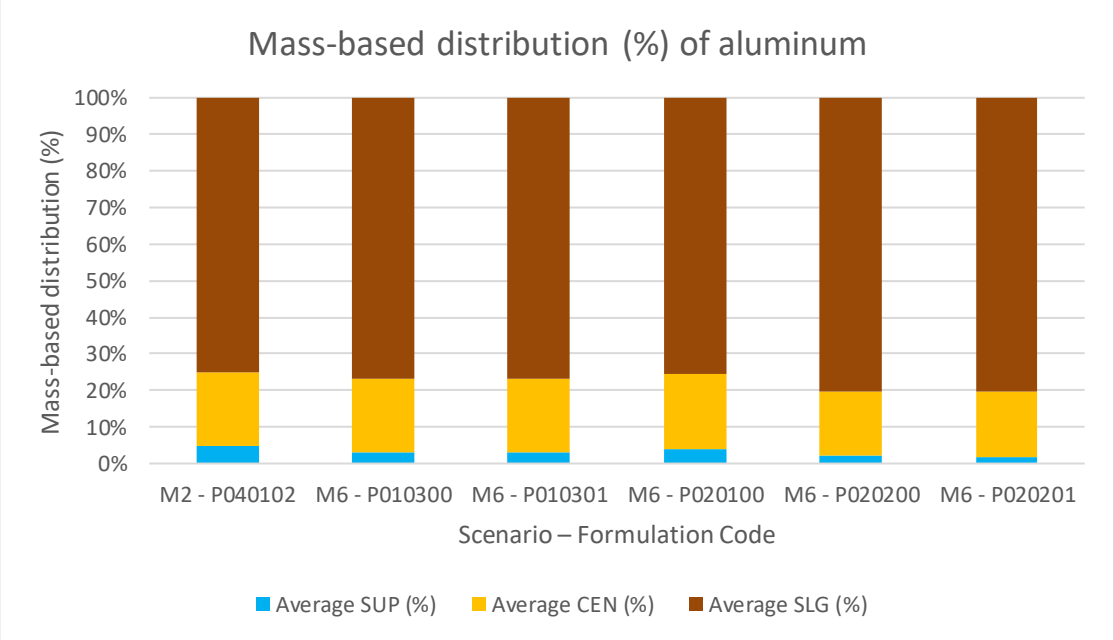


Figure 4.7. Mass-based distribution (%) of aluminum across supernatant (SUP), central (CEN), and sludge (SLG) phases for each coagulant formulation.

For instance, P020100 (50 g PAC 17 + 5 g PolyDADMAC) exhibited a SUP phase aluminum fraction of 3.96%, whereas P020200 (57 g PAC 17 + 0.8 g $FeCl_3$ + 5 g PolyDADMAC) achieved a substantially lower value of 1.92%. At face value, this reduction might suggest a performance improvement, yet it can largely be attributed to the higher total coagulant dose in P020200. Indeed, the increased PAC 17 content and presence of Fe^{3+} ions contributed significantly to the elevation of aluminum retention in the SLG phase—from 75.45% in P020100 to 80.85% in P020200. In addition, P020201, which mirrors P020200 in PAC and $FeCl_3$ content but substitutes PolyDADMAC with Polyamine, produced a virtually identical aluminum distribution. This reinforces the conclusion that in Fe-enhanced systems, polymer type exerts only a secondary influence on aluminum partitioning, while coagulant dose and multivalent ion synergy play dominant roles.

Despite the seemingly favorable SLG value, the elevated aluminum concentration in the supernatant suggests a lower retention efficiency. In contrast, hybrid coagulant systems demonstrated the ability to form denser and more compact flocs, which contributed to improved aluminum retention and reduced leakage into the aqueous phase.

Apart from the SUP and SLG phases, several noteworthy observations can also be made regarding the CEN phase and this phase, consistently retained around 17–20% of total aluminum across all formulations, regardless of polymer type. This stability suggests that microfloc formation remains relatively constant within optimized coagulant regimes and may reflect equilibrium between floc growth and sedimentation forces.

In conclusion, mass-based elemental distribution offers a more accurate representation of aluminum transport and retention within coagulation systems than concentration-based analysis alone. Hybrid coagulant systems, especially those incorporating $FeCl_3$ and PAC, demonstrate superior performance in terms of both aluminum retention in sludge and environmental safety. These systems minimize dissolved aluminum fractions while promoting the formation of compact and stable sludge, making them more suitable for advanced water treatment processes compared to traditional alum-based approaches.

Residual aluminum in treated water is a known concern due to its potential links to ecological toxicity and human health risks, particularly when present in dissolved or colloidal forms. Therefore, reducing the fraction of aluminum that remains in the aqueous phase is crucial for minimizing downstream environmental impacts. Simultaneously, promoting aluminum retention in the sludge phase improves process safety by ensuring that aluminum is captured in a more stable, settleable

form. These environmental considerations, including both water quality outcomes and sludge management implications, will be further elaborated in Section 4.3.2. Environmental Impact Matrix.

4.1.2.6. Fe distribution across phases. This section extends the mass-based elemental distribution approach used for aluminum to assess iron (Fe) partitioning across three operational phases—supernatant (SUP), centrifuged liquid (CEN), and sludge (SLG). Unlike aluminum, which was primarily introduced into the system through the coagulant formulations, influent iron concentrations were substantially higher in the raw tannery wastewater. On several sampling days, influent Fe levels exceeded 20 mg/L, reflecting considerable natural loading. This elevation is likely associated with increased wastewater complexity on specific days, where elevated COD levels suggested a higher burden of industrial pollutants, not necessarily limited to organics or metals but indicative of a more complex and contaminated influent composition.

Among the tested formulations, only P020200 and P020201 contained $FeCl_3$ (0.8 g per 100 g of formulation). The rest either used aluminum-based coagulants or PAC-polymer hybrids. The following figure (Figure 4.8.) displays the average mass-based phase distribution of iron for each formulation, providing a visual comparison of their retention performance.

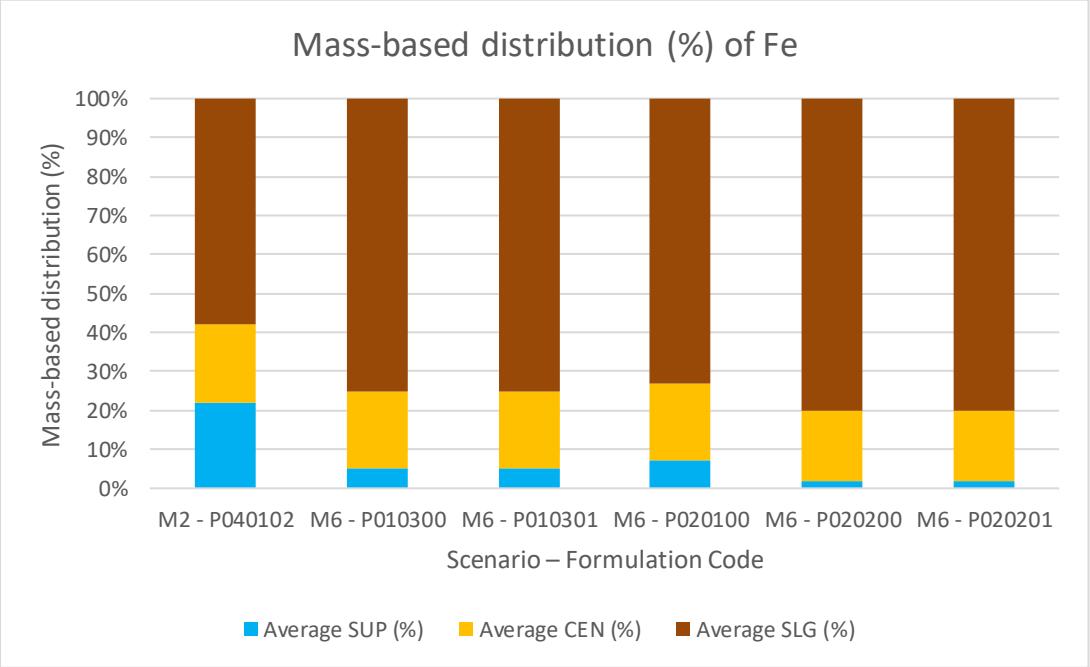


Figure 4.8. Average mass-based distribution (%) of iron across SUP, CEN, and SLG phases for each coagulant formulation.

The results reveal that P020200 and P020201 consistently achieved the lowest SUP fractions (~1.93%) and the highest SLG accumulation (~78%), indicating superior removal performance. In contrast, P020100, which lacks $FeCl_3$ but otherwise shares a similar PAC-polymer base, showed higher SUP retention (6.83%) and reduced SLG accumulation (71%). Similarly, P010300 and P010301, both hybrid formulations incorporating liquid PAC and polymer blends, yielded intermediate performance with SUP values around 4.8% and SLG retention around 72%.

Notably, P040102, which represents the traditional alum-only system (100 g of 40% $Al_2(SO_4)_3$), resulted in the highest residual iron in the supernatant (21.2%), with only 56% retained in the sludge. This poor performance is attributed to the absence of Fe^{3+} ions and the lower affinity of alum-based systems for iron removal.

These results clearly indicate that $FeCl_3$-containing formulations significantly improve iron retention, primarily by enhancing charge neutralization and facilitating compact floc formation. Notably, polymer type (PolyDADMAC vs. Polyamine) appeared to have minimal influence on iron partitioning in $FeCl_3$-enhanced systems, as evidenced by the nearly identical distribution profiles of P020200 and P020201. This reinforces previous findings in the literature, which emphasize that multivalent metal ions play a more dominant role than polymer type in metal precipitation processes (Starodoubtsev et al., 2003).

Furthermore, the total iron mass in the system was notably higher compared to aluminum. This suggests that iron partitioning reflects both the coagulant-derived contribution and the background load from influent wastewater. Consequently, observed differences in phase distribution cannot be solely attributed to formulation design; raw water quality must also be considered as a key determinant of metal behavior in treatment systems.

In summary, mass-based analysis of iron distribution confirms that $FeCl_3$ inclusion, even at a modest dose (0.8% w/w), significantly enhances iron capture in the sludge phase while minimizing residual concentrations in the treated effluent. These findings, supported by relevant literature, further validate the effectiveness of hybrid coagulant strategies and provide valuable insights into optimizing metal removal under varying influent conditions (Rebosura et al., 2018; Hassanpour et al., 2022). Detailed quantitative results, mass balances, and measurement uncertainty analyses can be found in **Appendix H.**

4.1.2.7. Chromium removal performance. This section evaluates the chromium (Cr) removal performance of different coagulant formulations in detail, based on their composition and system-specific behavior. Unlike aluminum and iron, chromium was not introduced through the coagulant itself but was present in the influent as a characteristic component of tannery wastewater. Due to its environmental significance and toxicity, chromium was specifically addressed within the scope of this study. The average total Cr removal efficiencies for each formulation are presented in Figure 4.9, offering a visual summary of comparative performance across coagulant systems.

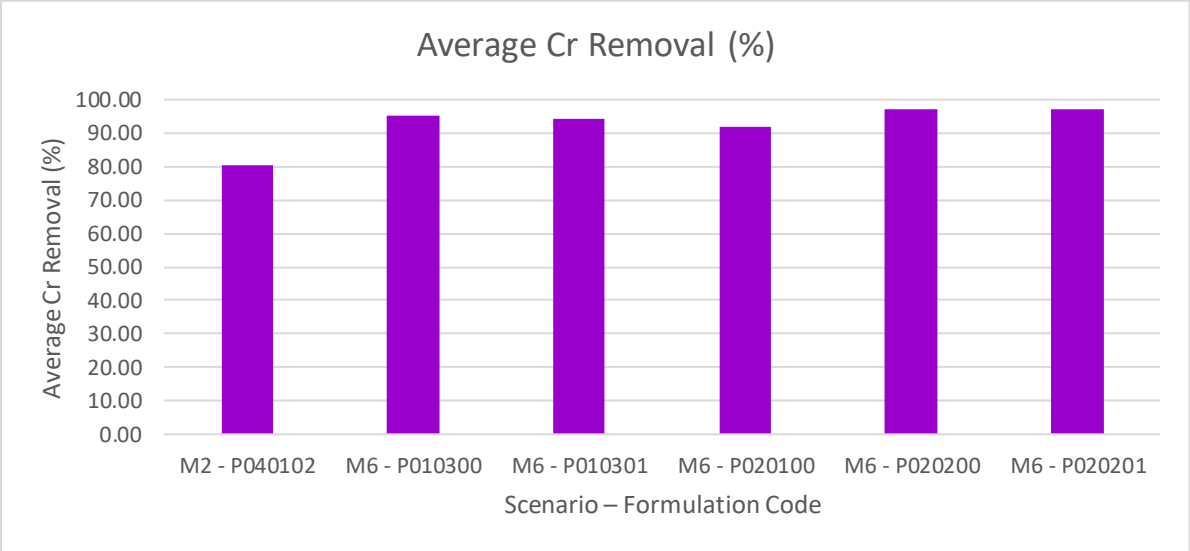


Figure 4.9. Average total chromium removal efficiency (%) for each coagulant formulation.

Among the tested systems, the conventional formulation P040102 exhibited the lowest chromium removal, with an average efficiency of approximately 80%. This outcome indicates that traditional alum-based systems may be less effective in generating dense flocs capable of capturing and retaining Cr species during coagulation. In contrast, all hybrid formulations demonstrated significantly higher chromium removal. P010300 and P010301 achieved over 94% removal, suggesting that the combination of PAC coagulants and polymer additives contributed to the formation of more compact flocs, which in turn enhanced Cr entrapment and sedimentation.

The highest Cr removal efficiencies were observed in P020200 and P020201, both exceeding 96.9%. The nearly identical performance of these two systems, despite differing polymer types, suggests that Fe^{3+} ions were the dominant factor influencing chromium removal, likely due to their enhanced binding and precipitation properties. The minimal impact of polymer type under these conditions further supports this conclusion. P020100, a formulation structurally similar to the above but lacking $FeCl_3$, yielded a comparatively lower removal efficiency of approximately 91.6%, further highlighting the contribution of Fe^{3+} to overall performance.

Overall, these findings suggest that chromium removal is strongly dependent on both the type and concentration of active metal ions within the system. The presence of trivalent metal ions—particularly iron—played a key role in promoting stable floc formation and improving Cr removal. As with aluminum and iron, a phase-based analytical approach was used; however, because chromium was not derived from the coagulants themselves, the evaluation here was based solely on removal efficiency. All quantitative results, mass calculations, and uncertainty analyses are detailed in **Appendix I.**

4.1.3. Comprehensive Performance Evaluation of Coagulant Formulations

The comparative analysis of the six tested coagulant formulations has revealed significant variations in terms of performance, environmental impact, and potential operational advantages. As previously detailed in the mass balance evaluation section (Section 4.1.2), parameter-specific behaviors were discussed extensively; this section aims to consolidate these findings into a comprehensive assessment, drawing from both average performance data and daily variations over the 22-day experimental period. Figure 4.10 illustrates the comparative treatment performance of all coagulant formulations evaluated in this study.

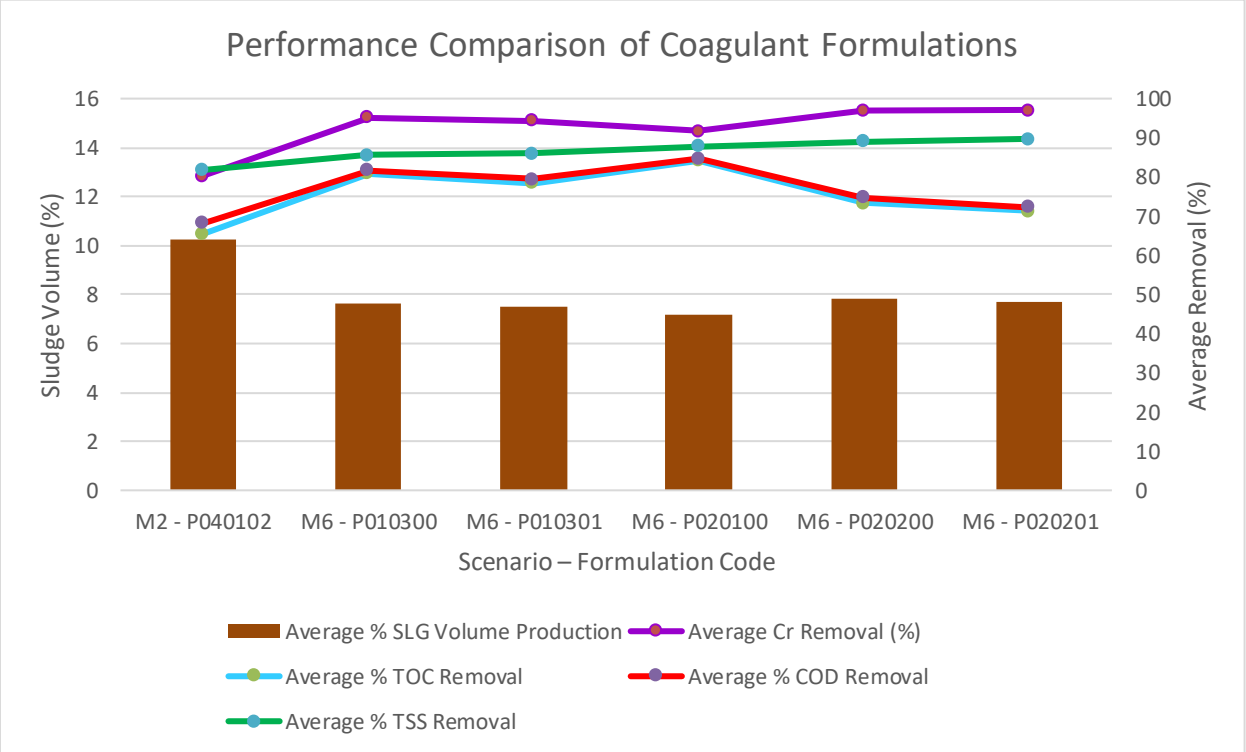


Figure 4.10. Performance comparison of coagulant formulations.

Among the formulations, hybrid coagulants consistently outperformed the conventional alum-based product (M2 – P040102) across all evaluated criteria. Notably, M6 – P020200 and M6 – P020201 each achieved chromium removal efficiencies above 96%, representing the highest performance levels among all tested systems. These were followed by M6 – P010300 and M6 – P010301, which also demonstrated strong Cr removal performance. Beyond chromium removal, hybrid formulations showed superior efficiency in reducing COD, TOC, TS, and TSS which are all critical parameters in the treatment of leather industry wastewater.

A key advantage of the hybrid formulations was their ability to achieve higher removal efficiencies while producing significantly lower sludge volumes (SLG). For instance, M6 – P020100 recorded the lowest average sludge volume (7.18%), indicating reduced sludge generation and more efficient solid–liquid separation. This directly translates into lower sludge handling and disposal requirements, contributing to both environmental and operational sustainability. This is further supported by the high average dry solids concentrations observed in the sludge phase; denser and more compact sludge is typically associated with more efficient particle removal. The hybrid formulations produced sludge with dry solids contents ranging between 42–46%, whereas the conventional alum-based system remained below 30%.

These quantitative results were further supported by laboratory-scale visual observations. Although all five selected formulations demonstrated strong overall performance, P010301 and P020201 were chosen for visual comparison because they represent two distinct hybrid chemistries and therefore provide clearer insight into how formulation differences influence floc structure and treated-water clarity. The conventional treatment method used at the facility was included alongside these two formulations purely as a reference point, allowing the hybrid systems to be visually compared against the baseline practice. The resulting visual contrast is presented in Figure 4.11.

In addition, sludge produced by these formulations formed well-defined, compact flocs with reduced turbidity in the supernatant, indicating effective coagulation and flocculation. Such visual cues are consistent with the recorded data on TSS removal and sludge production and further reinforce the overall effectiveness of these formulations. These differences are clearly reflected in the comparative images below, highlighting the superior settling behavior and effluent clarity achieved by the hybrid coagulants.



(a) (b) (c)

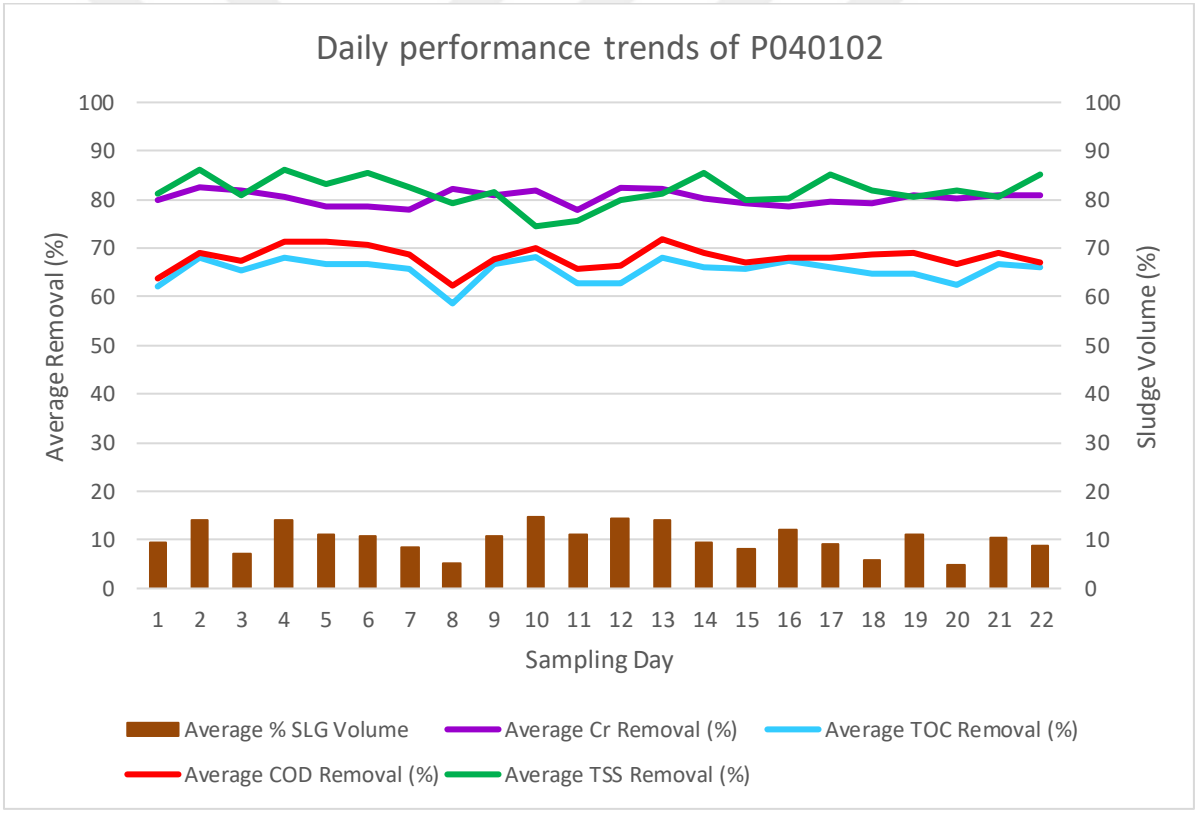
Figure 4.11. Comparative sludge images for selected formulations - (a) M2–P040102, (b) M6–P010301, (c) M6–P020201).

On the other hand, the absence of pH regulators in the application of hybrid coagulants presents another significant operational benefit. Unlike the alum-based method, which requires lime addition for optimal performance, hybrid formulations maintained effective coagulation at natural pH levels. This not only reduces the total chemical consumption but also simplifies the treatment process and lowers associated costs. Furthermore, the alum dosage in conventional treatment (8 g/L) was notably higher than the total active component in hybrid formulations (2.80 g/L), reinforcing the efficiency of hybrid systems in terms of chemical economy.

In addition, the required dosage of the coagulant aid (PAM) has emerged as a critical parameter in evaluating the efficiency of the coagulation-flocculation process. Optimization studies revealed that conventional 40% aluminum sulfate (alum) system required 4 g/L PAM, whereas hybrid coagulants achieved similar or superior performance with only 1.88 g/L PAM. This corresponds to an approximately 53% reduction in polymer demand.

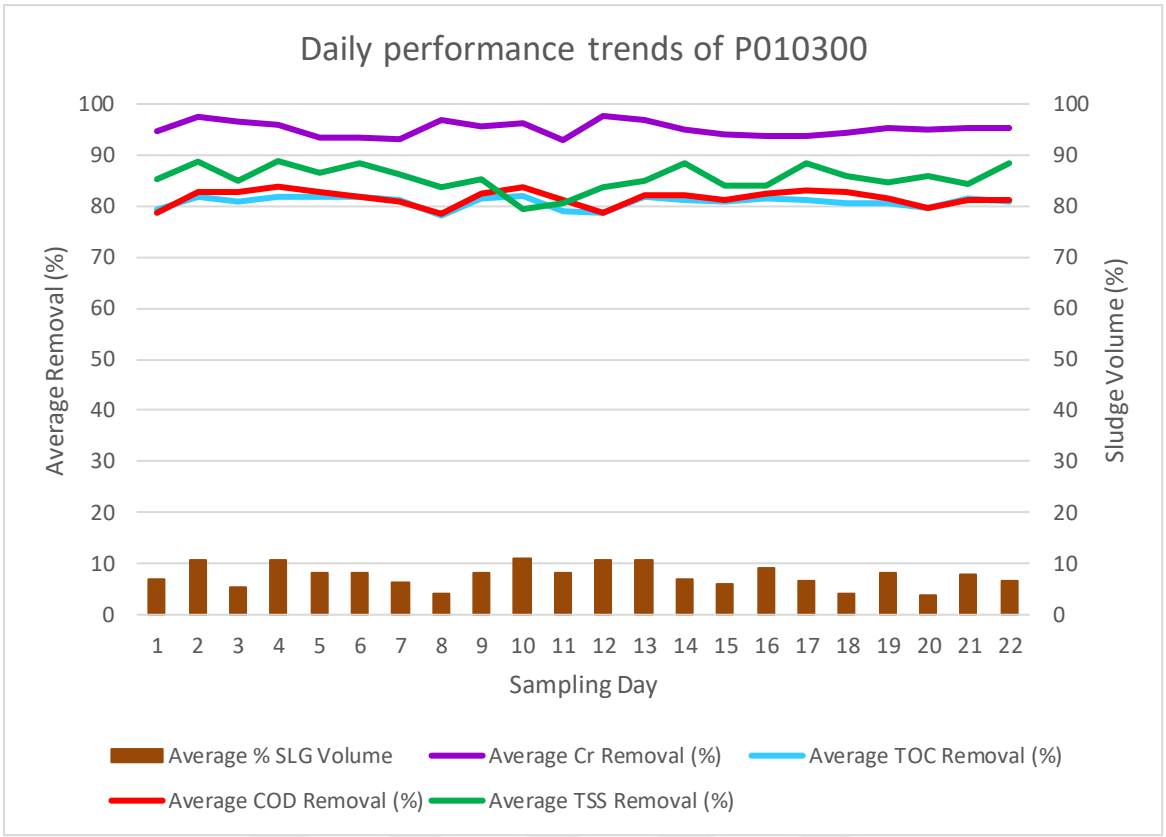
This advantage of hybrid systems can be attributed to the synergistic interaction between pre-polymerized aluminum species (e.g., PAC) and cationic organic polymers (such as PolyDADMAC and Polyamine) in their formulation. As highlighted in the literature, polymer-enhanced hybrid coagulants form higher molecular weight, more flexible flocs with greater adsorption capacity, thereby improving particle capture efficiency (Wang et al., 2018; Rong et al., 2013). Consequently, the same coagulation effectiveness can be achieved with a lower dose of auxiliary chemicals. Reduced chemical demand not only contributes to operational cost-efficiency but also minimizes sludge production and enhances the environmental sustainability of the treatment process.

When temporal variations are considered, the 22-day trend data offer insights into the stability and consistency of each formulation. Hybrid coagulants, particularly M6 – P020200 and M6 – P020100, exhibited smoother and more predictable removal profiles, with lower fluctuation margins compared to the alum-based formulation, which showed inconsistent performance across days. TOC and COD removal trends also moved in parallel, as expected, confirming that the primary organic loads were being simultaneously targeted by the treatment processes. Similarly, TSS and TS removal showed consistent alignment, reinforcing the reliability of sedimentation and solid separation mechanisms under the hybrid systems. To further illustrate these temporal dynamics, the graphs (Figure 4.12) below display the daily performance trends of each formulation over the 22-day monitoring period, providing a comparative perspective on their stability, efficiency, and overall treatment behavior across all parameters.

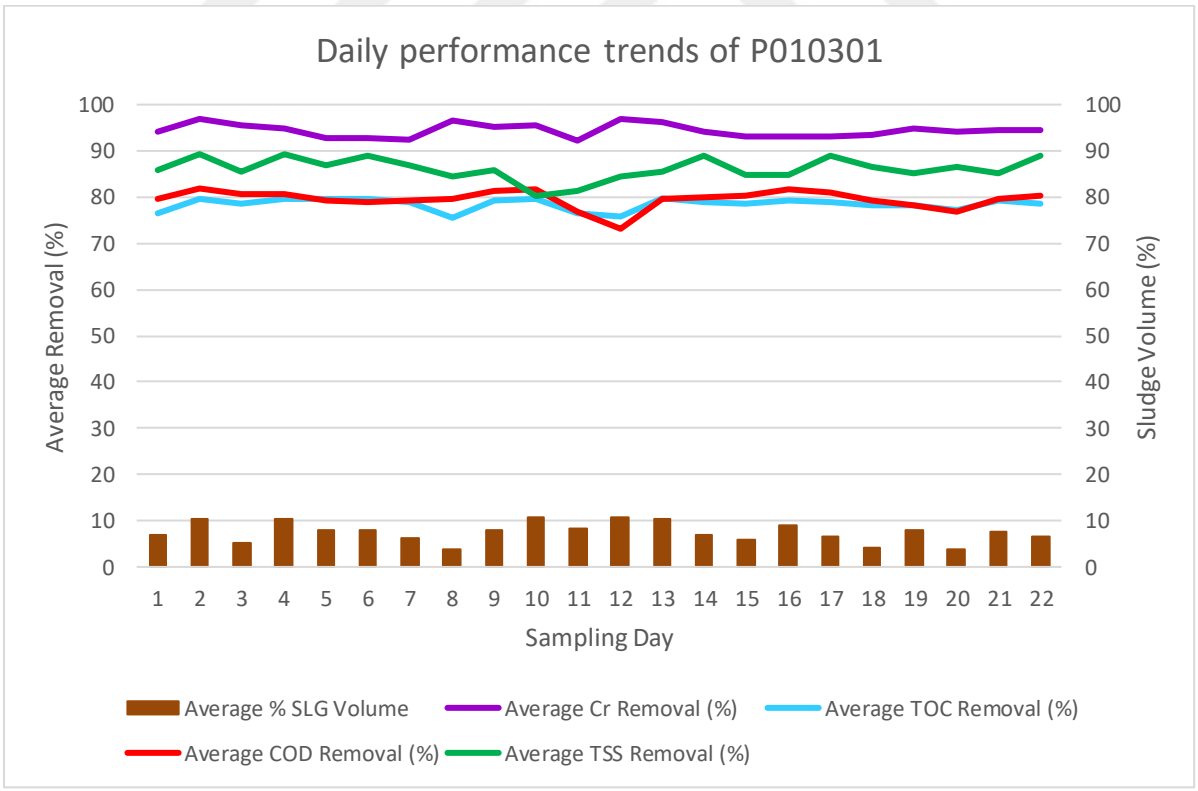


(a)

Figure 4.12. Daily performance trends of coagulant formulations over a 22-day period in terms of Cr, TOC, COD, TS, and TSS removal efficiencies. (Sub-figures: (a) M2 – P040102 (Alum-based), (b) M6 – P010300, (c) M6 – P010301, (d) M6 – P020100, (e) M6 – P020200, (f) M6 – P020201.)

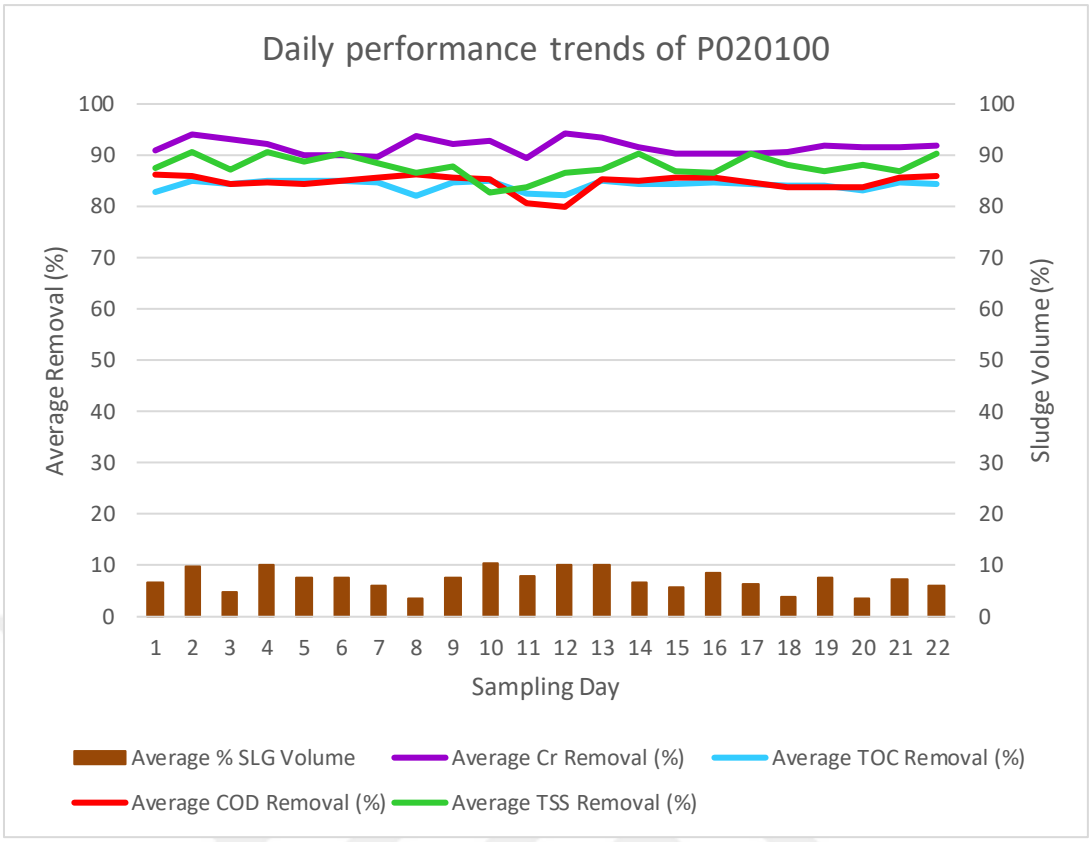


(b)

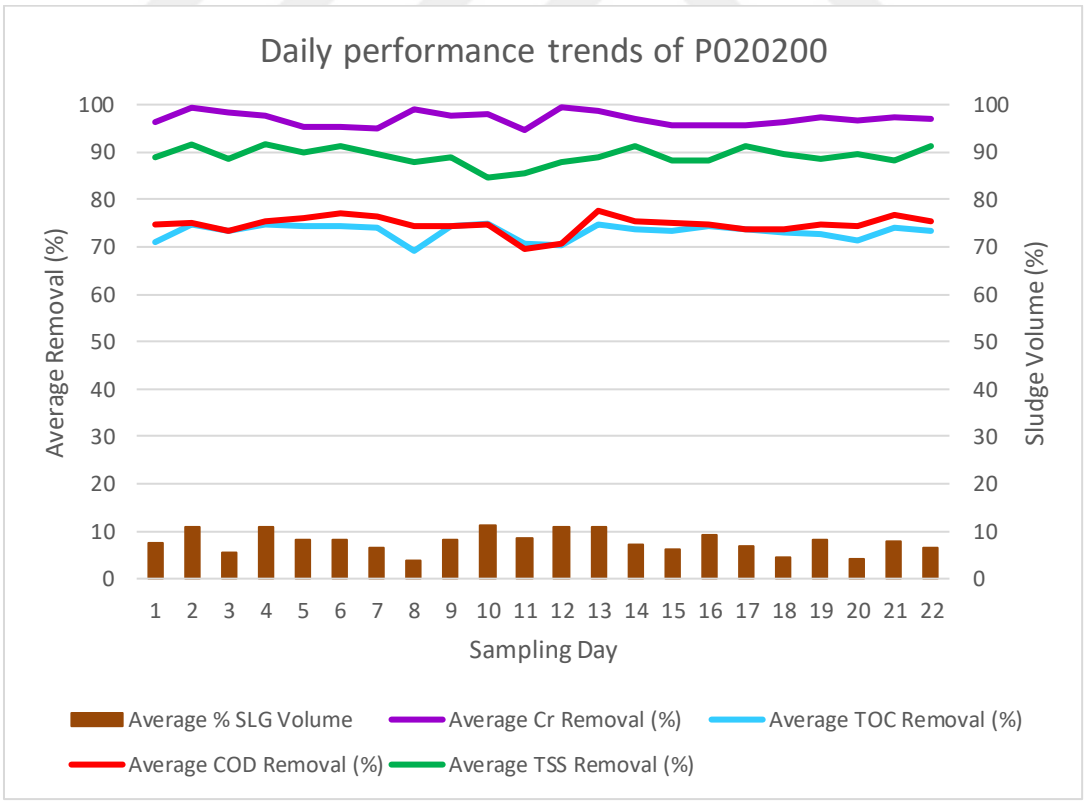


(c)

Figure 4.12. (continued)

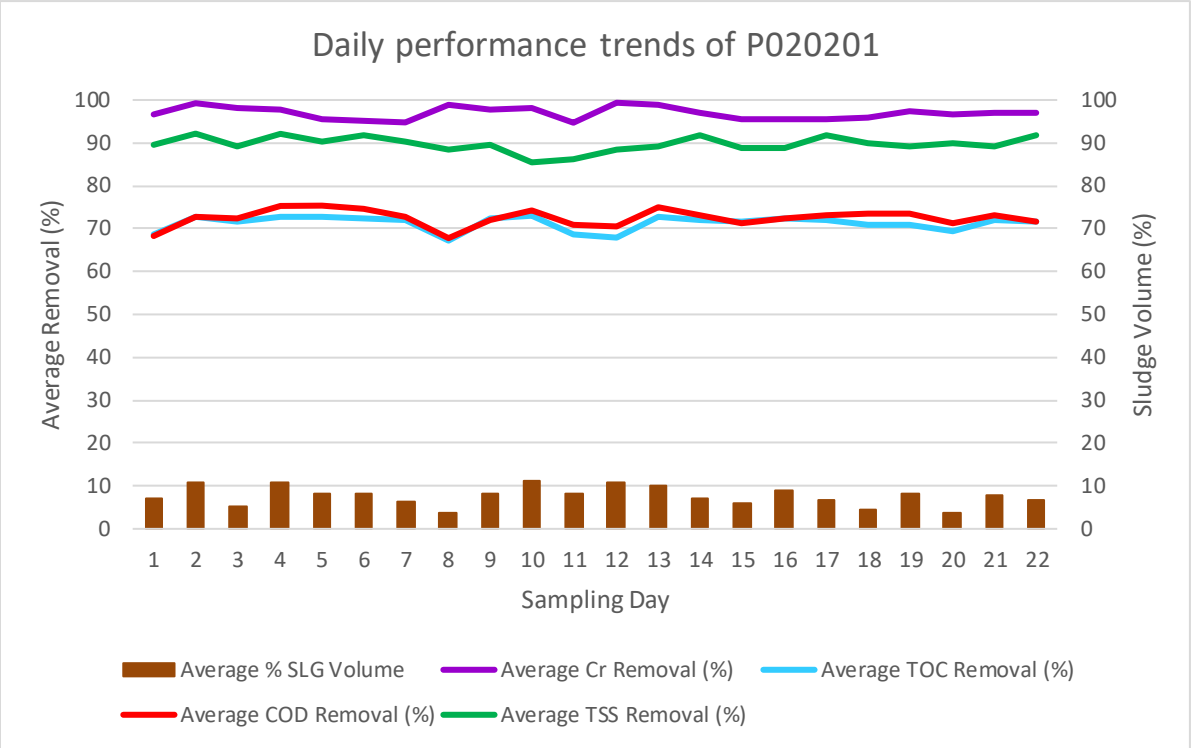


(d)



(e)

Figure 4.12. (continued)



(f)

Figure 4.12. (continued)

In light of these findings, hybrid coagulant formulations not only demonstrate superior removal efficiencies across all critical parameters but also offer tangible environmental and operational benefits. Lower sludge production, reduced chemical requirements, and enhanced process stability position these formulations as strong alternatives to traditional alum-based treatment, particularly in industrial settings like tanneries where pollutant loads are high and variable.

Although a detailed economic feasibility analysis is beyond the scope of this study, the observed reductions in chemical consumption and sludge handling requirements strongly suggest that hybrid formulations may also be more cost-effective in the long term. Further research incorporating lifecycle assessment and cost-benefit modeling is recommended to validate this potential.

In conclusion, the comparative assessment of the six coagulant formulations tested in this study clearly demonstrates the superior performance of hybrid coagulant systems over the conventional aluminum sulfate-based formulation (M2 – P040102). The conventional system consistently yielded the lowest removal efficiencies for Cr, TOC, COD, and TSS, while also generating the highest sludge volume. In contrast, hybrid systems achieved higher removal performance at lower dosages, offering both environmental and operational advantages.

Notably, M6 – P020100 recorded the lowest average sludge volume (7.2%) while achieving the highest TOC (84.1%) and COD (84.7%) removal efficiencies. Meanwhile, M6 – P020200 and M6 – P020201 achieved the highest Cr removal efficiencies (~96.95%), and also ranked highest in TSS removal performance. The M6 – P010300 and M6 – P010301 formulations provided well-balanced and consistently high results across all parameters, highlighting the beneficial impact of polymer additives. These findings collectively confirm that hybrid coagulant systems not only enhance treatment efficiency but also minimize sludge production and chemical consumption, making them highly promising alternatives for sustainable wastewater treatment, particularly in industrial applications.

4.2. BIOWIN Modeling Results and Interpretation

Understanding the biodegradability of synthetic organic polymers is essential for assessing their long-term environmental impact, especially in wastewater treatment systems where they are extensively applied as coagulants and flocculants. Experimental biodegradation studies with polymers are often resource-intensive and time-consuming, which makes predictive modeling tools valuable for preliminary assessments. In this context, the U.S. EPA's BIOWIN software was employed to provide indicative insights into the biodegradability of the polymers studied in this thesis (US EPA, 2015).

BIOWIN cannot directly process polymeric structures; therefore, predictions were generated for the repeating monomeric units and interpreted qualitatively as proxies for the polymers (US EPA, 2015). No scaling by degree of polymerization was attempted, and the results should be viewed as indicative rather than definitive. This approach has been widely adopted in previous QSAR-based assessments of synthetic polymers and is considered a cost-effective method for providing useful preliminary information (Kim et al., 2023). In practice, however, the actual polymers are expected to degrade more slowly than their monomer units because of their higher molecular weight, reduced bioavailability, and tendency to adsorb strongly onto sludge (Braun et al., 2021). As a result, monomer-based BIOWIN predictions can be regarded as representing an upper bound of biodegradability, while the true polymer behavior is likely equal or lower. Accordingly, the outputs are interpreted directionally and are triangulated with experimental mass balance results in the following discussion.

To ensure accuracy in monomer selection, technical data sheets (TDS) and safety data sheets (SDS) supplied by the manufacturers were reviewed in detail. From these documents, the chemical

names, CAS numbers, and available structural information were compiled. In cases where the monomer information was incomplete or ambiguous, clarification was directly requested from the suppliers to verify the specific functional groups used in the polymer formulations. Based on this process, the following representative monomers were identified for BIOWIN analysis: *diallyldimethylammonium chloride* for PolyDADMAC, *acrylamide* and *acrylic acid* for anionic PAM, and *dimethylamine* together with *epichlorohydrin* for PA-8060 polyamine. The canonical SMILES strings of these monomers were obtained from the PubChem database and entered into BIOWIN for prediction, ensuring consistency and reproducibility across the dataset.

BIOWIN provides seven different submodels that estimate biodegradability through various statistical and fragment-based algorithms. However, not all of these submodels are equally reliable for high-molecular-weight or ionic polymers. In this study, priority was given to BIOWIN 3 (ultimate biodegradation timeframe), BIOWIN 5 and 6 (MITI linear and nonlinear probabilities of ready biodegradability), and BIOWIN 7 (anaerobic biodegradation potential). These models were selected because they are most closely aligned with regulatory criteria (e.g., OECD 301 ready biodegradability tests) and provide direct insight into both aerobic and anaerobic degradation behavior (Posthumus et al., 2005).

The remaining models, BIOWIN 1, 2, and 4, were not emphasized because their predictive accuracy decreases substantially for large, branched, or ionized molecules. BIOWIN 1 and 2 are regression-based models developed primarily for small neutral organics, while BIOWIN 4 estimates only *primary* biodegradation (i.e., structural modification without full mineralization) (Posthumus et al., 2005). As such, they are less relevant for evaluating the ultimate environmental fate of polymers used in water treatment.

Accordingly, the results presented here focus on the four most informative and widely accepted models. Table 4.2 summarizes the predicted biodegradation outcomes for the representative monomers of the three target polymers (PolyDADMAC, anionic PAM, and Polyamine). These results provide the theoretical basis for the subsequent discussion and are interpreted in light of experimental mass balance findings. For transparency and reproducibility, full BIOWIN output screenshots for all representative monomers are provided in **Appendix J.** In the main text, report will be presented only the summarized/derived values (e.g., BIOWIN 3, BIOWIN 5–6, BIOWIN 7 and the ready/not-ready classification). *(Minor differences between Appendix screenshots and tabulated values may reflect rounding to two decimals or formatting.)*

Table 4.2. Predicted biodegradability of target polymers using BIOWIN models (representative monomer units).

Polymer (Representative Monomer)	BIOWIN 3 (Ultimate)	BIOWIN 5 (MITI Linear)	BIOWIN 6 (MITI Non-Linear)	BIOWIN 7 (Anaerobic)	Ready Biodegradability Prediction	Interpretation
PolyDADMAC (Diallyldimethylammonium chloride)	2.84 weeks	0.3587	0.3062	–0.1499 (**NO**)	**NO**	Persistent under both aerobic and anaerobic conditions; monomer not readily biodegradable; polymer expected to strongly accumulate in sludge.
Anionic PAM (Acrylamide)	2.99 weeks	0.6459	0.8092	0.0476 (**YES**)	**YES**	Readily biodegradable monomer; however, the actual high MW polymer shows lower degradation due to steric hindrance and strong sludge adsorption.
Anionic PAM (Acrylic acid)	3.40 days–weeks	0.6975	0.8410	0.8023 (**YES**)	**YES**	Monomer is readily biodegradable under both aerobic and anaerobic conditions; polymer biodegradation still limited by molecular weight and ionic form.
Polyamine (PA-8060) (Epichlorohydrin)	2.81 weeks	0.5210	0.4121	0.5096 (**YES**)	**YES (borderline)**	Biodegradation possible but borderline; polymeric structure expected to degrade more slowly.
Polyamine (PA-8060) (Dimethylamine)	3.12 weeks	0.6121	0.7268	0.8542 (**YES**)	**YES**	Readily biodegradable under both aerobic and anaerobic conditions; polymer expected to show slower kinetics despite favorable monomer prediction.

4.2.1. Biodegradability Prediction of PolyDADMAC (Diallyldimethylammonium Chloride Monomer)

The BIOWIN outputs for PolyDADMAC, represented by the monomer diallyldimethylammonium chloride, indicate a very low biodegradation potential. Both BIOWIN 5 (0.3587) and BIOWIN 6 (0.3062) were well below the OECD threshold of 0.5, leading to a classification of "not readily biodegradable." In addition, the anaerobic model (BIOWIN 7: –0.1499) predicted no significant degradation under oxygen-limited conditions. These results suggest that PolyDADMAC is highly persistent, especially in anaerobic environments such as sludge digesters. This finding is consistent with literature reports which emphasize that cationic, quaternary ammonium-based polymers are strongly adsorbed to negatively charged sludge solids and show limited bioavailability for microbial attack (Wang et al., 2024). Furthermore, the high molecular weight of the polymer creates steric hindrance, making enzymatic access more difficult and reducing the likelihood of ultimate mineralization. Therefore, even though BIOWIN predictions are based on the monomer unit, the actual polymer is expected to be equally or even less biodegradable in real wastewater treatment conditions.

4.2.2. Biodegradability Prediction of Anionic PAM (Acrylamide and Acrylic Acid Monomers)

Anionic PAM was represented by its two repeating units, acrylamide and acrylic acid, modeled separately in BIOWIN. Both monomers met the OECD "ready biodegradability" criterion: acrylamide yielded BIOWIN 5 = 0.6459 and BIOWIN 6 = 0.8092 with an ultimate timeframe of ~3 weeks and a positive anaerobic signal; acrylic acid showed BIOWIN 5 = 0.6975 and BIOWIN 6 = 0.8410 with an ultimate timeframe of days–weeks and a clearly positive anaerobic prediction. Taken together, these outputs indicate that the constituent functional groups are, in principle, amenable to rapid microbial degradation under both aerobic and anaerobic conditions.

In practice, however, the biodegradability of the full anionic PAM polymer will be lower than what is suggested by its monomers. The polymer chains are very large, which makes it harder for microorganisms to reach and break them down. In addition, the negative charges on the polymer (carboxylate groups) cause strong binding to suspended solids and sludge. These two factors reduce the polymer's availability to microbes and slow down its breakdown. For this reason, BIOWIN results should be interpreted with caution: while they provide useful insight into the inherent biodegradation potential of the monomers, the actual biodegradability of the intact polymer in environmental or

wastewater conditions can vary significantly—sometimes being lower due to limited bioavailability, but in some cases exceeding predictions under favorable experimental conditions.

4.2.3 Biodegradability Prediction of Polyamine (Epichlorohydrin and Dimethylamine Monomers)

The polyamine examined in this study is a cationic copolymer synthesized from epichlorohydrin and dimethylamine units. To approximate its biodegradability, each monomer was modeled separately in BIOWIN. Dimethylamine showed a strong tendency toward biodegradation, with BIOWIN 5 = 0.6121 and BIOWIN 6 = 0.7268, both exceeding the OECD threshold of 0.5. The ultimate timeframe was about three weeks, and BIOWIN 7 indicated positive degradation potential under anaerobic conditions. These results classify dimethylamine as "readily biodegradable." Epichlorohydrin, in contrast, produced more borderline results: $BIOWIN_5$ was just above the threshold (0.5210), while BIOWIN 6 fell below (0.4121). The ultimate timeframe was about 2–3 weeks, and the anaerobic model also predicted a positive outcome. Overall, epichlorohydrin can be considered moderately biodegradable, though not as strongly as dimethylamine.

When considered together, these results suggest that the polyamine has a moderate biodegradation potential. The presence of dimethylamine units contributes favorably, while the epichlorohydrin component places it closer to the borderline between "ready" and "not readily" biodegradable. Nevertheless, as with other polymers, the actual polyamine chains are much larger and carry ionic functional groups, which reduce microbial accessibility and slow down mineralization. Thus, the BIOWIN outputs should be viewed as optimistic estimates: they show that the building blocks are biodegradable, but the full polymer will likely degrade at a slower rate and may persist partly in sludge environments.

4.3. Environmental Evaluation and Impact Assessment

4.3.1. Comparison with Discharge Standards

In the context of environmental protection efforts in the Thrace region, the Turkish government has implemented the Ergene Basin Protection Action Plan, aiming to mitigate the chronic pollution of the Ergene River. As one of the focal provinces within the Ergene Basin, Tekirdağ hosts several key industrial zones, including the Çorlu Leather Organized Industrial Zone (Çorlu Deri OSB), where the present study was conducted.

The environmental and industrial infrastructure projects in this region are carried out under the coordination of the Ministry of Environment, Urbanization and Climate Change of the Republic of Türkiye (*T.C. Çevre, Şehircilik ve İklim Değişikliği Bakanlığı*). Within the scope of this basin-wide initiative, the Deep Discharge Project was commissioned in November 2020 to handle the treated effluent of 14 Organized Industrial Zones via a shared marine outfall system connected to the Marmara Sea. The Çorlu Leather OSB is not only integrated into this regional deep marine discharge system but also operates its own centralized wastewater treatment plant (WWTP), which is managed by the Çorlu Leather OSB Directorate. This facility treats the effluent prior to discharge, ensuring that wastewater quality meets regulatory standards before being conveyed through the regional pipeline infrastructure into the marine environment (Çorlu Leather OSB Directorate, personal communication, 2025).

The discharged wastewater in question is classified as industrial wastewater, defined by Turkish legislation as the wastewater generated in areas of commercial or industrial activity, excluding domestic wastewater and stormwater. This definition is formally outlined in the Regulation on Water Pollution Control (*Su Kirliliği Kontrolü Yönetmeliği*, hereinafter referred to as SKKY), which constitutes the primary legal framework for managing waterborne discharges in Türkiye. According to the national marine discharge provisions stipulated in the SKKY (Official Gazette No: 25687, Date: 31.12.2004), any direct release of wastewater into Türkiye's territorial coastal waters that may result in polluting effects is strictly prohibited unless explicitly authorized. Importantly, this prohibition also extends to indirect impacts on maritime zones where Türkiye exercises economic usage rights, thereby reflecting the regulation's preventive and precautionary governance philosophy (Türkiye Cumhuriyeti Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2004).

Given these strict legal constraints, deep marine discharge has become a permitted, yet tightly controlled method for disposing of treated industrial wastewater. Facilities using this approach must adhere not only to the general discharge standards presented in Table 4.3, but also to additional requirements specific to their industry.

Table 4.3. Characteristics of industrial wastewaters eligible for deep marine discharge (Türkiye Cumhuriyeti Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2004).

Parameter	**Limit**
Temperature	Regardless of the dilution capacity of the marine environment, the temperature of wastewater discharged into the sea must not exceed 35 °C. The reference point for evaluating discharge is the area within a 75-meter radius from the diffuser outlet (considered as the initial dilution zone). The discharge must not increase the ambient seawater temperature by more than 1 °C during the summer period (June–September) and by more than 2 °C during the rest of the year. However, if the ambient seawater temperature is above 28 °C, discharges that increase the seawater temperature by no more than 3 °C at the boundary of the initial dilution zone may be permitted.
Salinity	In the case of concentrated saline discharges under Deep Marine Discharge (DMD) systems, the increase in salinity must be evaluated at the reference discharge point (within a 75-meter radius from the diffuser, i.e., the initial dilution zone). In environmentally sensitive marine areas, the increase in salinity must not exceed two parts per thousand (2 ppt); in other marine areas, it must not exceed three parts per thousand.
pH	6-9
Other Parameters	The limit values specified in the relevant sectoral discharge tables shall apply.

According to the regulation, the leather and leather products sector is identified as one of sixteen industrial categories, each subject to its own effluent limits based on the characteristics of the production process. The specific discharge standards applicable to the leather and leather products sector are detailed in the corresponding table provided below.

Table 4.4. Discharge standards for leather industry wastewater (Türkiye Cumhuriyeti Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2004).

Parameter	**Unit**	**2-Hour Composite Sample**
Chemical Oxygen Demand (COD)	(mg/L)	250
Suspended Solids (SS)	(mg/L)	125
Total Kjeldahl Nitrogen (TKN)	(mg/L)	60*-120**
Oil and Grease	(mg/L)	30
Total Chromium	(mg/L)	3
Chromium (Cr^{+6})	(mg/L)	0.5
Sulfide (S^{-2})	(mg/L)	2
Zebrafish Static Bioassay (ZSF)	-	4
Color	(Pt-Co)	280
pH	-	6-9

Notes:

- ✓ *Applicable to industries processing small ruminant hides and to mixed industrial facilities where 20% to 65% of the wastewater originates from leather processing activities.
- ✓ ** Applicable to industries processing large ruminant hides.

In this study, the wastewater samples were collected from a treatment facility that discharges into the Sea of Marmara via a deep marine outfall system. In addition to meeting the effluent quality standards outlined in Table 4.3, such facilities must also comply with specific design and operational requirements to ensure safe dispersion of treated wastewater in the marine environment. These include meeting minimum criteria for dilution and discharge depth, maintaining appropriate monitoring infrastructure, and obtaining the necessary environmental permits. The facility evaluated in this study fulfills these obligations, operating within the national regulatory framework that governs the controlled and environmentally responsible release of industrial effluent into marine waters.

Taken together, this regulatory framework sets the operational boundary within which the treatment plant must function, ensuring that any effluent entering the deep marine discharge system

remains both legally compliant and environmentally safe. Within these constraints, the performance of alternative coagulant formulations becomes especially important, as improvements in pollutant removal, sludge reduction, or chemical efficiency can directly influence the plant's ability to consistently meet discharge standards. Building on this initial evaluation, the next section introduces the Environmental Impact Matrix, which provides a more comprehensive and structured assessment of the broader environmental implications associated with each formulation.

4.3.2. Environmental Impact Matrix

Environmental assessment of industrial wastewater management must extend beyond regulatory compliance and consider the broader ecological footprint of the discharge process. In the present study, the environmental implications of coagulation–flocculation processes applied to leather industry wastewaters were analyzed with respect to pollutant fate, sludge generation, chemical usage, and discharge characteristics. The Çorlu Leather Organized Industrial Zone (Çorlu Deri OSB), as the case study location, discharges its treated effluent through a centralized treatment plant into the Marmara Sea via a shared deep marine outfall system. This infrastructure inherently affects multiple environmental compartments—including the marine water column, benthic sediment layers, and sludge handling chain on land.

While compliance with discharge standards ensures regulatory sufficiency at the final stage, this matrix serves to highlight how intermediate process choices may influence other parts of the treatment system and its environmental footprint. For example, selecting a coagulant that improves pollutant removal might also increase chemical consumption or sludge production, which in turn affects energy use, handling requirements, or disposal impacts. Similarly, adjusting polymer dose can change settling behavior and sludge characteristics, potentially affecting downstream processes like dewatering or transport. In this sense, the matrix is designed to capture these interconnected effects that may not be visible when focusing solely on final effluent quality.

Moreover, the strategic use of deep marine discharge as a mitigation tool—although advantageous in dispersing pollutants—is not without risk (Besley and Birch, 2019). Seasonal variation in seawater temperature and stratification, salinity gradients, and marine biodiversity in the Marmara Sea must be taken into account when assessing the long-term ecological sustainability of such discharge strategies (Zapevalov and Dovgaya, 2007; Ergül, 2016; Türkeri and İşinibilir, 2024). The current study also acknowledges that receiving environments may include vulnerable coastal ecosystems, where cumulative impacts of multiple OSBs and limited circulation may amplify risks.

In order to comprehensively evaluate the environmental performance of the tested coagulant formulations, an Environmental Impact Matrix was developed, offering a holistic and structured framework that extends beyond conventional pollutant removal metrics. This matrix aims to reflect the full ecological footprint of each formulation by integrating a wide range of indicators, including not only removal efficiencies, but also chemical usage, sludge properties, and long-term environmental risks.

The development of this matrix was inspired by recent multi-criteria decision analysis (MCDA) approaches applied in the field of wastewater sustainability. Particularly, Llacer-Iglesias et al. (2023) proposed a comprehensive MCDA framework to assess the sustainability of wastewater energy recovery pathways. Their methodology structured environmental performance across multiple impact categories—such as toxicity, carbon footprint, and resource consumption—and applied normalization and weighting techniques to produce aggregate sustainability scores. Similarly, in the present study, the Environmental Impact Matrix integrates thematically grouped indicators and normalized scoring to enable a comparative assessment of alternative coagulant systems, reflecting both immediate and systemic environmental dimensions (Llacer-Iglesias et al., 2023).

4.3.2.1. Framework for Grouping Environmental Assessment Criteria. The thematic grouping of indicators in the Environmental Impact Matrix was based on their conceptual relevance to distinct dimensions of environmental sustainability, as commonly practiced in MCDA-based wastewater assessment studies. Each group clusters together indicators that reflect a shared ecological function or risk domain—for example, sludge-related outputs, long-term fate of residuals, chemical toxicity, or baseline treatment performance. This thematic structure improves the interpretability of results and aligns with methodological frameworks in the literature that advocate domain-based classification of sustainability criteria (Sharma et al., 2023; Carlos and Norońa, 2021).

While the specific group names were adapted to the context of this study, the overall structure follows a widely adopted practice in the literature. Environmental indicators in MCDA frameworks are frequently classified into thematic domains such as sludge production and handling, chemical dosage and toxicity, persistence and long-term ecological impact, and treatment performance metrics. For example, Omran et al. (2021) structured environmental indicators under distinct domains such as sludge generation, residual toxicity, and operational characteristics when evaluating treatment technologies in Iraq. Similarly, Zheng et al. (2016) employed scenario-based MCDA to compare centralized and decentralized wastewater systems by grouping indicators related to pollutant transfer risks, system resilience, and ecological persistence. A broader review by Ferla et al. (2024) further

confirms that such thematic structuring enhances both clarity and consistency in sustainability assessments, especially when integrating heterogeneous criteria such as sludge yield, metal residuals, chemical input, and resource efficiency.

Beyond standard MCDA considerations, the thematic domains selected in this study were also guided by insights from recent research on wastewater treatment systems, helping ensure that the evaluation is grounded in both methodological rigor and current scientific understanding. While these studies do not always present their indicators within strict matrix structures, they consistently frame environmental concerns around similar themes—such as sludge generation, chemical toxicity, residual persistence, and overall treatment performance.

For instance, Devanathan et al. (2024) discussed environmental sustainability aspects of conventional and alternative coagulants by addressing sludge load, residual metal content, and polymer biodegradability. Radović et al. (2022) assessed bio-based coagulants using a life cycle framework that highlighted energy use, organic residue generation, and sludge management concerns. Similarly, Balbinoti et al. (2023) structured their analysis around toxicity indicators, dosage requirements, and core performance metrics.

Although the terminology and structure differ across studies, the consistent overlap in these thematic areas offers a clear rationale for the four-group design adopted in this matrix. Building on this shared conceptual ground, the Environmental Impact Matrix was developed through a stepwise process that integrates insights from the literature with model-based formulation, as illustrated in Figure 4.13.

Building on this structured framework, the present study adopts a four-group classification designed to capture the most critical environmental dimensions relevant to coagulant formulation assessment:

i. Sludge Management & Disposal Impact,
ii. Systemic & Long-Term Environmental Robustness,
iii. Chemical Burden & Toxicity, and
iv. Treatment Efficiency & Organic Load Management.

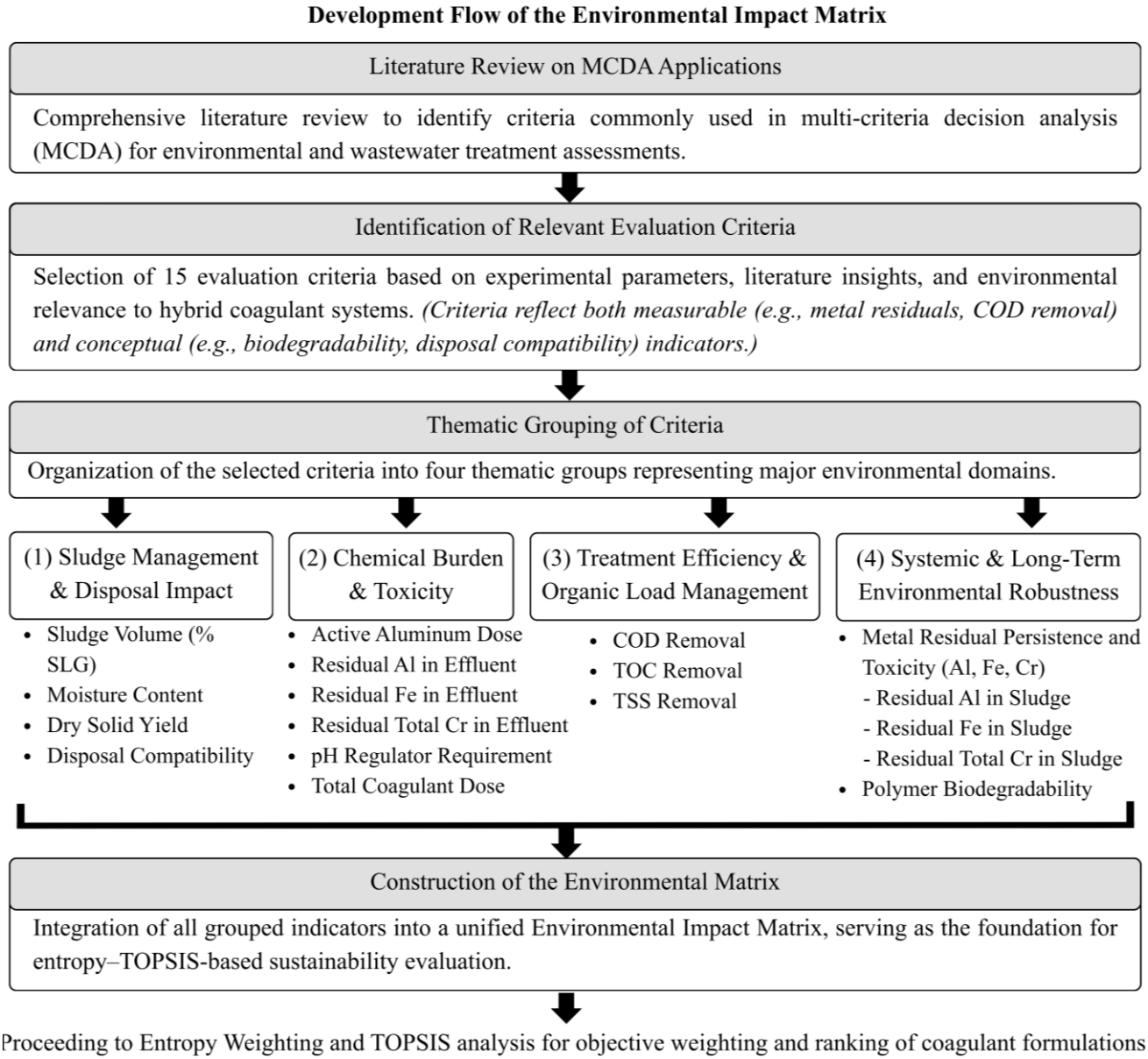


Figure 4.13. Flowchart of the environmental impact matrix development process.

In the following sections, each thematic group will be elaborated individually, including a justification for its inclusion and a detailed explanation of the specific indicators it comprises. The overall framework of the environmental impact matrix, including all thematic groups and sub-criteria, is provided in Table 4.5, which appears at the end of the group descriptions.

Although these thematic groups were not used directly in the computational steps of the MCDA model, they serve an important function in structuring and interpreting the results. Organizing the 15 evaluation criteria into four domains—Sludge Management & Disposal Impact, Chemical Burden & Toxicity, Treatment Efficiency & Organic Load Management, and Systemic & Long-Term Environmental Robustness—helps present the assessment in a clearer and more meaningful way. This

approach also reflects a broader trend in environmental decision-making, where grouping diverse indicators into conceptual clusters improves transparency and interpretability, especially when dealing with large and heterogeneous datasets. Similar thematic frameworks have been employed in previous MCDA studies addressing wastewater sustainability and treatment process selection (Omran et al., 2021; Zheng et al., 2016; Devanathan et al., 2024). In this sense, while the group structure does not influence the mathematical weighting or ranking of alternatives, it plays a key role in making the evaluation more communicable, transparent, and practically useful.

4.3.2.2. Determination of Sub-Criteria for the Sludge Management and Disposal Impact Group. The first thematic group, Sludge Management & Disposal Impact, was constructed to address the environmental burden posed by sludge-related outputs, which constitute a critical dimension of wastewater treatment sustainability. This group comprises four sub-criteria that reflect the volume, solids content, and handling characteristics of the produced sludge, all of which directly influence downstream management practices such as transport, dewatering, and disposal. Specifically, the criteria reflect how easily the sludge can be treated and moved, while disposal compatibility considers its suitability for end-use options and regulatory requirements. Together, they provide a well-rounded assessment of both environmental and operational impacts.

In sludge management evaluations using MCDA, criteria linked to sludge volume are often highlighted due to their impact on transport requirements and space constraints. For example, Eikelboom et al. (2018) conducted an MCDA to compare anaerobically digested sludge disposal options and emphasized composting and incineration as favorable alternatives, partly due to their potential to reduce sludge mass and improve manageability through drying and energy recovery. In addition, although "dry solid yield" was not explicitly defined as a standalone criterion in their study, related indicators—such as material and energy recovery—played a key role in the ranking of thermal processes like pyrolysis and incineration, underscoring the relevance of solid recovery considerations in MCDA-based evaluations (Eikelboom et al., 2018).

Dry solid yield also reflects the efficiency of coagulant formulations in recovering solids, directly affecting both resource recovery and landfill burden. Higher dry solid yields reduce residuals requiring further treatment, thus lowering both cost and environmental impact. This was demonstrated by Guo et al. (2018), who found that combining PAC with biopolymer flocculants significantly improved solid recovery and reduced sludge volume. In broader assessments of sludge treatment systems, dry solids concentration is considered a key performance indicator, as it directly affects disposal routes, chemical consumption, and operational efficiency. As Silva et al. (2016)

highlight, monitoring dry solids helps utilities improve sludge management and identify opportunities for process optimization. For these reasons, Dry Solid Yield was included in this thematic group as a key environmental performance indicator with direct implications for emissions, energy use, and treatment costs.

Furthermore, moisture content is widely recognized as a critical factor in sludge treatment processes, particularly due to its impact on dewatering efficiency, treatment costs, and final disposal feasibility. In the literature, there are studies that have incorporated moisture content directly into MCDA frameworks. For example, one study developed an optimization model for solidifying sewage sludge and explicitly included moisture content as a constraint within the decision model. Alongside other technical and environmental variables such as cost, pH, and pollutant concentrations, moisture content was used to assess the suitability of treatment conditions and ensure compliance with landfill standards (Zhou et al., 2012). This example supports the inclusion of moisture content as a legitimate sub-criterion in MCDA-based evaluations for sludge management alternatives.

The final sub-criterion in this group, Disposal Compatibility, reflects the degree to which a given sludge treatment or disposal option aligns with local infrastructure, regulatory frameworks, and site-specific limitations. In their sustainability-oriented MCDA framework, Liu and Ren (2022) incorporate several feasibility-related criteria—such as infrastructure availability, technical maturity, and stakeholder acceptance—that directly influence whether a disposal method can be realistically implemented. Similarly, Liu et al. (2020) prioritize sludge-to-energy technologies using a comprehensive set of criteria, including site adaptability, resource requirements, and process constraints, all of which speak to the practical viability of each option. Together, these studies demonstrate that beyond environmental and economic performance, successful sludge management depends on how compatible a disposal pathway is with local conditions, regulatory frameworks, and system integration capacity.

Taken together, these four criteria offer a well-rounded and scientifically sound foundation for assessing the sludge-related sustainability of different coagulant systems. Grouping them under a single thematic domain also aligns with the way recent wastewater treatment studies structure their MCDA and environmental assessment frameworks, helping maintain both clarity and consistency in the evaluation.

4.3.2.3. Determination of Sub-Criteria for the Chemical Burden & Toxicity Group. In MCDA studies focused on wastewater treatment, indicators related to chemical load, residual toxicity, and long-term

system sustainability are increasingly integrated to capture the broader environmental implications of treatment strategies. Rather than focusing solely on process efficiency, many recent studies have incorporated indicators such as coagulant dose, residual metal concentrations in effluent, and chemical input requirements to reflect the environmental footprint of treatment options. For instance, Liu and Ren (2022) included criteria such as pollution risk and chemical consumption, while Zhou et al. (2020) evaluated residual contaminants and the need for post-treatment conditioning. Inspired by such approaches, this study introduces the Chemical Burden & Toxicity group, which aggregates six sub-criteria that collectively capture the potential for chemical overloading, residual contamination, and the extent of chemical intervention required for effective coagulation.

To operationalize this concept, factors such as active aluminum dose, total coagulant dose, residual heavy metals in the treated effluent, and the requirement for pH regulation (e.g., lime addition) were selected as key indicators. While these parameters may not always result in immediate or acute environmental damage, they are essential for assessing chronic exposure risks, regulatory compliance, and the overall chemical footprint of each treatment process from a resource consumption perspective.

Active Aluminum Dose was included as a key indicator due to its direct impact on sludge system performance and potential for chemical overloading. Zhao et al. (2022) examined how different PAC doses affect activated sludge and observed that moderate dosing enhanced sludge structure and biological stability, whereas higher doses led to excessive production of extracellular polymeric substances and a decline in microbial activity. These results suggest that overdosing aluminum-based coagulants can disrupt sludge function, leading to operational inefficiencies and elevated residual aluminum levels (Zhao et al., 2022).

Residual Al in Effluent (%) represents the proportion of unremoved aluminum remaining in the SUP phase. This is a critical parameter given aluminum's ecological and human health risks. Babatunde and Zhao (2010) found that aluminum levels in treated effluent often exceeded regulatory limits, particularly during the early stages of system operation, highlighting the need for careful monitoring to maintain environmental compliance.

Residual Fe in Effluent (%) was included as a key indicator due to the environmental and operational implications of iron-based coagulant residues in treated wastewater. While iron is generally considered less toxic than other heavy metals, its residual presence in the effluent may still interfere with downstream biological processes and effluent quality. For instance, Comber et al.

(2021) highlighted that iron dosing for phosphorus removal can elevate Fe concentrations in treated effluent, potentially affecting the fate of other trace pollutants. In parallel, Lees et al. (2001) showed that excess iron residues can interfere with microbial respiration and disrupt sludge floc structure, underscoring their influence on both biological stability and effluent quality. These findings emphasize the need for careful dosing and residual management to avoid downstream environmental risks (Comber et al., 2021; Lees et al., 2001).

Residual Chromium in Effluent (%) was included as a critical indicator due to the environmental and toxicological significance of chromium contamination in treated wastewater. Chromium, particularly in its hexavalent form (Cr^{6+}), is known for its high toxicity, persistence, and carcinogenic potential even at trace levels. Laxmi and Kaushik (2020) noted that exposure to Cr^{6+} can lead to genotoxic, mutagenic, and carcinogenic effects, making its effective removal a key environmental objective. Although chromium can exist in multiple oxidation states, total chromium measurement is commonly used as a practical and conservative approach in wastewater monitoring to capture the cumulative risk (Laxmi & Kaushik, 2020). In this study, total chromium concentration was assessed to reflect overall removal performance and to ensure compliance with relevant discharge standards.

pH Regulator Requirement reflects the need for supplementary chemicals to optimize treatment efficiency. In this study, pH adjustment was conducted using lime or NaOH under the conditions required to achieve optimal coagulation. This requirement contributes to the overall chemical footprint of the process. Zhang et al. (2023) demonstrated that pH adjustment can strongly affect coagulant performance, but it also increases chemical use and the risk of residual contamination, making it important to balance process efficiency with environmental impact. For this reason, the need for pH regulation was included as an evaluation criterion in the matrix, capturing the variation observed among the formulations—some requiring substantial adjustment, while others performed effectively under natural pH conditions.

Total coagulant dose was included as an evaluation criterion because it directly reflects the chemical burden placed on the system and its influence on sludge production. Using lower dosages—particularly when working with optimized or naturally effective coagulants—can substantially reduce environmental load and enhance the overall sustainability of the treatment process. Ahmad et al. (2022) reported that high coagulant doses often result in excess sludge and increased chemical use, reinforcing the importance of dosage optimization for greener treatment processes.

Together, these six indicators offer a holistic evaluation of the chemical intensity and residual toxicity potential associated with each coagulant formulation. Rather than representing acute ecological harm, these parameters emphasize chronic environmental load, cumulative exposure risk, and treatment system sustainability from both operational and regulatory standpoints. Their inclusion under the Chemical Burden & Toxicity group enables a more nuanced understanding of how chemical composition, dosage, and residuals interact to influence downstream water quality, sludge stability, and long-term ecological compatibility.

4.3.2.4. Determination of Sub-Criteria for the Treatment Efficiency & Organic Load Management Group. The third thematic group, Treatment Efficiency & Organic Load Management, focuses specifically on core performance indicators such as COD removal, TOC removal, and TSS removal. In the context of MCDA applications, several studies have adopted these conventional metrics as decision criteria, particularly when comparing the technical efficiency of different treatment technologies (Ahmed et al., 2024), (Simanjuntak et al., 2022), (Badawi et al., 2021). While these parameters are fundamental for verifying that a coagulation formulation achieves its primary treatment goals, their relative environmental significance is downplayed in this matrix. This is because all tested formulations already demonstrated acceptable removal efficiencies. Therefore, this group primarily serves as a baseline validation of treatment performance, rather than acting as a major driver of environmental preference in the overall assessment.

COD removal (%) was included as a key indicator because it reflects how effectively each coagulant formulation reduces the organic load in the wastewater, which is central to assessing overall treatment performance. Industrial effluents are often characterized by high COD levels, which pose significant environmental risks if discharged untreated. As highlighted by Azli and Azoddein (2020), such effluents can severely pollute aquatic environments, making COD removal a primary environmental objective. Furthermore, COD is internationally recognized as a standardized and regulated indicator of water pollution, forming the basis for many environmental policies and guidelines, as emphasized by Kolb et al. (2017). This approach is also supported by previous MCDA applications; for example, Simanjuntak et al. (2022) explicitly included COD removal as part of the "Effluent Meets Quality Standard" criterion in an analytic hierarchy process-based MCDA evaluation of wastewater treatment systems in the tofu processing industry. Therefore, its inclusion as a sub-criterion under the "Treatment Efficiency and Organic Load Management" group in MCDA frameworks is both scientifically justified and environmentally imperative.

TOC removal is a crucial parameter in evaluating the environmental performance of wastewater treatment systems. Additionally, TOC serves as a practical and reliable alternative to COD for monitoring organic pollution in wastewater, as demonstrated by Dubber and Gray (2010). Its application extends to both operational control and regulatory monitoring. In fact, several countries, including South Korea, have formally adopted TOC as a key water quality parameter, reflecting its growing importance in environmental legislation (Jeong et al., 2014). TOC removal has also been included as a decision criterion in MCDA-based evaluations. For example, Ahmed et al. (2024) incorporated TOC, alongside COD and TSS, as one of the core performance indicators in a multi-criteria decision model comparing electrode pairs for textile wastewater treatment (Ahmed et al., 2024). Accordingly, TOC removal is considered an essential environmental indicator and has been integrated as a criterion in the MCDA matrix to support informed decision-making in wastewater treatment.

TSS removal is a critical indicator of wastewater treatment performance due to its direct environmental implications. TSS not only contributes to the physical degradation of receiving waters, but also serves as a carrier for other pollutants such as heavy metals, phosphates, and hydrophobic organic compounds, thereby amplifying their ecological impact (Rossi et al., 2005). Elevated TSS levels have been shown to harm aquatic organisms; for example, Montoya et al. (2024) reported that environmentally relevant concentrations of suspended solids can impair gill function and structure in zebrafish, highlighting potential toxicological implications. Additionally, wastewater from industrial sectors such as oleochemical processing typically contains high TSS concentrations, which, if left untreated, pose considerable risks to ecosystems (Azli and Azoddein, 2020).

In line with these environmental concerns, TSS removal has been widely adopted as a performance indicator in MCDA frameworks comparing wastewater treatment options, reflecting its central role as an environmentally significant decision criterion. The environmental significance of TSS removal is also reflected in its inclusion as a decision criterion in MCDA-based evaluations. For instance, Hilmi et al. (2022) used TSS removal efficiency in an AHP model comparing effluent treatment options, while Ahmed et al. (2024) included TSS as one of the key performance indicators in a multi-method MCDA analysis of electrode configurations for textile wastewater treatment. Therefore, TSS removal has been appropriately integrated as a key sub-criterion under this group.

4.3.2.5. Determination of Sub-Criteria for the Systemic & Long-term Environmental Robustness Group. The last thematic group, Systemic & Long-term Environmental Robustness, was designed to evaluate the broader and more persistent environmental impacts associated with hybrid coagulant applications. Unlike short-term efficiency metrics, the criteria in this group address long-term environmental concerns. They consider factors such as the potential for metals to accumulate in sludge and soils and the persistence of synthetic polymer additives in the environment. This focus aligns with a growing emphasis in recent literature on incorporating long-term environmental considerations into decision-making processes. One notable example of this trend is the Multi-Criteria Decision Analysis for Assessments of Chemical Alternatives (MCDA-ACA) framework, which systematically incorporates long-term environmental hazard criteria—such as persistence, bioaccumulation, and carcinogenicity—into the evaluation of chemical substitutes (London et al., 2024).

Building on this perspective, even though the specific mix of long-term environmental criteria used in this study—such as metal accumulation and polymer persistence—has not been evaluated together in previous MCDA work, the idea of considering persistent and chronic environmental risks is already well recognized in the literature. Therefore, this study adopts and tailors MCDA principles to evaluate criteria that reflect the long-term robustness of hybrid coagulant applications, particularly in terms of their residual impact on land and water systems. These include the potential for metal accumulation in sludge and soils and the environmental persistence of synthetic polymer additives. Collectively, this group aims to assess how resilient a treatment strategy is in preventing chronic environmental harm over extended timescales, particularly in land and water systems affected by post-treatment residues.

The inclusion of metal residuals such as aluminum (Al), iron (Fe), and chromium (Cr) as a sub-criterion reflects their potential to cause long-term ecological harm when retained in sludge and applied to land. Prior studies have highlighted that alum-based coagulants can lead to aluminum accumulation in treated sludge, which, under certain pH conditions, becomes bioavailable and may impair soil health and plant uptake. For example, Kluczka et al. (2017) reported that alum-based sludge can contain bioavailable forms of aluminum, which raises concerns about soil stability and long-term fertility when such sludge is applied as a fertilizer. Loganathan et al. (2024) further noted that high levels of soluble Al in sludge could suppress plant growth, particularly in acidic soils. Additionally, aluminum is considered a potential environmental neurotoxin, and Wang et al. (2016) reported that chronic exposure may significantly increase the risk of Alzheimer's disease, highlighting broader ecological and public health concerns.

Beyond aluminum, chromium and iron residues in sludge also raise environmental alarms. Chromium—especially in its hexavalent form (Cr^{6+}), is highly toxic and persistent, and can leach from sludge when not properly stabilized. According to Malaviya and Singh (2011), Physicochemical treatment processes often produce sludge containing chromium, which poses significant disposal problems due to its toxicity and large volume. Therefore, additional stabilization steps are often necessary before final disposal (Malaviya and Singh, 2011). Furthermore, according to Lin et al. (2023), sludge that contains chromium must undergo additional treatment—such as oxidation or calcination—to minimize its potential to leach harmful substances into the environment. Without such stabilization, chromium residues may escape into soils over time, posing long-term ecological risks (Lin et al., 2023).

Iron, though generally considered less toxic than chromium or aluminum, can still influence the fate and transport of other pollutants in sludge. For example, Singh and Singh (2001) found that iron-bearing industrial sludges not only interacted chemically with chromium but also affected its residual mobility through complex formation, thereby complicating sludge stabilization and disposal (Singh and Singh, 2001).

Given their mobility, toxicity, and biological accessibility, residual heavy metals in sludge pose both an immediate contamination risk and a long-term ecological concern, especially when the sludge is applied to land or disposed of in uncontrolled areas. Unlike short-term performance metrics, this criterion captures the persistent nature of metal-related hazards, including leaching to groundwater and bioaccumulation in soil ecosystems. For this reason, Metal Residual Persistence and Toxicity was placed under the Systemic & Long-term Environmental Robustness group, reflecting the enduring risks posed by sludge-bound metals after treatment.

The Polymer Biodegradability criterion was introduced to evaluate the long-term environmental fate of organic polymer additives used in hybrid coagulants. While these polymers improve coagulation performance, their persistence in natural systems can pose a significant environmental risk. As highlighted by Zumstein et al. (2022), non-biodegradable water-soluble polymers can accumulate in soils and aquatic systems, potentially disrupting microbial communities and biogeochemical processes. Moreover, they have become a focus of regulatory attention, as concerns grow regarding their environmental persistence and implications for polymer sustainability (Albright and Chai, 2021).

To assess this risk, predictive tools such as the BIOWIN models are increasingly used in environmental assessments. They provide a practical and cost-effective way to estimate the biodegradability and persistence of organic compounds, which is especially valuable when experimental data are limited or unavailable (Posthumus et al., 2005). Additionally, Wang et al. (2023) emphasized that some synthetic polymers used in industrial flocculants show high environmental persistence and can exert ecotoxic effects despite low inherent toxicity. Given these findings, polymer biodegradability is a necessary sub-criterion, ensuring that materials selected for water treatment do not leave behind persistent, non-degradable residues in the environment.

Collectively, these four thematic groups and their respective sub-criteria provide a comprehensive framework for evaluating the environmental sustainability of coagulant formulations. By integrating both operationally measurable and conceptually derived indicators, the Environmental Impact Matrix captures a wide spectrum of environmental interactions—from short-term treatment performance to long-term ecological persistence. This multidimensional structure thus serves as a robust foundation for the subsequent entropy-based weighting and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) evaluation, enabling an objective and holistic comparison of the environmental performance of all coagulant alternatives.

Table 4.5. Structure of the environmental impact matrix and evaluation domains.

Group	Criterion	Description	Source / Basis	Environmental Interpretation
Sludge Management & Disposal Impact	Sludge Volume (% SLG)	Volume of sludge produced during treatment.	Experimental results	Higher volume results in increased handling and disposal burden.
	Moisture Content	Water content in produced sludge.	Experimental results	Lower values improve dewaterability and reduce drying or disposal energy.
	Dry Solid Yield	Total dry sludge produced per liter of treated water.	Calculated from sludge mass balance	Reflects real sludge burden of each formulation; higher values may increase environmental load.
	Disposal Compatibility	Suitability for standard sludge disposal methods.	Evaluation based on composition and stability	Compact, dense sludge is favorable for landfilling or incineration.
Chemical Burden & Toxicity	Active Aluminum Dose	Amount of Al^{3+} introduced via coagulant per dose.	Based on formulation and dosing	Higher Al means risk of long-term soil accumulation & leaching.
	Residual Al in Effluent	Aluminum remaining in supernatant after treatment.	ICP-OES measurements	Higher values imply lower capture in sludge and greater aquatic environmental exposure.
	Residual Fe in Effluent	Iron remaining in supernatant after treatment.	ICP-OES measurements	Lower residual Fe means less aquatic and sediment toxicity.

Group	Criterion	Description	Source / Basis	Environmental Interpretation
	Residual Total Cr in Effluent	Total chromium concentration in treated effluent	ICP-OES measurements	Lower residual total Cr means less aquatic and sediment toxicity.
	pH Regulator Requirement	Whether lime or acid/base was used in application.	Experimental pH control records	High demand increases chemical use and environmental footprint.
	Total Coagulant Dose	Total dosage applied during treatment.	Experimental dosing records	Lower dosage means better chemical consumption.
Treatment Efficiency & Organic Load Management	COD Removal	Chemical Oxygen Demand removal efficiency (%).	Experimental results	Proxy for organic pollutant load removal; strong indicator of general treatment efficiency.
	TOC Removal	Total Organic Carbon removal efficiency (%).	Experimental results	Indicates effectiveness of organic carbon removal; environmentally meaningful parameter.
	TSS Removal	Total Suspended Solids removal (%).	Experimental results	Consistent TSS removal improves discharge quality and reduces sedimentation risk in aquatic bodies.
Systemic & Long-term Environmental Robustness	Metal Residual Persistence and Toxicity (Al, Fe, Cr)	Risk of transferring pollutants from water to land.	ICP-OES measurements	Persistent metals can leach into soils and groundwater, leading to chronic toxicity, bioaccumulation, and potential ecological disruption over extended timescales.
	Polymer Biodegradability	Environmental persistence of polymer additives.	BIOWIN assessment data	Non-biodegradable polymers may accumulate in ecosystems.

4.3.2.6. Integrated entropy–TOPSIS approach for environmental performance assessment. In this study, a multi-criteria decision analysis (MCDA) framework is applied to assess the environmental performance of the alternative coagulant formulations using a broad set of experimentally derived indicators. To strengthen the objectivity of the evaluation and limit dependence on subjective expert input, the analysis combines the Entropy weighting method with the TOPSIS model, allowing the formulations to be compared on a transparent and data-driven basis. This integrated method has been widely adopted in wastewater treatment assessment studies for its capacity to deliver data-driven, reproducible results (Yu et al., 2020), (Yu et al., 2023).

To ensure objectivity in determining the relative importance of evaluation criteria, the Entropy weighting method was employed prior to the application of the TOPSIS model. This method derives weights directly from the variation in data across alternatives, thereby eliminating the need for expert judgment. These entropy-derived weights were subsequently used within the TOPSIS model to evaluate and rank the coagulant formulations based on their weighted distances to ideal solutions. The following section outlines the step-by-step procedure for implementing the Entropy weighting method used in this study.

A decision matrix was developed in which each row represents an alternative formulation and each column corresponds to one of the 15 environmental criteria, which are categorized into four thematic groups as detailed in Table 4.5. The matrix is defined as:

$$D = [x_{ij}]_{mxn} \tag{4.1}$$

Where x_{ij} denotes the performance score of the ith alternative with respect to the jth criterion; m is the number of alternatives and n is the number of criteria.

The entropy weighting method calculates the relative importance of each criterion by analyzing the variation in values across the decision alternatives. Rooted in Shannon's entropy theory (Shannon and Weaver, 1949), this approach defines entropy as a measure of uncertainty or disorder within a data distribution. When a criterion exhibits little variation across alternatives, it indicates that the formulations behave similarly in that respect, meaning the criterion contributes limited useful information to the decision process. In contrast, criteria that show greater variability help distinguish the alternatives more clearly and therefore carry higher informational value. The entropy method incorporates this logic by assigning lower weights to criteria with uniform values and higher weights

to those with larger dispersion, reflecting the principle that information gain increases as uncertainty decreases (Wang and Lee, 2009).

The procedure involves the following steps:

1. Normalization of the decision matrix:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{4.2}$$

Where, p_{ij} is the normalized value of x_{ij}.

2. Calculation of the entropy value:

$$e_j = -k \sum_{i=1}^{m} p_{ij} \,.\, ln(p_{ij}), \qquad where\ k = \frac{1}{\ln(m)} \tag{4.3}$$

Where, e_j is entropy of the jth criterion and k is a constant ensuring normalization of entropy values (depends on number of alternatives).

3. Derivation of the divergence measure:

$$d_j = 1 - e_j \tag{4.4}$$

Where, d_j is degree of divergence of the jth criterion. A higher d_j indicates greater variation among alternatives for that criterion.

4. Entropy-based weight assignment:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{4.5}$$

Where, w_j is final entropy weight of the jth criterion and $\sum_{j=1}^{n} d_j$ is total divergence across all criteria (used to normalize the weights).

The entropy-based weighting technique was implemented following the formulation described by Yu et al. (2020), in which the normalized entropy of each criterion is calculated from its value distribution across alternatives, and subsequently transformed into objective weights based on their information content. To structure the decision model, all 15 criteria were organized into four thematic groups, as detailed in Table 4.5.

Given the absence of expert elicitation for group-level weighting, a data-driven aggregation strategy was adopted instead. Specifically, the overall weight of each group was calculated by summing the individual entropy-based weights of its corresponding criteria. This approach aligns with previous MCDA studies in the field of water and environmental resource management. For example, Li et al. (2019) grouped water quality indicators into environmental, social, and economic domains and derived group-level weights by aggregating the entropy scores of sub-criteria.

In line with this precedent, the present study also utilizes group-level weights exclusively for interpretive purposes. Although the TOPSIS analysis was performed at the individual criterion level using the entropy-based weights, organizing the indicators into thematic groups helps clarify the results by showing which environmental domains most strongly influence the final rankings. This additional interpretive layer not only improves the readability of the findings but also reinforces their ecological coherence and practical relevance for environmental decision-making.

The resulting group weight $W_G^{(k)}$ is therefore obtained by summing the entropy-derived weights w_j of all criteria j that belong to the thematic group G_k, as expressed in the following equation:

$$W_G^{(k)} = \sum_{j \in G_k} w_j \tag{4.6}$$

Where:

$W_G^{(k)}$ = Aggregated weight of the kth thematic group.

w_j = Entropy-derived weight of the jth criterion within group k.

G_k = Set of all criteria belonging to the kth group.

$\sum_{j \in G_k} w_j$ = Summation of all entropy-derived weights for criteria j that belong to group G_k.

Following the derivation of both criterion and group weights, the final multi-criteria evaluation was conducted using the TOPSIS method. This approach was chosen because TOPSIS supports the simultaneous consideration of multiple technical and environmental criteria, making it well-suited for comparing coagulant formulations with different performance trade-offs. By integrating entropy-based weights into the TOPSIS framework, the approach enabled an objective and transparent ranking of coagulant formulations based on their weighted distances to the ideal and negative ideal solutions.

The core principle of TOPSIS is that the optimal alternative should have the shortest Euclidean distance to the positive ideal solution (PIS) and the farthest distance from the negative ideal solution (NIS), thus enabling consistent comparisons across multiple, and potentially conflicting, criteria (Yahya et al., 2020). The formulation adopted here is based on the original method developed by Hwang and Yoon (1981), with computational procedures elaborated by Huang and Tzeng (2011, pp. 69–79). In this study, entropy-derived criterion weights were used to ensure objectivity. While thematic grouping supported interpretability, the TOPSIS computation focused directly on the criterion level.

The procedure consists of the following steps:

1. Normalization of the Decision Matrix:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} {x_{ij}}^2}} \tag{4.7}$$

To eliminate the influence of differing units and scales among criteria, the original decision matrix $X = [x_{ij}]$was normalized using vector normalization. Where r_{ij} represents the normalized value of coagulant option i with respect to criterion j.

2. Weighted normalization of the decision matrix:

$$v_{ij} = w_j \, x \, r_{ij} \tag{4.8}$$

Each normalized value was then multiplied by its corresponding entropy-derived weight $w_j$to obtain the weighted normalized matrix. Where v_{ij} denotes the weighted normalized score of alternatives i for criterion j.

3. Positive and Negative Ideal Solutions:

$$A^{+} = \{\max(v_{ij}) \mid j \in J_1 \; ; \min(v_{ij}) \; j \in J_2\} \tag{4.9a}$$

$$A^{-} = \{\min(v_{ij}) \mid j \in J_1 \; ; \max(v_{ij}) \; j \in J_2\} \tag{4.9b}$$

J_1 = the set of criteria for which higher values are environmentally desirable (e.g., removal efficiencies),

J_2 = the set of criteria for which lower values are environmentally desirable (e.g., residual concentrations, chemical dosages).

The positive and negative ideal solutions were determined based on the environmental desirability of each criterion, guided by relevant literature and sustainability standards. For example, higher COD, TOC, and TSS removal efficiencies were considered environmentally beneficial and thus aligned with the positive ideal. Conversely, for indicators such as residual metal concentrations or chemical dosage, higher values were interpreted as environmentally unfavorable and therefore associated with the negative ideal. This approach ensured that the evaluation reflected real-world ecological priorities. The detailed computational steps and results are presented in the following section. While the general approach to identifying ideal and anti-ideal solutions has been outlined above, the exact values assigned to each criterion are presented in detail in the following section.

4. Euclidean Distances from Ideal Solutions:

$$S_i^{+} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^{+})^2} \tag{4.10a}$$

$$S_i^{-} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^{-})^2} \tag{4.10b}$$

The Euclidean distance of each alternative to the positive ideal solution is denoted as S_i^{+}, representing how far an alternative is from the most environmentally favorable scenario. Conversely, S_i^{-} denotes the distance to the negative ideal solution, indicating the proximity of the alternative to the least desirable environmental outcome.

5.Closeness Coefficient:

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{4.11}$$

Finally, a relative closeness coefficient (C_i) was calculated for each alternative to quantify its similarity to the ideal solution. This coefficient measures the balance between an alternative's distance to the positive ideal and negative ideal solutions. The value of $C_i$ranges between 0 and 1, where a higher $C_i$indicates greater proximity to the ideal solution and, consequently, represents a more environmentally favorable coagulant formulation.

After calculating the closeness coefficients (C_i) for all alternatives, the coagulant formulations were ranked in descending order based on their proximity to the ideal solution. The formulation with the highest $C_i$value was identified as the most environmentally favorable option. A summary of the calculated closeness coefficients and the resulting rankings is presented in Section 4.3.2.7, along with the corresponding evaluation results.

The overall computational procedure of the integrated entropy–TOPSIS approach is summarized in Figure 4.14. Building upon the conceptual framework previously outlined in the Flowchart of the Environmental Impact Matrix Development Process (Figure 4.13), this stage represents the quantitative implementation phase of the assessment. As shown, the process follows a structured and sequential logic that begins with data normalization and entropy-based weight determination, continues through weighted matrix construction and the identification of positive and negative ideal solutions, and culminates in the calculation of Euclidean distances and closeness coefficients for ranking. By visually connecting each step of the process, the flowchart offers a clear and streamlined overview of the analytical pathway used to evaluate and compare the environmental performance of the coagulant formulations.

The detailed computational steps and tabulated results corresponding to each phase of the analysis are presented in **Appendix K** for reference and verification.

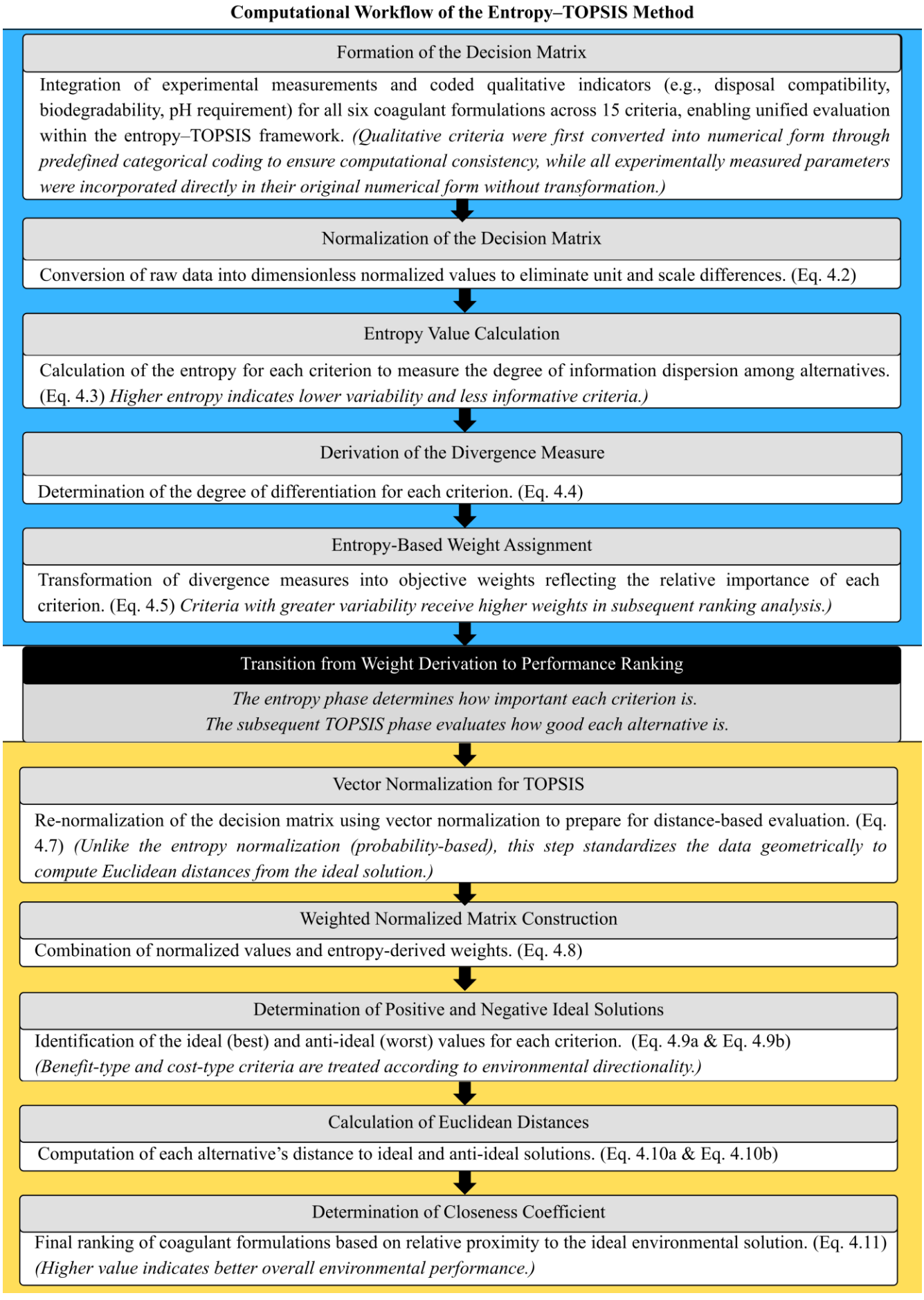


Figure 4.14. Computational flow of the entropy–TOPSIS method applied in this study.

4.3.2.7. Results of the environmental performance evaluation of coagulant formulations. In this section, the environmental performance of the six coagulant formulations was evaluated based on the multi-criteria decision analysis (MCDA) framework, using the previously described Entropy-TOPSIS methodology. Most of the evaluation criteria—such as sludge volume, moisture content, dry solid yield, active aluminum dose, residual metal concentrations, total coagulant dose, and COD, TOC, and TSS removal—were obtained directly from experimental data.

However, three criteria required conceptual interpretation and conversion into numerical form to fit the MCDA framework: pH Regulator Requirement, Disposal Compatibility, and Polymer Biodegradability. Due to their qualitative nature or composite derivation, each of these indicators was systematically quantified based on literature-supported frameworks and scientific modeling principles. This approach allowed both measurable experimental outcomes and conceptually important environmental considerations to be incorporated into a single evaluation framework, ensuring that the sustainability of each coagulant formulation could be assessed in a clear and balanced way.

In order to incorporate qualitative criteria into the MCDA framework, the pH regulator requirement was represented using a binary coding system. This criterion indicates whether a given coagulant formulation requires additional chemical adjustment to maintain optimal pH levels during treatment, which may affect both environmental compatibility and process efficiency. Following the guidance of Roszkowska (2011), who argued that qualitative and linguistic attributes can be effectively translated into numerical scales to ensure their compatibility with quantitative MCDA techniques, and Rodríguez et al. (2013), who emphasized that binary descriptors can be directly embedded into the TOPSIS decision matrix to reflect the presence or absence of desirable features, a simple binary evaluation approach was used in this study to express these attributes clearly and directly.

Specifically, a value of "1" was assigned to formulations not requiring pH regulation—indicating greater environmental favorability—while "0" was assigned to those that did. This representation ensured that the criterion could be consistently evaluated alongside quantitatively measured variables within the TOPSIS model. The coded values were subsequently processed using the Entropy weighting method, as demonstrated by Kumar et al. (2023), which enabled an objective weighting of this qualitative indicator based on its variability across alternatives. Through this integration, the pH regulator requirement was successfully incorporated into the environmental evaluation, enabling a more comprehensive and methodologically coherent assessment of coagulant formulations.

The disposal compatibility, which refers to the environmental and operational suitability of sludge for various disposal or reuse options, was represented in this study as a single score derived from relevant experimental parameters, in order to enable integration into the MCDA framework. This value was intended to reflect how appropriate the sludge is for common management practices such as dewatering, land application, composting, or incineration. The conceptual basis for this approach draws on Andreoli et al. (2015), who identified key sludge characteristics—including moisture content, solids content, and heavy metal levels—as critical determinants for selecting suitable disposal routes. Similarly, Kacprzak et al. (2017) emphasized the importance of evaluating sludge management strategies through multi-criteria decision-making tools that incorporate both physical and chemical indicators, including sludge volume and residual metal content.

Building on this conceptual basis, disposal compatibility in this study was quantified using four experimentally measured parameters: moisture content, sludge volume, dry solid yield, and heavy metal concentration. These variables were grouped into three dimensions to represent different aspects of sludge manageability. Moisture content was used to indicate physical suitability, as lower moisture levels generally improve dewatering efficiency. Sludge volume and dry solid yield together defined volumetric suitability, since both the space occupied by the sludge and the amount of solids it contains influence transport and disposal efforts. Finally, heavy metal concentration was considered an indicator of chemical suitability, given its relevance to environmental safety and regulatory compliance. The grouping of parameters in this way allowed for a balanced evaluation that considers operational practicality alongside environmental risk. The parameter values were processed into a single normalized score reflecting overall disposal compatibility, which was then integrated into the MCDA matrix for further evaluation.

The final semi-qualitative criterion integrated into the MCDA framework was polymer biodegradability, which was numerically represented to evaluate the environmental persistence of organic constituents in hybrid coagulant formulations. To quantify this parameter, the output of the BIOWIN 6 model was selected as the biodegradability indicator, as it estimates the likelihood of rapid biodegradation under standardized MITI (OECD 301C) test conditions, generating a quantitative probability score (Çeçen and Gül, 2021). This model was particularly suited for the purposes of this study due to its enhanced predictive capability. In particular, Boethling and Costanza (2010) highlighted that BIOWIN 6, which utilizes a non-linear regression approach, yields more accurate and robust predictions than its linear predecessor, BIOWIN 5—especially when applied to structurally complex or unconventional organic compounds. Given these advantages, BIOWIN 6 was

deemed the most appropriate tool for representing the biodegradability profiles of polymer-containing hybrid coagulants.

To enable the inclusion of polymer biodegradability within the MCDA framework, the model-derived outputs from BIOWIN 6 were processed into weighted biodegradability scores for each hybrid coagulant formulation. These scores were calculated by combining the individual biodegradability values of organic components—such as PolyDADMAC and polyamines—based on their respective proportions in each mixture. This component-weighted aggregation logic is conceptually consistent with the findings of Dunn et al. (2001), who demonstrated that weighting the polymer blend ratio directly influences the degradation behavior of composite materials. Similarly, Scaffaro and Botta (2014) observed that the degradation behavior of polymer blends tends to follow a composition-dependent trend, with overall biodegradability reflecting the relative proportions of individual polymer constituents. This approach allowed the overall biodegradability potential of each formulation to be captured in a single, representative value. The final biodegradability scores were normalized and then incorporated into the entropy weighting step, enabling their integration into the TOPSIS evaluation alongside the other environmental criteria.

This integration was applied exclusively to formulations containing organic constituents. In contrast, inorganic coagulant formulations (e.g., P040102), which lack any organic components, were excluded from both the normalization, entropy weighting processes and TOPSIS related to this criterion. Since biodegradability is not conceptually applicable to such formulations, the corresponding entries were marked as “not applicable” and omitted from the evaluation. This ensured that the influence of the biodegradability criterion was restricted to formulations where polymer degradation is environmentally relevant, thereby preserving the objectivity of the overall decision-making process.

Following the inclusion of both quantitative and conceptually transformed criteria—including the semi-qualitative indicators *Disposal Compatibility*, *pH Regulator Requirement*, and *Polymer Biodegradability*—all data were structured into a comprehensive decision matrix, where columns represented the evaluation criteria and rows corresponded to the six coagulant formulations under study. This matrix, presenting the initial arrangement of all raw criterion values prior to the application of the entropy weighting method, is provided in **Appendix K.**

I In the entropy weighting method, the central aim is to assess how much useful information each criterion adds to the decision process—that is, to evaluate how much its values vary across the

alternatives (Shannon, 1948). To achieve this, the values of each criterion are treated as elements of a probability distribution and are therefore normalized by dividing each value by the column total, as shown in Equation (4.2).

Even though some criteria—such as *Disposal Compatibility*, *pH Regulator Requirement*, and *Polymer Biodegradability*—had already been normalized to a 0–1 range, this second normalization step was still necessary. This is because the first normalization only ensures that all criteria are on a comparable scale, whereas the entropy method specifically requires normalization that reflects information diversity (i.e., how much each criterion varies across alternatives). Therefore, each criterion's values were once again normalized by their column sums to obtain the p_{ij} values, which represent the relative contribution of formulation i to criterion j.

This step does not contradict the earlier normalization; rather, it serves a different purpose—measuring informational variation instead of scale alignment. Such re-normalization is essential to accurately capture how much each criterion differentiates among alternatives, rather than merely equalizing their measurement units. As emphasized in previous studies, this re-normalization step is fundamental to the entropy approach. Zou et al. (2006) explained that it allows the weighting process to reflect the intrinsic diversity of data, ensuring that criteria with greater variability contribute more information to the decision model. In line with this reasoning, Boroushaki (2017) also implemented a two-stage normalization framework in a spatial MCDA context, where initially standardized data were further normalized by column totals prior to entropy calculation. His results showed that while the first normalization serves to remove dimensional inconsistencies among criteria, the second—entropy-oriented—normalization transforms these standardized values into probabilistic proportions that express the relative information content of each criterion.

Therefore, this additional normalization, does not aim at rescaling data once again but rather at quantifying the internal dispersion and informational richness within the dataset. Accordingly, in this study, all criteria defined on a 0–1 scale—such as Di*sposal Compatibility, pH Regulator Requirement, and Polymer Biodegradability*—were first re-normalized by their column totals before applying entropy weighting. This step ensures that the resulting information-based weights genuinely reflect the variability and distinguishing power of each environmental indicator.

Consequently, the normalized proportions p_{ij} obtained in Equation (4.2) were used as the input for the entropy evaluation stage, where each criterion's entropy value e_j was determined following Equation (4.3). This step quantified the degree of variation or information contribution of each

criterion by assessing the dispersion of its normalized values among all alternatives. Subsequently, the divergence degree (d_j) and final entropy weight (w_j) were derived according to Equations (4.4) and 4.5(41), respectively. Through this process, criteria exhibiting higher variability among coagulant formulations received greater weights, reflecting their stronger discriminatory power within the decision matrix. In contrast, criteria with relatively uniform values contributed less to the overall information content. The full computational results—including the intermediate p_{ij}, e_j, and w_j values—are presented in **Appendix K**, where the entropy weighting procedure is summarized in two detailed tables.

Following the derivation of the entropy-based weights, the analysis proceeded with the TOPSIS phase to comparatively evaluate the environmental performance of the six coagulant formulations. Conceptually, the entropy method determines how important each criterion is—by quantifying its information value—whereas TOPSIS determines how good each alternative is—by measuring its relative proximity to the ideal solution. In this study, entropy provided objective weighting, while TOPSIS enabled systematic multi-criteria ranking under a unified evaluation framework. The computational procedure followed the formulations presented in Section 4.3.2.6 (Equations 4.7–4.11).

Before performing the TOPSIS calculations, it was essential to determine the environmental directionality of each criterion—specifically, whether higher values represent environmental benefits or costs. This step ensures that the evaluation accurately reflects the sustainability implications of each parameter within the decision-making process. Accordingly, all criteria were classified as either benefit-type (the-higher-the-better) or cost-type (the-lower-the-better) based on their environmental relevance and operational significance. The rationale and supporting literature for these classifications were discussed in detail in Sections 4.3.2.2–4.3.2.5, where each thematic group was examined with reference to relevant studies and environmental assessment frameworks. A summary of the environmental directionality for all 15 criteria is presented in Table 4.6, providing a concise overview of how each indicator was treated within the analysis framework.

Table 4.6. Classification of environmental criteria and their environmental directions.

Thematic Group	Criterion	Environmental Direction	Justification (Environmental Logic)
Sludge Management & Disposal Impact	Sludge Volume	Cost-type	Larger volumes increase disposal demand and energy use.
	Moisture Content	Cost-type	Higher moisture requires more drying energy and handling effort.
	Dry Solid Yield	Cost-type	More solids imply greater mass to transport/dispose.
	Disposal Compatibility	Benefit-type	Higher compatibility means easier, safer, and more sustainable disposal.
Chemical Burden & Toxicity	Active Aluminum Dose	Cost-type	Lower active Al input reduces chemical load and environmental footprint.
	Residual Al in Effluent	Cost-type	Excess Al can be toxic to ecosystems and humans.
	Residual Fe in Effluent	Cost-type	Elevated Fe affects biological stability in effluent.
	Residual Cr in Effluent	Cost-type	Cr^{6+} is highly toxic and persistent; minimal values preferred.
	Total Coagulant Dose	Cost-type	Lower chemical use = higher sustainability.
	pH Regulator Requirement	Benefit-type	No need for pH correction = less secondary chemical consumption.
Treatment Efficiency & Organic Load Management	COD Removal	Benefit-type	Higher COD removal improves effluent quality.
	TOC Removal	Benefit-type	Lower organic carbon load supports water quality.
	TSS Removal	Benefit-type	Less suspended solids = clearer and less polluted effluent.
Systemic & Long-term Environmental Robustness	Residual Metal Persistence	Cost-type	Long-term accumulation of metals in sludge/soil is harmful.
	Polymer Biodegradability	Benefit-type	Polymer biodegradability was treated as a benefit-type criterion because higher biodegradability reduces environmental persistence and long-term ecological risks. In this context, formulations with higher BIOWIN6 scores (indicating faster and more likely biodegradation) represent more favorable environmental performance. For this reason, biodegradability serves as an important indicator for distinguishing polymers with lower long-term environmental impact.

Please be noted that all criteria in Table 4.6 were categorized as either benefit-type or cost-type according to their environmental implications. For benefit-type indicators, higher numerical values correspond to environmentally favorable outcomes (e.g., higher removal efficiencies or biodegradability), whereas for cost-type indicators, lower numerical values indicate improved environmental performance by reflecting reduced chemical dosage, sludge volume, or residual metal content. This classification ensures consistency in interpreting and comparing the criteria within the entropy–TOPSIS evaluation framework.

Finally, following the entropy-based weight determination, the weighted normalized decision matrix was constructed, and the TOPSIS procedure was applied to rank the alternative coagulant formulations. The obtained closeness coefficients (C_i) for each formulation are summarized in Table 4.7 below, representing their relative environmental performance:

Table 4.7. Calculation of the closeness coefficient and final ranking of coagulant alternatives.

Scenario & Coagulant Code	Closeness Coefficients (C^+)
M2 - P040102	0.0115
M6 - P010300	0.8238
M6 - P010301	0.8165
M6 - P020100	0.6986
M6 - P020200	0.8470
M6 - P020201	0.9182

The results presented in Table 4.7 illustrate the relative proximity of each coagulant formulation to the ideal environmental performance profile, where higher C^+ values indicate more sustainable alternatives. This ranking provides a quantitative basis for comparing the overall environmental favorability of the evaluated coagulant systems. The detailed interpretation and comparative discussion of these results are provided in Section 4.3.2.8.

4.3.2.8. Interpretation of environmental evaluation results. The environmental performance evaluation of the six coagulant formulations was conducted through an MCDA framework that combined entropy-based weighting with the TOPSIS ranking method. This combined approach allowed both quantitatively measurable and conceptually derived indicators to be objectively analyzed within a unified decision matrix. The resulting dataset provides a multidimensional understanding of how formulation chemistry, operational dosage, and material characteristics jointly shape environmental sustainability. The following discussion synthesizes these outcomes by

examining general ranking trends, group-specific variations, and criterion-level implications, thereby linking the computational results to their broader environmental significance.

The overall ranking derived from the TOPSIS closeness coefficients (C^+) revealed a distinct separation between the conventional and hybrid coagulant formulations in terms of environmental compatibility. The C^+ values represent each formulation's relative proximity to the ideal environmental solution, where higher coefficients indicate greater sustainability and overall environmental favorability. Among all evaluated alternatives, P020201 ($C^+ = 0.9182$) demonstrated the highest environmental performance, followed closely by P020200 ($C^+ = 0.8470$) and P010300 ($C^+ = 0.8238$). The formulations P010301 ($C^+ = 0.8165$) and P020100 ($C^+ = 0.6986$) also performed well, maintaining consistent improvement over the conventional system. In contrast, the traditional aluminum sulfate formulation P040102 ($C^+ = 0.0115$) ranked the lowest by a substantial margin, underscoring its markedly higher environmental burden. This clear differentiation confirms that the integration of polymeric and multi-metal components significantly enhances environmental compatibility and reduces chemical intensity compared to the conventional coagulant structure.

A closer examination of the entropy weighting results provides a more nuanced understanding of how the different environmental dimensions contributed to the overall ranking. The weighting structure revealed that certain criterion groups exerted a markedly stronger influence on the final environmental assessment than others. In particular, parameters associated with chemical dosage, residual toxicity, and coagulant composition emerged as the most decisive factors shaping the ranking outcomes. By contrast, indicators related to sludge handling and treatment efficiency played a more supporting role, reflecting relatively consistent performance across formulations. This observation indicates that the environmental differentiation among alternatives was primarily driven by variations in chemical burden rather than by treatment efficiency itself. Overall, this pattern shows how the entropy–TOPSIS approach can reveal the natural hierarchy of environmental importance among the criteria, clearly identifying which factors carry the most weight in distinguishing the sustainability performance of the coagulant formulations.

While the numerical ranking underscores the overall environmental advantage of hybrid formulations, the extent of this advantage varies across groups, with the most pronounced improvements observed in chemical-related and long-term persistence domains. This suggests that the environmental superiority of hybrid coagulants stems less from operational efficiency and more from a fundamental reduction in chemical and residual burdens. However, it should be acknowledged that part of this improvement may also reflect the inherently lower dosage requirements of hybrid

systems, which naturally reduce environmental loading independent of the intrinsic properties of the polymer components. Consequently, a more comprehensive life cycle assessment (LCA) would be beneficial in future studies to isolate the true environmental contribution of polymer chemistry from dosage-related advantages. Nonetheless, within the experimental and methodological scope of the present analysis, the results clearly highlight the substantial sustainability gains associated with lower active coagulant usage.

To further elucidate the underlying causes of these observed trends, a detailed examination of the environmental performance across the individual criterion groups was carried out. This group-level assessment provides insight into how specific environmental domains—such as sludge management, chemical burden, treatment efficiency, and long-term robustness—contributed differently to the overall sustainability hierarchy. By analyzing these dimensions in sequence, the distinct functional advantages and trade-offs among the hybrid formulations can be more clearly identified.

The Chemical Burden & Toxicity group exhibited by far the highest entropy weight, indicating that differences in chemical dosing, active aluminum concentration, and residual metals were the dominant drivers of environmental distinction among the alternatives. The computed positive and negative ideal distances (S^+ and S^-) indicated that the conventional aluminum sulfate formulation (P040102) was by far the least sustainable alternative, exhibiting the largest deviation from the ideal environmental condition due to its excessive dosage requirement (8000 mg/L), high active aluminum input, and substantial residual metal concentrations. In contrast, all hybrid coagulants achieved significantly smaller S^+ and larger S^- distances, confirming a reduced chemical and residual burden across the board.

The hybrid coagulant formulations collectively demonstrated a markedly improved environmental profile compared to the conventional aluminum sulfate system, primarily due to their optimized chemical composition and synergistic interaction between inorganic and organic components. The substantially lower active aluminum input and reduced total coagulant dosage (2800 mg/L) not only minimized the overall chemical footprint but also led to significantly lower concentrations of residual metals in the treated effluent. This finding is especially important because residual aluminum, iron, and chromium are the main contributors to downstream toxicity and long-term environmental persistence.

Among the hybrid systems, those incorporating both aluminum and iron salts alongside cationic polymers exhibited the most balanced environmental performance. The combined Fe–Al matrix likely enhanced charge neutralization and co-precipitation efficiency, thereby improving metal removal from the effluent phase and reducing residual concentrations. Conversely, polymer-only hybrids relying on PAC and PolyDADMAC achieved comparable sustainability benefits through lower active aluminum loading and the absence of additional pH regulation needs. Polyamine-containing formulations also performed well, although small differences in residual metal levels indicate that the type of polymer can slightly affect how metal complexes interact with the organic chains during floc formation. Taken together, these results indicate that the superior environmental behavior of hybrid coagulants stems not from marginal improvements in treatment efficiency, but from a fundamental shift in formulation chemistry that minimizes chemical input and residual persistence.

Overall, these results show that the environmental benefits of hybrid coagulants come primarily from their optimized chemical composition and lower metal load, rather than from small differences in treatment efficiency. The combination of reduced active aluminum dosing, lower residual accumulation, and the synergistic interactions between metals and polymers collectively strengthens the sustainability performance of hybrid systems when compared with the conventional aluminum sulfate formulation.

When the analysis transitions to the *Sludge Management & Disposal Impact* dimension, the differences among coagulant formulations become subtler yet environmentally relevant. Although this group contributed less to the overall entropy-derived weighting compared to chemical burden indicators, it offered essential insights into the physical and operational manageability of the generated sludge. The raw data revealed that the conventional aluminum sulfate formulation (P040102) produced the largest sludge volume and the highest moisture content, corresponding to its low TOPSIS closeness value. This indicates a greater handling and disposal burden due to excessive water retention and low solids stability.

In contrast, all hybrid formulations exhibited markedly improved sludge characteristics, confirming their ability to generate denser and more stable matrices. Among them, P020100 achieved the most favorable overall performance, combining the lowest sludge volume, minimal moisture content, and the highest disposal compatibility. This behavior is likely due to the PAC–PolyDADMAC combination, which strengthens floc structure and helps reduce the amount of water trapped inside the sludge. P020200 and P020201, both containing $FeCl_3$, also showed advantageous

outcomes with higher dry solid yields, reflecting improved sludge compactness. Meanwhile, P010300 and P010301 displayed intermediate results, consistent with their moderate sludge volumes and slightly higher moisture contents.

These findings collectively suggest that hybrid coagulants—particularly those combining PAC with optimized polymer content—produce sludge with more stable physical properties and greater disposal suitability. The overall improvement is driven primarily by compositional synergy between inorganic and organic components, which enhances floc structure and limits moisture retention, thereby reducing the downstream environmental footprint of sludge management operations.

A similar pattern of convergence was observed in the Treatment Efficiency & Organic Load Management group, where all formulations performed within a narrow efficiency range. As expected, all formulations achieved high organic and suspended solids removal efficiencies, indicating that the shift from conventional to hybrid coagulants did not compromise core treatment functionality. However, variations among formulations provide insight into how compositional and structural differences affect pollutant removal pathways.

The conventional coagulant (P040102) exhibited the lowest overall removal efficiencies for COD, TOC, and TSS, indicating the limited treatment effectiveness of traditional alum-based systems under comparable conditions. Despite its widespread use, aluminum sulfate often forms less stable and less compact flocs, which leads to incomplete organic matter removal and relatively lower clarity in the treated effluent. In contrast, all hybrid formulations showed markedly better removal performance, highlighting the stronger charge neutralization and more robust floc formation achieved through the combined action of the polymeric components and multivalent metals.

The PAC–PolyDADMAC formulation (P020100) achieved the most balanced and superior performance, delivering the highest COD and TOC removal efficiencies (84.69% and 84.12%) while maintaining strong TSS reduction (87.84%). This demonstrates an optimal synergy between PAC's pre-hydrolyzed aluminum species and the high charge density of PolyDADMAC, yielding compact and well-structured flocs. The Fe-enhanced hybrids (P020200 and P020201) exhibited the greatest solids removal efficiency—exceeding 89% TSS removal—driven by sweep flocculation and co-precipitation effects characteristic of Fe(III)-containing systems; however, their slightly lower organic removal indicates a shift toward particulate aggregation rather than soluble pollutant adsorption. The dual-polymer system (P010301) performed comparably to its single-polymer

counterpart (P010300), though minor decreases in COD and TOC removal suggest that blending PolyDADMAC with Polyamine alters floc compactness and charge distribution.

Collectively, these results suggest that while all hybrid coagulants meet the necessary treatment performance, their pollutant removal pathways vary. PAC–PolyDADMAC systems (e.g., P020100) tend to offer a more balanced removal of organic matter and suspended solids, whereas Fe-polymer formulations promote faster particle settling. This indicates that the hybrids provide different compositional strengths, allowing the selection of a formulation that best fits the characteristics of the wastewater being treated.

As a whole, the removal results confirm the expected performance hierarchy among the formulations rather than introducing major surprises or decisive differences for the environmental assessment. Consequently, the treatment efficiencies observed here served primarily as a verification step, rather than a key determinant in the overall sustainability ranking. From an environmental assessment perspective, this group therefore served as a performance confirmation layer rather than a key differentiator in sustainability ranking.

More pronounced contrasts reappeared in the Systemic & Long-Term Environmental Robustness dimension, which encompasses parameters related to persistence, residual toxicity, and polymer biodegradability. In this context, the conventional aluminum sulfate formulation (P040102) exhibited the highest residual metal concentrations in sludge—particularly for Al—indicating its greater tendency to generate metal-laden waste with limited reuse potential.

This result is mainly due to the much higher dosage required for the alum formulation (8000 mg/L) compared with the hybrid systems (2800 mg/L). Because such a large amount of aluminum is added, a greater portion inevitably ends up in the solid phase, increasing the residual metal load regardless of the coagulant's composition. Beyond these operational implications, the persistence of aluminum residues also carries broader environmental relevance. As outlined in Section 4.1.2.5, aluminum retained in sludge can become bioavailable under certain pH conditions, potentially affecting soil fertility and contributing to long-term ecological or even neurotoxic risks.

In contrast, the hybrid coagulants, operated at substantially lower doses, achieved effective coagulation with reduced residual metal accumulation, demonstrating a clear advantage in dosage efficiency and environmental load minimization. However, it is worth noting that the Fe-containing hybrids (P020200 and P020201) showed slightly higher total metal concentrations in sludge

compared to other hybrid formulations. This observation can be attributed to two factors: first, the deliberate inclusion of a small amount of $FeCl_3$ in their composition, and second, their enhanced ability to capture and retain heavy metals within the sludge phase rather than allowing their passage into the treated effluent. From an environmental standpoint, this behavior may even be considered beneficial, as it indicates improved immobilization of metals in the solid fraction, thereby reducing the risk of residual toxicity in the discharged water.

Beyond the behavior of metallic residues, the long-term environmental robustness of coagulant systems is also influenced by the fate of their organic constituents. In this regard, the degradability of polymer additives becomes a critical factor, as their persistence or breakdown potential determines the extent of long-term ecological impact. The polymer biodegradability criterion further distinguished the formulations. Systems containing only PolyDADMAC (BIOWIN 6 ≈ 0.31) showed low biodegradability because this type of cationic polymer is not easily broken down by microorganisms and tends to bind strongly to sludge solids. In contrast, formulations containing Polyamine (P010301 and P020201) exhibited higher predicted biodegradability (BIOWIN 6 ≈ 0.44/ 0.57), suggesting a lower risk of long-term accumulation in the environment. Although this parameter was not applicable to the conventional aluminum sulfate formulation (P040102) due to the absence of organic constituents, it provided an additional layer of differentiation among the hybrid systems.

While the inclusion of organic polymers markedly improves coagulation efficiency and overall treatment performance, it simultaneously introduces compounds with limited biodegradability, which may persist in the environment over longer timescales. Nevertheless, this limitation should be interpreted in context: both the concentration of these polymers within each formulation and the applied dosages in practice are relatively low, meaning their contribution to long-term environmental persistence remains minimal. Thus, the trade-off observed here reflects a balance between performance enhancement and environmental degradability. In a broader perspective, this finding points to a valuable direction for future work: designing next-generation hybrid coagulants that maintain strong treatment performance while offering greater biodegradability, helping align process improvements with long-term environmental compatibility.

Taken together, these group-level trends reveal that the environmental advantages of hybrid formulations are not uniform across all sustainability dimensions but are instead function-specific and composition-dependent. The entropy weighting structure indicates that the overall ranking is predominantly influenced by the chemical intensity of each formulation, whereas long-term robustness and sludge-related parameters act as secondary determinants. In practical terms, the

hybrids' superior performance primarily stems from their reduced coagulant dosage and lower residual toxicity, which together lessen the overall environmental burden. However, the specific polymer and metal compositions of each hybrid formulation further shape how these benefits persist over time—affecting factors such as sludge stability, residual metal mobility, and the biodegradability of organic additives.

At the criterion level, several parameters proved particularly influential in shaping the final ranking. Residual metal concentrations (Al, Fe, Cr) carried high entropy weights, revealing their strong discriminating capacity across formulations. The pH regulator requirement, represented through a binary code, demonstrated that most hybrid systems maintained optimal pH without external adjustment, further reducing secondary chemical consumption. The polymer biodegradability criterion was evaluated as a benefit-type parameter in line with the BIOWIN 6 outputs. Finally, the disposal compatibility index, derived from moisture, solids, and heavy metal content, confirmed that hybrid systems yield sludge more suitable for dewatering, composting, and energy recovery applications.

Overall, the findings illustrate that the environmental performance hierarchy among the six coagulants reflects a nuanced interplay between chemical efficiency, compositional design, and persistence-related characteristics. The conventional aluminum sulfate formulation imposes a substantially higher environmental burden, primarily due to its excessive dosage requirement and the consequent elevation in residual metal concentrations. In contrast, the hybrid coagulants collectively demonstrate superior sustainability outcomes; however, the extent and mechanism of this advantage vary with polymer type and metal composition. Polyamine-containing hybrids exhibit comparatively higher biodegradability and slightly improved long-term robustness, whereas PAC–PolyDADMAC–Fe systems achieve a more balanced environmental profile by simultaneously minimizing chemical consumption, residual metal accumulation, and overall toxicity potential.

In summary, the entropy–TOPSIS analysis confirms that optimizing coagulant composition—through careful polymer selection, controlled metal dosing, and balanced formulation design—can markedly enhance environmental performance without compromising treatment efficiency. The sustainability of a coagulation system therefore depends not solely on high removal rates but on achieving equilibrium between chemical efficiency, material persistence, and ecological safety. These findings underscore the need to integrate treatment performance with long-term environmental criteria, guiding the development of hybrid coagulants that unite process effectiveness with improved degradability and resource efficiency.

5. CONCLUSION AND RECOMMENDATIONS

The findings of this study indicate that hybrid coagulants incorporating organic polymers can offer promising results in the treatment of tannery wastewater. The investigated formulations achieved effective pollutant removal even at lower dosages compared to conventional metal salt coagulants. Notably, efficient treatment was achieved without requiring pH adjustment, which presents a significant operational advantage. To fully validate these results under large-scale conditions, further studies should investigate a broader spectrum of organic polymers, test different formulation ratios, and evaluate performance across diverse wastewater characteristics. Such efforts would provide a more comprehensive understanding of the applicability of hybrid systems in real industrial contexts.

In addition to removal performance, sludge-related outcomes highlight further economic and operational benefits. The reduction in sludge volume observed with hybrid systems can ease handling, lower disposal requirements, and reduce associated costs. Moreover, the reduced need for chemicals due to lower coagulant dosages may yield savings in storage, transport, and safety management. Nonetheless, detailed cost–benefit analyses and real-world economic assessments are still necessary to confirm these advantages.

From an environmental perspective, this study highlights that the benefits of hybrid coagulants extend far beyond conventional treatment efficiency metrics. The entropy–TOPSIS analysis clearly demonstrated that the key environmental gains arise from reduced coagulant dosage, lower residual metal concentrations, and the minimized need for pH correction—factors that collectively translate into tangible reductions in chemical burden and sludge generation. Moreover, by decreasing the total input of aluminum, the hybrid systems likely reduce the long-term environmental risks associated with residual metal accumulation in sludge, thereby lowering the potential for downstream ecological exposure. These outcomes position hybrid coagulants as a cleaner and more resource-efficient alternative within the broader context of sustainable wastewater management.

At the same time, the findings emphasize that environmental sustainability is not an inherent property of hybrid systems but rather a function of formulation design and material balance. While the inclusion of synthetic polymers enhances flocculation efficiency and reduces operational demands, their limited biodegradability introduces a mild trade-off in long-term persistence. Nonetheless, given their low dosage levels and minimal environmental concentrations, these

drawbacks remain secondary when compared to the clear reductions in chemical intensity and toxicity potential. Moving forward, advancing hybrid coagulant research toward more biodegradable, low-impact polymers—potentially derived from natural or green-chemistry-based sources—could further enhance the ecological compatibility of these systems. In this way, hybrid coagulants may evolve from an operational innovation into a cornerstone of sustainable water treatment, aligning process optimization with long-term environmental stewardship.

To more comprehensively evaluate the environmental sustainability of hybrid coagulants, future research should apply life cycle assessment (LCA). Such an approach would provide valuable insights into their environmental footprint from production to disposal, allow for a more balanced assessment of long-term impacts, and contribute to guiding potential regulatory developments.

This study was designed with the primary aim of moving beyond conventional approaches to develop treatment models that are both more efficient and more environmentally sustainable. In this context, the incorporation of organic polymers is presented as a purposeful design choice that enables higher performance, improved sludge outcomes and reduced chemical demand. Although certain considerations, such as the persistence of small polymer residues, merit attention, these are outweighed by the clear advantages demonstrated throughout the study. In this way, the results reinforce the overall value of hybrid coagulants as a robust and forward-looking alternative to conventional treatment methods. Future studies could further advance these systems by exploring more biodegradable alternatives, thereby enhancing alignment with green chemistry principles without compromising performance.

In conclusion, this study has demonstrated that hybrid coagulant systems represent a promising alternative to conventional treatment methods. Beyond their strong removal performance, operational benefits, and environmental advantages, the findings highlight the broader potential of developing more efficient and environmentally responsible materials that could surpass traditional approaches. Importantly, such research carries direct relevance to real-world applications, where adopting alternative methods could yield substantial environmental benefits. For this reason, it is essential to expand research efforts and further explore hybrid systems, thereby paving the way for innovative and sustainable solutions in wastewater treatment.

REFERENCES

Abujazar, M. S. S., Karaağaç, S. U., Abu Amr, S. S., Alazaiza, M. Y. D., Bashir, M. JK., 2022. Recent advancement in the application of hybrid coagulants in coagulation-flocculation of wastewater: A review. Journal of Cleaner Production, 345, 131133. https://doi.org/10.1016/j.jclepro.2022.131133

Ahmad, A., Kurniawan, S. B., Ahmad, J., Alias, J., Marsidi, N., Said, N. S. M., Yusof, A. S. M., Buhari, J., Ramli, N. N., Rahim, N. F. M., Abdullah, S. R. S., Othman, A. R., Hasan, H. A., 2022. Dosage-based application versus ratio-based approach for metal- and plant-based coagulants in wastewater treatment: Merits, limitations, and applicability. Journal of Cleaner Production, 334, 130245. https://doi.org/10.1016/j.jclepro.2021.130245

Ahmed, T., Ahsan, A., Rahman, H., Nahian, T. K., Antar, R. H., Hasan, A., Karim, M. R., Shafiquzzaman, M., Imteaz, M., 2024. Comprehensive study on the selection and performance of the best electrode pair for electrocoagulation of textile wastewater using multi-criteria decision-making methods (TOPSIS, VIKOR and PROMETHEE II). Journal of Environmental Management, 363, 121337–121337. https://doi.org/10.1016/j.jenvman.2024.121337

Ahmad, A., Wong, S., Teng, T. T., Zuhairi, A., 2008. Improvement of alum and PACl coagulation by polyacrylamides (PAMs) for the treatment of pulp and paper mill wastewater. Chemical Engineering Journal, 137(3), 510–517. https://doi.org/10.1016/j.cej.2007.03.088

Ahmed, M., and Kotb, A. E.-A., 1999. Pollution Abatment at the Beamhouse of El-Nasr Tanning Company. Journal of High Institute of Public Health, 29(4), 659–670. https://doi.org/10.21608/jhiph.1999.324840

AKKİM, n.d.-a. Demir 3 Klorür TDS. Retrieved November 15, 2025, from https://akkim.com.tr/wp-content/uploads/2021/01/Demir-3-Klorur-TDS.pdf

AKKİM, n.d.-b. Polialüminyum Klorür TDS. Retrieved November 15, 2025, from https://akkim.com.tr/wp-content/uploads/2021/01/Polialuminyum-Klorur-TDS.pdf

Albright, V. C., and Chai, Y., 2021. Knowledge Gaps in Polymer Biodegradation Research. Environmental Science & Technology, 55(17), 11476–11488. https://doi.org/10.1021/acs.est.1c00994

Andreoli, C. V., von Sperling, M., Fernandes, F., 2015. Sludge Treatment and Disposal. Water Intelligence Online, 6(0), 9781780402130-9781780402130. https://doi.org/10.2166/9781780402130

APHA, AWWA, WEF, 2017. Standard Methods for the Examination of Water and Wastewater (23rd ed.). American Public Health Association.

Ayoub, G. M., Hamzeh, A., Al-Hindi, M., 2012. The Impact of Process Sequences on Pollutant Removal Efficiencies in Tannery Wastewater Treatment. Water, Air, & Soil Pollution, 224(1). https://doi.org/10.1007/s11270-012-1379-y

Azli, F., and Azoddein, A., 2020. Removal of chemical oxygen demand (COD) and total suspended solid (TSS) using electrocoagulation process for treatment of oleochemical wastewater. IOP Conference Series Materials Science and Engineering, 736(2), 022104–022104. https://doi.org/10.1088/1757-899x/736/2/022104

Babatunde, A. O., and Zhao, Y. Q., 2010. Leachability and leaching patterns from aluminium-based water treatment residual used as media in laboratory-scale engineered wetlands. Environmental Science and Pollution Research, 17(7), 1314–1322. https://doi.org/10.1007/s11356-010-0311-5

Baird, R., & Bridgewater, L. (2017). *Standard methods for the examination of water and wastewater.* 23rd edition. American Public Health Association.

Bajza, Z., Hitrec, P., and Muzic, M., 2004. Influence of different concentrations of Al2(SO4)3 and anionic polyelectrolytes on tannery wastewater flocculation. Desalination, 171, 13–20. https://doi.org/10.1016/j.desal.2004.04.003

Balbinoti, J. R., dos Santos Junior, R. E., de Sousa, L. B. F., de Jesus Bassetti, F., Balbinoti, T. C. V., de Matos Jorge, L. M., Matos Jorge, R. M., 2023. Plant-based coagulants for food industry wastewater treatment. Journal of Water Process Engineering, 52, 103525–103525. https://doi.org/10.1016/j.jwpe.2023.103525

Balcı, D. D., Dilek, F. B., Ünlü, K., 2016. Sektörel Atık Kılavuzları - Deri Sektörü. In Çevre Şehir İklim Kütüphanesi. Türkiye Cumhuriyeti Çevre ve Şehircilik Bakanlığı. https://cevresehiriklimkutuphanesi.csb.gov.tr/Books/Book/6c91bba2-4a78-4c43-aba3-d7ccbd07c0f2

Besley, C. H., and Birch, G. F., 2019. Deepwater ocean outfalls: A sustainable solution for sewage discharge for mega-coastal cities (Sydney, Australia): A synthesis. Marine Pollution Bulletin, 145, 675–677. https://doi.org/10.1016/j.marpolbul.2019.06.010

Bhamidipati, S. H., Vadlamudi, D. P., Moka, S., 2021. Polymers as Coagulants for Wastewater Treatment. In Advanced Materials and Technologies for Wastewater Treatment. https://doi.org/10.1201/9781003138303-5

Boethling, R. S., Lynch, D. G., Thom, G. C., 2003. Predicting ready biodegradability of premanufacture notice chemicals. Environmental Toxicology and Chemistry, 22(4), 837–844. https://doi.org/10.1002/etc.5620220423

Boroushaki, S., 2017. Entropy-Based Weights for MultiCriteria Spatial Decision-Making. Yearbook of the Association of Pacific Coast Geographers, 79(1), 168–187. https://doi.org/10.1353/pcg.2017.0009

Braun, O., Coquery, C., Kieffer, J., Blondel, F., Favero, C., Besset, C., Mesnager, J., Voelker, F., Delorme, C., Matioszek, D., 2021. Spotlight on the Life Cycle of Acrylamide-Based Polymers Supporting Reductions in Environmental Footprint: Review and Recent Advances. Molecules, 27(1), 42. https://doi.org/10.3390/molecules27010042

Cainglet, A., Kujala, K., Liimatainen, M., Prokkola, H., Piippo, S., Postila, H., Ronkanen, A.-K., Heiderscheidt, E., 2023. The influence of coagulant type on the biological treatment of sewage sludge. Science of the Total Environment, 869, 161706. https://doi.org/10.1016/j.scitotenv.2023.161706

Cao, B., Zhang, W., Wang, Q., Huang, Y., Meng, C., Wang, D., 2016. Wastewater sludge dewaterability enhancement using hydroxyl aluminum conditioning: Role of aluminum speciation. Water Research, 105, 615–624. https://doi.org/10.1016/j.watres.2016.09.016

Carlos, N. B., and Noroña, M. I., 2021. Selection of a Sustainable Municipal Wastewater Treatment Technology: A Multi-Criteria Decision Analysis Approach Using AHP and TOPSIS with Fuzzy Sets. Proceedings of the International Conference on Industrial Engineering and Operations Management. https://doi.org/10.46254/an11.20210885

Çeçen, F., and Gül, G., 2021. Biodegradation of five pharmaceuticals: estimation by predictive models and comparison with activated sludge data. International Journal of Environmental Science and Technology, 18(2), 327–340. https://doi.org/10.1007/s13762-020-02820-y

Çeçen, F., and Kılıç, B., 2023. Review of experimental biodegradation data on pharmaceuticals and comparison with predictive BIOWIN models. Journal of Environmental Management, 344, 118310–118310. https://doi.org/10.1016/j.jenvman.2023.118310

Chowdhury, M., Mostafa, M. G., Biswas, T. K., Saha, A. K., 2013. Treatment of leather industrial effluents by filtration and coagulation processes. Water Resources and Industry, 3, 11–22. https://doi.org/10.1016/j.wri.2013.05.002

Cheng, Y.-C., Wang, C.-P., Liu, K.-Y., Pan, S.-Y., 2024. Towards sustainable management of polyacrylamide in soil-water environment: Occurrence, degradation, and risk. The Science of the Total Environment, 926, 171587–171587. https://doi.org/10.1016/j.scitotenv.2024.171587

Comber, S. D. W., Gardner, M. J., Ellor, B., 2021. Effects of iron dosing used for phosphorus removal at wastewater treatment works; impacts on forms of phosphorus discharged and secondary effects on concentrations and fate of other contaminants. Science of the Total Environment, 767, 145434. https://doi.org/10.1016/j.scitotenv.2021.145434

Çorlu Deri OSB., 2025. Expert Insight from Facility Engineers during Site Visit [Personal communication].

Çorlu Deri İhtisas ve Karma Organize Sanayi Bölge Müdürlüğü., n.d. Atıksu Arıtma Tesisi Faaliyetleri İş Akım Şeması ve Proses Özetleri . Çorlu Deri İhtisas ve Karma Organize Sanayi Bölge Müdürlüğü Atıksu Arıtma Tesisi.

Çorlu Deri ve Karma OSB., n.d. Fotoğraf Galerisi | Çorlu Deri Karma Organize Sanayi Bölgesi. Çorlu Deri ve Karma OSB. Retrieved July 1, 2025, from https://www.corluderiosb.org.tr/fotograf-galerisi

Čuláková, M., Vilčeková, S., Katunská, J., Krídlová Burdová, E., 2013. Multicriteria Decision Analysis of Material Selection of High Energy Performance Residential Building. Sspjce, 8(2), 103–114. https://doi.org/10.2478/sspjce-2013-0023

Dayarathne, H. N. P., Angove, M. J., Aryal, R., Abuel-Naga, H., Mainali, B., 2021. Removal of natural organic matter from source water: Review on coagulants, dual coagulation, alternative coagulants, and mechanisms. Journal of Water Process Engineering, 40, 101820. https://doi.org/10.1016/j.jwpe.2020.101820

Devanathan, R., Babu, R. S., Prasanna, K., 2024. A conceptual review on performance and environmental impact of current and ensuing coagulants used in treatment facilities. International Journal of Environmental Science and Technology, 21(15), 9799–9818. https://doi.org/10.1007/s13762-024-05659-9

Dubber, D., and Gray, N. F., 2010. Replacement of chemical oxygen demand (COD) with total organic carbon (TOC) for monitoring wastewater treatment performance to minimize disposal of toxic analytical waste. Journal of Environmental Science and Health, Part A, 45(12), 1595–1600. https://doi.org/10.1080/10934529.2010.506116

Dubcová, M., Škultétyová, I., Galbová, K., Trošanová, M., 2017. POSSIBILITIES OF SLUDGE RECOVERY FROM WASTEWATER TREATMENT PLANT. Czech Journal of Civil Engineering, 3(2), 35–39. https://doi.org/10.51704/cjce.2017.vol3.iss2.pp35-39

Dunn, A. S., Campbell, P. G., Marra, K. G., 2001. The influence of polymer blend composition on the degradation of polymer/hydroxyapatite biomaterials. Journal of Materials Science. Materials in Medicine, 12(8), 673–677. https://doi.org/10.1023/a:1011204106373

ECHA, 2020. Chemicals Strategy for Sustainability - ECHA. European Chemical Agency. https://www.echa.europa.eu/web/guest/hot-topics/chemicals-strategy-for-sustainability

Eikelboom, M., do Carmo Precci Lopes, A., Silva, C. M., de Avila Rodrigues, F., Zanuncio, A. J. V., Zanuncio, J. C., 2018. A multi-criteria decision analysis of management alternatives for anaerobically digested kraft pulp mill sludge. PloS One, 13(1), e0188732–e0188732. https://doi.org/10.1371/journal.pone.0188732

El-taweel, R. M., Mohamed, N., Alrefaey, K. A., Husien, S., Abdel-Aziz, A. B., Salim, A. I., Mostafa, N. G., Said, L. A., Fahim, I. S., Radwan, A. G., 2023. A review of coagulation explaining its definition, mechanism, coagulant types, and optimization models; RSM, and ANN. Current Research in Green and Sustainable Chemistry, 6, 100358. https://doi.org/10.1016/j.crgsc.2023.100358

Ergül, H. A., 2016. Evaluation of seasonal physicochemical conditions and chlorophyll-a concentrations in Izmit Bay , Marmara Sea. J. Black Sea - Mediterranean Environment , 22(3), 201–217.

Ferla, G., Mura, B., Falasco, S., Caputo, P., Matarazzo, A., 2024. Multi-Criteria Decision Analysis (MCDA) for sustainability assessment in food sector. A systematic literature review on methods, indicators and tools. Science of the Total Environment, 946, 174235. https://doi.org/10.1016/j.scitotenv.2024.174235

Freitas, T. K. F. S., Almeida, C. A., Manholer, D. D., Geraldino, H. C. L., de Souza, M. T. F., Garcia, J. C., 2017. Review of Utilization Plant-Based Coagulants as Alternatives to Textile Wastewater Treatment. Textile Science and Clothing Technology, 27–79. https://doi.org/10.1007/978-981-10-4780-0_2

Gajbhiye, T., 2020. Review on Treatment of Dyes in Wastewater Using Organic Coagulants. International Research Journal of Modernization in Engineering Technology and Science, 02(11), 308–319.

Ginisty, P., Guei, F., Girault, R., Tosoni, J., Olivier, J., Vaxelaire, J., 2013. DRYNESS LIMIT: A USEFUL PARAMETER TO ASSESS SLUDGE DEWATERING. FILTECH 2013, Wiesbaden – Germany.

Guillén, D., Ginebreda, A., Petrovic, M., Barceló, D., Darbra, R. M., Rydin, S., 2011. Additives in the Leather Industry. The Handbook of Environmental Chemistry, 35–55. https://doi.org/10.1007/698_2011_105

Gungor, K., Karakaya, N., Gunes, Y., Yatkin, S., Evrendilek, F., 2015. Utilizing aluminum etching wastewater for tannery wastewater coagulation: performance and feasibility. Desalination and Water Treatment, 57(6), 2413–2421. https://doi.org/10.1080/19443994.2015.1007489

Guo, J., Chen, C., Jiang, S., Zhou, Y., 2018. Feasibility and Mechanism of Combined Conditioning with Coagulant and Flocculant To Enhance Sludge Dewatering. ACS Sustainable Chemistry & Engineering, 6(8), 10758–10765. https://doi.org/10.1021/acssuschemeng.8b02086

Ireland Environmental Protection Agency, 2002. Water treatment manuals : coagulation, flocculation & clarification. E.P.A.

Hassanpour, M., Cai, G., Cooper, T., Wang, Q., O'Hara, I. M., Zhang, Z., 2022. Triple action of FeCl3-assisted hydrothermal treatment of digested sludge for deep dewatering. The Science of the Total Environment, 848, 157727–157727. https://doi.org/10.1016/j.scitotenv.2022.157727

Hilmi, F. M., Betta, T., Handayani, S. D., Priutama, Y. E., Rahmalia, I., Sofiyah, E. S., Sarwono, A., Koko, W., 2022. Selection of Ammonia And TSS Removal in Effluent Water from Duri Kosambi IPLT Using Analytic Hierarchy Process (AHP). Jurnal Arsip Rekayasa Sipil Dan Perencanaan, 5(1), 1–7. https://doi.org/10.24815/jarsp.v5i1.24481

Huang, J. J., and Tzeng, G. H., 2011. Multiple Attribute Decision Making: methods and applications (pp. 69–79). CRC Press.

Jeong, D. H., Choi, I. C., Cho, Y., Ahn, K., Chung, H. M., Kwon, O., Park, H., Shin, H., Hur, J., 2014. Characteristics of TOC in effluent discharge from public sewage treatment works in Korea. Journal of the Korean Society of Water and Wastewater, 28(6), 657–668. https://doi.org/10.11001/jksww.2014.28.6.657

Joaquin, A. A., and Nirmala, G., 2019. Statistical modeling and process optimization of coagulation-flocculation for treatment of municipal wastewater. DESALINATION and WATER TREATMENT, 157, 90–99. https://doi.org/10.5004/dwt.2019.24162

Kasal, K. İ., 2000. Deri Endüstrisi Atıksularından Krom (III) Geri Kazanımı [MSc Thesis].

Kacprzak, M., Neczaj, E., Fijałkowski, K., Grobelak, A., Grosser, A., Worwag, M., Rorat, A., Brattebo, H., Almås, Å., Singh, B. R., 2017. Sewage sludge disposal strategies for sustainable development. Environmental Research, 156, 39–46. https://doi.org/10.1016/j.envres.2017.03.010

Kesarwani, P., Jahan, S., Kesarwani, K., 2015. A Review on Leather Processing. International Journal of Applied Research, 1, 977–982.

Kim, J. R., Thelusmond, J.-R., Albright, V. C., Chai, Y., 2023. Exploring structure-activity relationships for polymer biodegradability by microorganisms. Science of the Total Environment, 890, 164338–164338. https://doi.org/10.1016/j.scitotenv.2023.164338

Kluczka, J., Zołotajkin, M., Ciba, J., Staroń, M., 2017. Assessment of aluminum bioavailability in alum sludge for agricultural utilization. Environmental Monitoring and Assessment, 189(8). https://doi.org/10.1007/s10661-017-6133-x

Kolb, M., Bahadir, M., Teichgräber, B., 2017. Determination of chemical oxygen demand (COD) using an alternative wet chemical method free of mercury and dichromate. Water Research, 122, 645–654. https://doi.org/10.1016/j.watres.2017.06.034

Kolçak, S., 1999. Atıksulardan Kimyasal Çöktürme ile Azot Giderimi ve Deri Endüstrisinde Bir Uygulama [MSc Thesis].

Kumar, M., Raj, N., Singh, R. R., 2023. Ranking Indian Companies on Sustainability Disclosures Using the GRI-G4 Framework and MCDM Techniques. International Journal of Sustainable Development and Planning, 18(9), 2791–2799. https://doi.org/10.18280/ijsdp.180917

Küçükpelvan, H., Can Yarımtepe, C., Ayman Öz, N., 2017. Deri Atıksuyunun Arıtım Metotları. Çanakkale Onsekiz Mart Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 3(1), 59–96. https://doi.org/10.28979/comufbed.317004

Kweinor Tetteh, E., and Rathilal, S., 2019. Application of Organic Coagulants in Water and Wastewater Treatment. Organic Polymers. https://doi.org/10.5772/intechopen.84556

Lavagnolo, M. C., Poli, V., Zampini, A. M., Grossule, V., 2023. Biodegradability of bioplastics in different aquatic environments: A systematic review. Journal of Environmental Sciences, 142. https://doi.org/10.1016/j.jes.2023.06.013

Laxmi, V., and Kaushik, G., 2020. Toxicity of Hexavalent Chromium in Environment, Health Threats, and Its Bioremediation and Detoxification from Tannery Wastewater for Environmental Safety. Bioremediation of Industrial Waste for Environmental Safety, 223–243. https://doi.org/10.1007/978-981-13-1891-7_11

Lee, E., Min, K. J., Choi, H., Park, K. Y., 2023. Impact of dewatering inorganic coagulants on anaerobic digestion treating food waste leachate. Bioresource Technology, 393, 130136–130136. https://doi.org/10.1016/j.biortech.2023.130136

Lees, E. J., Noble, B., Hewitt, R., Parsons, S. A., 2001. The Impact of Residual Coagulant on the Respiration Rate and Sludge Characteristics of an Activated Microbial Biomass. Process Safety and Environmental Protection, 79(5), 283–290. https://doi.org/10.1205/095758201753189721

Lee, K. E., Morad, N., Teng, T. T., Poh, B. T., 2012. Development, characterization and the application of hybrid materials in coagulation/flocculation of wastewater: A review. Chemical Engineering Journal, 203, 370–386. https://doi.org/10.1016/j.cej.2012.06.109

Li, M., Sun, H., Singh, V., Zhou, Y., Ma, M., 2019. Agricultural Water Resources Management Using Maximum Entropy and Entropy-Weight-Based TOPSIS Methods. Entropy, 21(4), 364. https://doi.org/10.3390/e21040364

Lim, S., 2016. EPI Suite: A Fascinate Predictive Tool for Estimating the Fates of Organic Contaminants. Journal of Bioremediation & Biodegradation. https://doi.org/10.4172/2155-6199.1000e171

Lin, W., Xu, Y., Wu, S., Qiu, Z., Yao, H., Wang, Y., Wang, Y., 2023. Oxygen-rich and moderate/low temperature calcination treatment of chromium containing sludge for high efficient Cr recovery and toxicity reduction. Surfaces and Interfaces, 43, 103537–103537. https://doi.org/10.1016/j.surfin.2023.103537

Liu, Y., and Ren, J., 2022. Developing a sustainability-oriented multi-criteria game theoretical decision analysis framework: A case study of sludge management. Journal of Cleaner Production, 354, 131807. https://doi.org/10.1016/j.jclepro.2022.131807

Liu, Y., Ren, J., Man, Y., Lin, R., Lee, C. K. M., Ji, P., 2020. Prioritization of sludge-to-energy technologies under multi-data condition based on multi-criteria decision-making analysis. Journal of Cleaner Production, 273, 123082. https://doi.org/10.1016/j.jclepro.2020.123082

Loganathan, P., Kandasamy, J., Ratnaweera, H., Vigneswaran, S., 2024. Use of wastewater alum-coagulation sludge as a phosphorus fertiliser – a mini review. Environmental Science and Pollution Research, 31(12), 18412–18421. https://doi.org/10.1007/s11356-024-32497-6

London, R. L., Glüge, J., Scheringer, M., 2024. Multiple-Criteria Decision Analysis for Assessments of Chemical Alternatives (MCDA-ACA). Environmental Science & Technology, 58(43), 19315–19324. https://doi.org/10.1021/acs.est.4c03980

Malaviya, P., and Singh, A., 2011. Physicochemical Technologies for Remediation of Chromium-Containing Waters and Wastewaters. Critical Reviews in Environmental Science and Technology, 41(12), 1111–1172. https://doi.org/10.1080/10643380903392817

Mandal, T., Dasgupta, D., Mandal, S., Datta, S., 2010. Treatment of leather industry wastewater by aerobic biological and Fenton oxidation process. Journal of Hazardous Materials, 180(1-3), 204–211. https://doi.org/10.1016/j.jhazmat.2010.04.014

May Asit, 2020. Güvenlik Bilgi Formu Alüminyum Sülfat (Katı). https://www.mayasit.com.tr/pdf/aluminyum-sullfat-kati.pdf

Meles, D. B., 2014. Review of Methods of Wastewater Reuse to Diminish Non-Biodegradable Organic Compounds.

Mella, B., Barcellos, B. S. de C., da Silva Costa, D. E., Gutterres, M., 2017. Treatment of Leather Dyeing Wastewater with Associated Process of Coagulation-Flocculation/Adsorption/Ozonation. Ozone: Science & Engineering, 40(2), 133–140. https://doi.org/10.1080/01919512.2017.1346464

Ming-min, G., 2013. Chloride Ion Content in Wastewaters of Leather Making Processes and Analysis of its Origin. Leather Science and Engineering.

Montoya, X. C., Thompson, W. A., Smith, C. M., Wilson, J. M., Vijayan, M. M., 2024. Exposure to Total Suspended Solids (TSS) Impacts Gill Structure and Function in Adult Zebrafish. Bulletin of Environmental Contamination and Toxicology, 113(2). https://doi.org/10.1007/s00128-024-03922-w

Muniz, G. L., Pereira, M. dos S., Borges, A. C., 2021. Dairy Wastewater Treatment with Organic Coagulants: A Comparison of Factorial Designs. Water, 13(16), 2240. https://doi.org/10.3390/w13162240

Naumczyk, J., and Rusiniak, M., 2005. Physicochemical and Chemical Purification of Tannery Wastewaters. Polish Journal of Environmental Studies, 14(6), 789–797.

OECD, 1992. OECD Guidelines for the Testing of Chemicals, Section 3. OECD.

Olukowi, O. M., Xie, Y., Zhou, Z., Adebayo, I. O., Zhang, Y., 2022. Performance improvement and mechanism of composite PAC/PDMDAAC coagulant via enhanced coagulation coupled with rapid sand filtration in the treatment of micro-polluted surface water. Journal of Environmental Chemical Engineering, 10(5), 108450. https://doi.org/10.1016/j.jece.2022.108450

Omran, I. I., Al-Saati, N. H., Al-Saati, H. H., Hashim, K. S., Al-Saati, Z. N., 2021. Sustainability assessment of wastewater treatment techniques in urban areas of Iraq using multi-criteria decision analysis (MCDA). Water Practice and Technology, 16(2), 648–660. https://doi.org/10.2166/wpt.2021.013

Owodunni, A. A., and Ismail, S., 2021. Revolutionary technique for sustainable plant-based green coagulants in industrial wastewater treatment—A review. Journal of Water Process Engineering, 42, 102096. https://doi.org/10.1016/j.jwpe.2021.102096

Padhye, L. P., Luzinova, Y., Cho, M., Mizaikoff, B., Kim, J. H., Huang, C.-H., 2011. PolyDADMAC and dimethylamine as precursors of N-nitrosodimethylamine during ozonation: reaction kinetics and mechanisms. Environmental Science & Technology, 45(10), 4353–4359. https://doi.org/10.1021/es104255e

Park, S. H., Wei, S., Mizaikoff, B., Taylor, A. E., Favero, C., Huang, C. H., 2009. Degradation of Amine-Based Water Treatment Polymers during Chloramination as N-Nitrosodimethylamine (NDMA) Precursors. Environmental Science & Technology, 43(5), 1360–1366. https://doi.org/10.1021/es802732z

Posthumus, R., Traas, T. P., Peijnenburg, W. J. G. M., Hulzebos, E. M., 2005. External validation of EPIWIN biodegradation models. SAR and QSAR in Environmental Research, 16(1-2), 135–148. https://doi.org/10.1080/10629360412331319899

Pradel, M., Reverdy, A. L., Richard, M., Chabat, L., 2014. Environmental impacts of sewage sludge treatment and disposal routes: A Life Cycle Assessment perspective. 4th European Conference on Sludge Management, İzmir, Türkiye.

Radović, S., Sekulic, M. T., Agarski, B., Pap, S., Vukelic, D., Budak, I., Prodanovic, J., 2022. Life cycle assessment of new bio-based coagulant production for sustainable wastewater treatment. International Journal of Environmental Science and Technology, 20(7), 7433–7462. https://doi.org/10.1007/s13762-022-04440-0

Rebosura, M., Salehin, S., Pikaar, I., Sun, X., Keller, J., Sharma, K., Yuan, Z., 2018. A comprehensive laboratory assessment of the effects of sewer-dosed iron salts on wastewater treatment processes. Water Research, 146, 109–117. https://doi.org/10.1016/j.watres.2018.09.021

Rizzo, L., Belgiorno, V., Gallo, M., Meriç, S., 2005. Removal of THM precursors from a high-alkaline surface water by enhanced coagulation and behaviour of THMFP toxicity on D. magna. Desalination, 176(1-3), 177–188. https://doi.org/10.1016/j.desal.2004.10.020

Rodríguez, A., Ortega, F. B., Concepción, R., 2013. A method for the selection of customized equipment suppliers. Expert Systems with Applications, 40(4), 1170–1176. https://doi.org/10.1016/j.eswa.2012.08.021

Rong, H., Gao, B., Li, J., Zhang, B., Sun, S., Wang, Y., Yue, Q., Li, Q., 2013. Floc characterization and membrane fouling of polyferric–polymer dual/composite coagulants in coagulation/ultrafiltration hybrid process. Journal of Colloid and Interface Science, 412, 39–45. https://doi.org/10.1016/j.jcis.2013.09.013

Rossi, L., Krejci, V., Rauch, W., Kreikenbaum, S., Fankhauser, R., Gujer, W., 2005. Stochastic modeling of total suspended solids (TSS) in urban areas during rain events. Water Research, 39(17), 4188–4196. https://doi.org/10.1016/j.watres.2005.07.041

Roszkowska, E., 2011. Multi-Criteria Decision-Making Models by Applying the TOPSIS Method to Crisp and Interval Data. 200–230.

Sarkar, M., 2023. Light-responsive biodegradation of wastewater pollutants: new developments and potential perspectives. Journal of Hazardous Materials Advances, 100281. https://doi.org/10.1016/j.hazadv.2023.100281

Scaffaro, R., and Botta, L., 2013. Degradation Behavior of Nanocomposite Polymer Blends. Elsevier EBooks, 423–447. https://doi.org/10.1016/b978-1-4557-3159-6.00012-2

Shandong Jiahua Water Treatment Technology Co., Ltd., 2025. Chemical Pac 30% Liquid Chemicals For Waste Water Treatment. Jiahuapac.com. https://www.jiahuapac.com/product/chemical-pac-30-liquid-chemicals-for-waste-water-treatment

Sharma, T., Kumar, A., Pant, S., Kotecha, K., 2023. Wastewater Treatment and Multi-Criteria Decision-Making Methods: A Review. IEEE Access, 11, 143704–143720. https://doi.org/10.1109/access.2023.3343150

Shegani, G., 2014. Treatment of Tannery Effluents by the Process of Coagulation. World Academy of Science, Engineering and TechnologyInternational Journal of Environmental and Ecological Engineering, 8(4), 240–244. https://publications.waset.org/9997910/pdf

Shirafkan, A., Nowee, S. M., Ramezanian, N., Etemadi, M. M., 2016. Hybrid coagulation/ozonation treatment of pharmaceutical wastewater using ferric chloride, polyaluminum chloride and ozone. International Journal of Environmental Science and Technology, 13(6), 1443–1452. https://doi.org/10.1007/s13762-016-0965-8

Shokri, A., Soleimani, F., Fard, M. S., 2022. The removal of COD in industrial wastewater by electro-persulfate process using central composite design. Chemical Papers, 76(11), 7133–7145. https://doi.org/10.1007/s11696-022-02370-2

Silva, C., Saldanha Matos, J., Rosa, M. J., 2016. Performance indicators and indices of sludge management in urban wastewater treatment plants. Journal of Environmental Management, 184, 307–317. https://doi.org/10.1016/j.jenvman.2016.09.056

Simanjuntak, N. A. M. B., Zahra, N. L., Suryawan, I. W. K., 2022. Decision Making for Biological Tofu Wastewater Treatment to Improve Quality Wastewater Treatment Plant (WWTP) Using Analytical Hierarcy Process (AHP). Jurnal Riset Teknologi Pencegahan Pencemaran Industri, 13(1), 20–34. https://doi.org/10.21771/jrtppi.2022.v13.no1.p20-34

Singh, I. B., and Singh, D. R., 2001. Hexavalent chromium removal using iron bearing industrial sludges. Indian Journal of Chemical Technology, 8, 487–495.

SNF Floerger Kimya San. ve Tic. Ltd. Şti., 2025. FLOPAM AN 934 SH TDS. SNF Floerger Kimya San. ve Tic. Ltd. Şti.

Starodoubtsev, S. G., Lyubimov, A. A., Khokhlov, A. R., 2003. Interaction of Sodium Poly(2-acrylamide-2-methyl-1-propanesulfonate) Linear Polymer and Gel with Metal Salts. The Journal of Physical Chemistry B, 107(44), 12206–12211. https://doi.org/10.1021/jp027011u

Strotmann, U. J., Schwarz, H., Pagga, U., 1995. The combined CO2/DOC test - a new method to determine the biodegradability of organic compounds. Chemosphere, 30(3), 525–538. https://doi.org/10.1016/0045-6535(94)00415-q

Swartz, C. D., Jackson-Moss, C., Rowswell, R. A., Mpofu, A. B., Welz, P. J., 2017. Water and Wastewater Management in Tanning and Leather Finishing Industry. Water Research Commission.

Tan, J., Huang, Y., Chi, B., Xiong, Z., Zhou, W., Yang, Z., Zhou, K., Ruan, X., Duan, X., Wang, M., Zhang, J., 2024. Comparative study of iron and aluminium coagulants in conditioning sludge: sludge dewatering performance, physicochemical properties, and risk of heavy metal migration. Journal of Environmental Chemical Engineering, 113168–113168. https://doi.org/10.1016/j.jece.2024.113168

Taşeli, B. K., 2020. Comparative Life Cycle Assessment of Sewage Sludge (Biosolid) Management Options. IntechOpen EBooks. https://doi.org/10.5772/intechopen.91190

Türkeri, E., and İşinibilir, M., 2024. Seasonal Zooplankton Distribution and Species Composition in the Eastern Sea of Marmara. Aquatic Sciences and Engineering, 0(0). https://doi.org/10.26650/ase20241433561

Türkiye Cumhuriyeti Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, (2004, December 31). Su Kirliliği Kontrol Yönetmeliği. https://mevzuat.gov.tr/mevzuat?MevzuatNo=7221&MevzuatTur=7&MevzuatTertip=5

US EPA, 1994. Method 200.7: Determination of Metals and Trace Elements in Water and Wastes by ICP-OES.

US EPA, 1994b. Method 200.8: Determination of Trace Elements in Waters and Wastes by ICP-MS.

US EPA, 2000. Emergency Planning and Community Right-To-Know Act Section 313 Reporting Guidance for the Leather Tanning and Finishing Industry. United States Environmental Protection Agency.

US EPA, 2015. EPI Suite™-Estimation Program Interface | US EPA. https://www.epa.gov/tsca-screening-tools/epi-suitetm-estimation-program-interface

UNIDO, 2011. Introduction to Treatment of Tannery Effluents. United Nations Industrial Development Organization.

Vizade, E., 2025. Biodegradation Testing Strategies in the Framework of REACH & CLP Regulations. https://bluefrogscientific.com/chemical-regulatory-news-and-views/biodegradation-testing-strategies-framework-reach-clp

Wang, C., Zhu, G., Ren, B., Zhang, P., Hursthouse, A., 2018. A cationic polymer enhanced PAC for the removal of dissolved aquatic organic carbon and organic nitrogen from surface waters. The Canadian Journal of Chemical Engineering, 97(4), 955–966. https://doi.org/10.1002/cjce.23234

Wang, D., Zheng, Y., Deng, Q., Liu, X., 2023. Water-Soluble Synthetic Polymers: Their Environmental Emission Relevant Usage, Transport and Transformation, Persistence, and Toxicity. Environmental Science & Technology, 57(16), 6387–6402. https://doi.org/10.1021/acs.est.2c09178

Wang, P., Ding, S., Xiao, R., An, G., Fang, C., Chu, W., 2021. Enhanced coagulation for mitigation of disinfection by-product precursors: A review. Advances in Colloid and Interface Science, 296, 102518. https://doi.org/10.1016/j.cis.2021.102518

Wang, T. C., and Lee, H. D., 2009. Developing a fuzzy TOPSIS approach based on subjective weights and objective weights. Expert Systems with Applications, 36(5), 8980–8985. https://doi.org/10.1016/j.eswa.2008.11.035

Wang, X., Zhang, Z., Yang, X., Wang, Y., Li, Y., Zhu, T., Zhao, Y., Ni, B.-J., Liu, Y., 2024. Interaction of poly dimethyl diallyl ammonium chloride with sludge components: Anaerobic digestion performance and adaptive changes of anaerobic microbes. Water Research, 266, 122368–122368. https://doi.org/10.1016/j.watres.2024.122368

Wang, Z., Wei, X., Yang, J., Suo, J., Chen, J., Liu, X., Zhao, X., 2016. Chronic exposure to aluminum and risk of Alzheimer's disease: A meta-analysis. Neuroscience Letters, 610, 200–206. https://doi.org/10.1016/j.neulet.2015.11.014

Wuxi Lansen Chemicals Co., Ltd., 2023a. China Polyamine Manufacturers and Suppliers | Lansen. Https://Www.lansenchems.com/. https://www.lansenchems.com/factory-price-polyamine-water-treatment-coagulant-cationic-dyefixing-agent-product/

Wuxi Lansen Chemicals Co., Ltd., 2023b. China Polydadmac Manufacturers and Suppliers | Lansen. Https://Www.lansenchems.com/. https://www.lansenchems.com/wastewater-treatment-color-removal-polydadmac-low-dosage-guarantees-fast-flocculation-product/

Yahya, M. N., Gökçekuş, H., Uzun Ozsahin, D., Uzun, B., 2020. Evaluation of wastewater treatment technologies using TOPSIS. Desalination and Water Treatment, 177, 416–422. https://doi.org/10.5004/dwt.2020.25172

Young, S. M., Kumara, A. M. I. U., Kattange, K. G. R. D. H., Amaraweera, T. H. N. G., Yapa, Y. M. S. S., 2021. Assessment and Removal of Suspended Solids in Hospital Wastewater Using Clay in Sri Lanka. Journal of the Geological Society of Sri Lanka, 22(1), 11–11. https://doi.org/10.4038/jgssl.v22i1.54

Yu, X., Suntrayuth, S., Carayannis, E. G., Sindakis, S., Showkat, S., 2023. Advancing industrial wastewater treatment through comprehensive evaluation and innovative technology: a G1-entropy improved TOPSIS model approach. The Journal of Technology Transfer. https://doi.org/10.1007/s10961-023-10032-y

Yue, W., Cai, Y., Rong, Q., Cao, L., Wang, X., 2014. A hybrid MCDA-LCA approach for assessing carbon foot-prints and environmental impacts of China's paper producing industry and printing services. Environmental Systems Research, 3(1), 4. https://doi.org/10.1186/2193-2697-3-4

Zapevalov, A. S., and Dovgaya, S. V., 2007. Transformation of black-sea waters in the Sea of Marmara. Physical Oceanography, 17(2), 106–112. https://doi.org/10.1007/s11110-007-0009-5

Zhang, L., Liu, X., Zhang, M., Wang, T., Hong, T.-P., Jia, Y., 2023. The effect of pH/PAC on the coagulation of anionic surfactant wastewater generated in the cosmetic production. Journal of Environmental Chemical Engineering, 11(2), 109312–109312. https://doi.org/10.1016/j.jece.2023.109312

Zouboulis, A. I., and Traskas, G., 2005. Comparable evaluation of various commercially available aluminium-based coagulants for the treatment of surface water and for the post-treatment of urban wastewater. Journal of Chemical Technology & Biotechnology, 80(10), 1136–1147. https://doi.org/10.1002/jctb.1300

Zhao, J., Wu, Q., Tang, Y., Zhou, J., Guo, H., 2022. Tannery wastewater treatment: conventional and promising processes, an updated 20-year review. Journal of Leather Science and Engineering, 4(1). https://doi.org/10.1186/s42825-022-00082-7

Zhao, Y., Xiao, F., Wang, D., Yan, M., Bi, Z., 2013. Disinfection byproduct precursor removal by enhanced coagulation and their distribution in chemical fractions. Journal of Environmental Sciences, 25(11), 2207–2213. https://doi.org/10.1016/s1001-0742(12)60286-1

Zhao, Z., Li, M., Huang, W., Guo, N., Zhang, Q., 2022. Evaluation of activated sludge properties' changes in industrial-wastewater pre-treatment: role of residual aluminum hydrolyzed species with different polymerization degree. Frontiers of Environmental Science & Engineering, 17(6). https://doi.org/10.1007/s11783-023-1675-3

Zheng, J., Egger, C., Lienert, J., 2016. A scenario-based MCDA framework for wastewater infrastructure planning under uncertainty. Journal of Environmental Management, 183, 895–908. https://doi.org/10.1016/j.jenvman.2016.09.027

Zhou, G., Gu, Y., Yuan, H., Gong, Y., Wu, Y., 2020. Selecting sustainable technologies for disposal of municipal sewage sludge using a multi-criterion decision-making method: A case study from China. Resources, Conservation and Recycling, 161, 104881. https://doi.org/10.1016/j.resconrec.2020.104881

Zhou, J., Liu, J., Li, X., Zhang, Y., Liu, Y., 2012. Multi-objective model of fast-solidification sludge. Journal of Central South University, 19(5), 1383–1387. https://doi.org/10.1007/s11771-012-1154-7

Zou, Z., Yun, Y., Sun, J., 2006. Entropy method for determination of weight of evaluating indicators in fuzzy synthetic evaluation for water quality assessment. Journal of Environmental Sciences, 18(5), 1020–1023. https://doi.org/10.1016/S1001-0742(06)60032-6

Zumstein, M., Battagliarin, G., Kuenkel, A., Sander, M., 2022. Environmental Biodegradation of Water-Soluble Polymers: Key Considerations and Ways Forward. Accounts of Chemical Research, 55(16), 2163–2167. https://doi.org/10.1021/acs.accounts.2c00232

APPENDIX A: SCREENING TEST RESULTS

Table A.1. Screening test results.

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
1	3.04.2025	M1	-	-	-	7.39	-	-	-	-	-	-	1100>	1661.0	694.00
1	3.04.2025	M2	P040102	Lime (10%)	3.4	7.37	8.36	180.7	60.9	69.3	8.4	3.36	640	1534.3	572.05
1	3.04.2025	M3	P040102	NaOH (50%)	0.44	7.41	8.32	185.6	58.5	64.4	5.9	2.38	635	1565.8	576.57
1	3.04.2025	M4	P040100	NaOH (50%)	0.52	7.42	8.51	186.2	59.3	63.8	4.5	1.79	625	1368.0	501.59
1	3.04.2025	M5	P010100	NaOH (50%)	0.52	7.42	8.52	186.7	59.6	63.3	3.6	1.45	625	1335.6	511.62
1	3.04.2025	M5	P010101	NaOH (50%)	0.48	7.36	8.42	186.8	59.7	63.2	3.5	1.42	625	1359.0	513.24
1	3.04.2025	M5	P010102	NaOH (50%)	0.44	7.42	8.38	186.9	59.7	63.1	3.4	1.36	625	1446.2	512.37
1	3.04.2025	M5	P010200	NaOH (50%)	0.44	7.42	8.36	185.7	59.0	64.3	5.3	2.14	613	1366.2	513.38
1	3.04.2025	M5	P010201	NaOH (50%)	0.44	7.42	8.4	185.7	59.0	64.3	5.3	2.10	613	1381.2	514.90
1	3.04.2025	M5	P010202	NaOH (50%)	0.48	7.41	8.44	185.8	59.0	64.2	5.1	2.05	617	1434.7	514.89
1	3.04.2025	M5	P010300	NaOH (50%)	0.44	7.4	8.33	186.3	59.3	63.7	4.4	1.75	609	1356.3	509.79
1	3.04.2025	M5	P010301	NaOH (50%)	0.44	7.42	8.36	186.3	59.3	63.7	4.3	1.73	608	1361.2	509.99
1	3.04.2025	M5	P010302	NaOH (50%)	0.48	7.37	8.38	187.1	59.6	62.9	3.3	1.34	628	1401.2	512.35
1	3.04.2025	M5	P010303	NaOH (50%)	0.52	7.4	8.51	186.3	59.4	63.7	4.3	1.72	609	1371.5	511.27
1	3.04.2025	M5	P020100	NaOH (50%)	0.44	7.4	8.34	185.9	58.8	64.1	5.3	2.12	601	1343.4	509.12
1	3.04.2025	M5	P020101	NaOH (50%)	0.48	7.37	8.43	185.8	59.0	64.2	5.2	2.08	603	1358.6	510.55
1	3.04.2025	M5	P020102	NaOH (50%)	0.48	7.4	8.39	186.1	59.2	63.9	4.7	1.88	607	1416.6	510.63
1	3.04.2025	M5	P020200	NaOH (50%)	0.44	7.38	8.35	185.5	58.9	64.5	5.6	2.25	593	1322.8	509.08
1	3.04.2025	M5	P020201	NaOH (50%)	0.48	7.36	8.4	185.6	58.9	64.4	5.6	2.22	593	1338.9	510.46
1	3.04.2025	M5	P020202	NaOH (50%)	0.44	7.38	8.33	185.7	58.9	64.3	5.4	2.17	596	1396.0	510.82
1	3.04.2025	M6	P010100	pH adjustment was not performed	-	7.4	-	187.0	59.5	63.0	3.5	1.40	622	1387.2	516.07
1	3.04.2025	M6	P010101	pH adjustment was not performed	-	7.38	-	187.1	59.5	62.9	3.4	1.37	623	1401.5	517.71
1	3.04.2025	M6	P010102	pH adjustment was not performed	-	7.4	-	187.1	59.6	62.9	3.3	1.31	625	1454.2	516.83
1	3.04.2025	M6	P010200	pH adjustment was not performed	-	7.4	-	185.9	58.8	64.1	5.2	2.09	613	1368.8	517.85
1	3.04.2025	M6	P010201	pH adjustment was not performed	-	7.37	-	186.0	58.9	64.0	5.1	2.06	613	1383.8	519.38
1	3.04.2025	M6	P010202	pH adjustment was not performed	-	7.36	-	186.1	58.9	63.9	5.0	2.01	615	1454.2	519.37
1	3.04.2025	M6	P010300	pH adjustment was not performed	-	7.36	-	186.5	59.2	63.5	4.3	1.71	609	1359.0	514.23
1	3.04.2025	M6	P010301	pH adjustment was not performed	-	7.41	-	186.6	59.2	63.4	4.2	1.69	608	1363.8	514.43
1	3.04.2025	M6	P010302	pH adjustment was not performed	-	7.37	-	187.3	59.5	62.7	3.2	1.29	628	1403.9	516.81
1	3.04.2025	M6	P010303	pH adjustment was not performed	-	7.37	-	186.6	59.2	63.4	4.2	1.67	609	1374.2	515.72

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
1	3.04.2025	M6	P020100	pH adjustment was not performed	-	7.38	-	186.1	58.7	63.9	5.2	2.07	600	1346.1	513.55
1	3.04.2025	M6	P020101	pH adjustment was not performed	-	7.36	-	186.0	58.9	64.0	5.1	2.03	601	1361.3	514.99
1	3.04.2025	M6	P020102	pH adjustment was not performed	-	7.36	-	186.3	59.1	63.7	4.6	1.83	607	1419.1	515.07
1	3.04.2025	M6	P020200	pH adjustment was not performed	-	7.38	-	185.7	58.7	64.3	5.5	2.21	593	1325.5	513.51
1	3.04.2025	M6	P020201	pH adjustment was not performed	-	7.38	-	185.8	58.8	64.2	5.4	2.17	593	1341.6	514.90
1	3.04.2025	M6	P020202	pH adjustment was not performed	-	7.4	-	185.9	58.8	64.1	5.3	2.12	596	1398.3	515.26
2	4.04.2025	M1	-	-	-	7.07	-	-	-	-	-	-	1100>	2540.6	1130.00
2	4.04.2025	M2	P040102	Lime (10%)	4.92	7.08	8.52	138.1	98.7	111.9	13.2	5.28	1042	2323.4	948.97
2	4.04.2025	M3	P040102	NaOH (50%)	0.64	7.1	8.51	145.1	95.2	104.9	9.7	3.87	1034	2371.0	956.47
2	4.04.2025	M4	P040100	NaOH (50%)	0.68	7.06	8.49	146.2	96.6	103.8	7.2	2.90	1017	2071.6	832.09
2	4.04.2025	M5	P010100	NaOH (50%)	0.68	7.09	8.52	147.1	97.0	102.9	5.9	2.35	1018	2029.2	848.72
2	4.04.2025	M5	P010101	NaOH (50%)	0.64	7.08	8.48	147.2	97.1	102.8	5.7	2.29	1018	2058.0	851.40
2	4.04.2025	M5	P010102	NaOH (50%)	0.64	7.08	8.43	147.3	97.2	102.7	5.5	2.20	1018	2190.0	849.97
2	4.04.2025	M5	P010200	NaOH (50%)	0.6	7.06	8.34	145.4	96.0	104.6	8.7	3.47	998	2068.9	851.65
2	4.04.2025	M5	P010201	NaOH (50%)	0.6	7.06	8.39	145.4	96.0	104.6	8.5	3.41	999	2091.6	854.17
2	4.04.2025	M5	P010202	NaOH (50%)	0.6	7.09	8.42	145.6	96.1	104.4	8.3	3.33	1005	2172.5	854.14
2	4.04.2025	M5	P010300	NaOH (50%)	0.6	7.1	8.36	146.4	96.5	103.6	7.1	2.84	991	2053.9	845.70
2	4.04.2025	M5	P010301	NaOH (50%)	0.68	7.04	8.54	146.4	96.6	103.6	7.0	2.82	990	2061.3	846.02
2	4.04.2025	M5	P010302	NaOH (50%)	0.64	7.06	8.41	147.6	97.0	102.4	5.4	2.16	1022	2121.8	849.94
2	4.04.2025	M5	P010303	NaOH (50%)	0.64	7.08	8.46	146.4	96.6	103.6	7.0	2.78	992	2076.9	848.15
2	4.04.2025	M5	P020100	NaOH (50%)	0.64	7.1	8.44	145.6	95.8	104.4	8.6	3.44	979	2034.3	844.59
2	4.04.2025	M5	P020101	NaOH (50%)	0.68	7.06	8.48	145.5	96.1	104.5	8.4	3.37	981	2057.4	846.95
2	4.04.2025	M5	P020102	NaOH (50%)	0.68	7.09	8.51	146.0	96.4	104.0	7.6	3.05	988	2145.1	847.07
2	4.04.2025	M5	P020200	NaOH (50%)	0.68	7.08	8.5	145.0	95.8	105.0	9.1	3.66	965	2003.2	844.52
2	4.04.2025	M5	P020201	NaOH (50%)	0.68	7.09	8.54	145.1	95.9	104.9	9.0	3.61	966	2027.5	846.81
2	4.04.2025	M5	P020202	NaOH (50%)	0.68	7.09	8.54	145.3	95.9	104.7	8.8	3.52	970	2114.0	847.39
2	4.04.2025	M6	P010100	pH adjustment was not performed	-	7.06	-	147.4	96.9	102.6	5.7	2.28	1013	2100.6	857.21
2	4.04.2025	M6	P010101	pH adjustment was not performed	-	7.1	-	147.5	96.9	102.5	5.6	2.22	1014	2122.3	859.92
2	4.04.2025	M6	P010102	pH adjustment was not performed	-	7.08	-	147.7	97.0	102.3	5.3	2.14	1018	2202.2	858.47
2	4.04.2025	M6	P010200	pH adjustment was not performed	-	7.08	-	145.7	95.8	104.3	8.5	3.41	998	2072.8	860.16
2	4.04.2025	M6	P010201	pH adjustment was not performed	-	7.04	-	145.8	95.9	104.2	8.4	3.35	999	2095.5	862.71
2	4.04.2025	M6	P010202	pH adjustment was not performed	-	7.06	-	145.9	95.9	104.1	8.2	3.27	1002	2202.2	862.69
2	4.04.2025	M6	P010300	pH adjustment was not performed	-	7.04	-	146.7	96.4	103.3	6.9	2.78	991	2058.0	854.16
2	4.04.2025	M6	P010301	pH adjustment was not performed	-	7.08	-	146.7	96.4	103.3	6.9	2.75	990	2065.2	854.48
2	4.04.2025	M6	P010302	pH adjustment was not performed	-	7.09	-	147.9	96.8	102.1	5.2	2.10	1022	2125.9	858.44
2	4.04.2025	M6	P010303	pH adjustment was not performed	-	7.1	-	146.7	96.5	103.3	6.8	2.72	992	2081.0	856.64
2	4.04.2025	M6	P020100	pH adjustment was not performed	-	7.09	-	146.0	95.6	104.0	8.4	3.37	976	1900.0	853.03
2	4.04.2025	M6	P020101	pH adjustment was not performed	-	7.05	-	145.8	95.9	104.2	8.3	3.31	979	2061.5	855.42

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
2	4.04.2025	M6	P020102	pH adjustment was not performed	-	7.04	-	146.3	96.2	103.7	7.5	2.98	988	2149.0	855.54
2	4.04.2025	M6	P020200	pH adjustment was not performed	-	7.04	-	145.4	95.6	104.6	9.0	3.59	965	2007.2	852.96
2	4.04.2025	M6	P020201	pH adjustment was not performed	-	7.08	-	145.5	95.7	104.5	8.8	3.54	966	2031.6	855.28
2	4.04.2025	M6	P020202	pH adjustment was not performed	-	7.05	-	145.6	95.8	104.4	8.6	3.45	970	2117.5	855.86
3	8.04.2025	M1	-	-	-	7.61	-	-	-	-	-	-	1100>	1905.2	710.00
3	8.04.2025	M2	P040102	Lime (10%)	2.6	7.58	8.34	180.4	61.7	69.6	7.9	3.17	655	1764.3	594.44
3	8.04.2025	M3	P040102	NaOH (50%)	0.44	7.58	8.54	184.1	59.8	65.9	6.1	2.43	650	1800.5	600.00
3	8.04.2025	M4	P040100	NaOH (50%)	0.32	7.62	8.32	184.8	60.7	65.2	4.5	1.81	639	1573.1	521.22
3	8.04.2025	M5	P010100	NaOH (50%)	0.36	7.6	8.33	185.4	60.9	64.6	3.7	1.47	639	1540.9	531.65
3	8.04.2025	M5	P010101	NaOH (50%)	0.36	7.63	8.37	185.4	61.0	64.6	3.6	1.43	640	1562.7	533.33
3	8.04.2025	M5	P010102	NaOH (50%)	0.32	7.63	8.33	185.5	61.0	64.5	3.4	1.38	640	1663.0	532.42
3	8.04.2025	M5	P010200	NaOH (50%)	0.4	7.6	8.48	184.2	60.3	65.8	5.5	2.18	627	1571.0	533.47
3	8.04.2025	M5	P010201	NaOH (50%)	0.4	7.6	8.5	184.3	60.3	65.7	5.4	2.15	628	1588.3	535.05
3	8.04.2025	M5	P010202	NaOH (50%)	0.36	7.63	8.38	184.4	60.4	65.6	5.2	2.09	632	1649.7	535.04
3	8.04.2025	M5	P010300	NaOH (50%)	0.4	7.64	8.5	184.9	60.7	65.1	4.5	1.79	623	1559.6	529.75
3	8.04.2025	M5	P010301	NaOH (50%)	0.36	7.62	8.4	184.9	60.7	65.1	4.4	1.76	622	1565.2	529.95
3	8.04.2025	M5	P010302	NaOH (50%)	0.4	7.63	8.48	185.7	60.9	64.3	3.4	1.36	642	1611.2	532.40
3	8.04.2025	M5	P010303	NaOH (50%)	0.4	7.6	8.42	184.9	60.7	65.1	4.4	1.75	624	1577.1	531.29
3	8.04.2025	M5	P020100	NaOH (50%)	0.32	7.63	8.33	184.5	60.2	65.5	5.4	2.15	615	1544.8	529.05
3	8.04.2025	M5	P020101	NaOH (50%)	0.4	7.62	8.44	184.4	60.4	65.6	5.3	2.12	616	1562.3	530.53
3	8.04.2025	M5	P020102	NaOH (50%)	0.36	7.6	8.4	184.7	60.5	65.3	4.8	1.91	621	1628.9	530.61
3	8.04.2025	M5	P020200	NaOH (50%)	0.4	7.58	8.45	184.1	60.2	65.9	5.7	2.30	606	1521.1	529.01
3	8.04.2025	M5	P020201	NaOH (50%)	0.4	7.63	8.48	184.1	60.2	65.9	5.7	2.26	607	1539.6	530.44
3	8.04.2025	M5	P020202	NaOH (50%)	0.4	7.64	8.47	184.2	60.3	65.8	5.5	2.21	609	1605.3	530.81
3	8.04.2025	M6	P010100	pH adjustment was not performed	-	7.58	-	185.6	60.9	64.4	3.6	1.43	636	1595.1	536.17
3	8.04.2025	M6	P010101	pH adjustment was not performed	-	7.62	-	185.6	60.9	64.4	3.5	1.40	637	1611.6	537.86
3	8.04.2025	M6	P010102	pH adjustment was not performed	-	7.58	-	185.7	60.9	64.3	3.4	1.34	640	1672.2	536.95
3	8.04.2025	M6	P010200	pH adjustment was not performed	-	7.59	-	184.4	60.2	65.6	5.4	2.14	627	1574.0	538.00
3	8.04.2025	M6	P010201	pH adjustment was not performed	-	7.64	-	184.5	60.2	65.5	5.3	2.11	628	1591.2	539.60
3	8.04.2025	M6	P010202	pH adjustment was not performed	-	7.62	-	184.6	60.3	65.4	5.1	2.05	629	1672.2	539.59
3	8.04.2025	M6	P010300	pH adjustment was not performed	-	7.63	-	185.1	60.6	64.9	4.4	1.75	623	1562.7	534.25
3	8.04.2025	M6	P010301	pH adjustment was not performed	-	7.59	-	185.1	60.6	64.9	4.3	1.73	622	1568.3	534.46
3	8.04.2025	M6	P010302	pH adjustment was not performed	-	7.59	-	185.9	60.8	64.1	3.3	1.32	642	1614.3	536.93
3	8.04.2025	M6	P010303	pH adjustment was not performed	-	7.63	-	185.1	60.6	64.9	4.3	1.71	624	1580.3	535.80
3	8.04.2025	M6	P020100	pH adjustment was not performed	-	7.6	-	184.6	60.1	65.4	5.3	2.12	614	1547.9	533.55
3	8.04.2025	M6	P020101	pH adjustment was not performed	-	7.6	-	184.5	60.3	65.5	5.2	2.08	615	1565.4	535.04
3	8.04.2025	M6	P020102	pH adjustment was not performed	-	7.59	-	184.9	60.4	65.1	4.7	1.88	621	1631.9	535.12
3	8.04.2025	M6	P020200	pH adjustment was not performed	-	7.64	-	184.3	60.1	65.7	5.6	2.26	606	1524.2	533.51

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
3	8.04.2025	M6	P020201	pH adjustment was not performed	-	7.59	-	184.3	60.1	65.7	5.6	2.22	607	1542.7	534.95
3	8.04.2025	M6	P020202	pH adjustment was not performed	-	7.64	-	184.4	60.2	65.6	5.4	2.17	609	1608.0	535.32
4	10.04.2025	M1	-	-	-	7.03	-	-	-	-	-	-	1100>	2578.8	1178.00
4	10.04.2025	M2	P040102	Lime (10%)	5.16	7	8.51	133.3	103.0	116.7	13.8	5.51	1087	2376.7	981.81
4	10.04.2025	M3	P040102	NaOH (50%)	0.64	7.01	8.4	140.7	99.2	109.3	10.1	4.03	1078	2425.4	989.57
4	10.04.2025	M4	P040100	NaOH (50%)	0.6	7.05	8.34	141.8	100.7	108.2	7.5	3.01	1060	2119.1	860.88
4	10.04.2025	M5	P010100	NaOH (50%)	0.6	7.05	8.35	142.8	101.1	107.2	6.1	2.44	1061	2075.7	878.10
4	10.04.2025	M5	P010101	NaOH (50%)	0.64	7.04	8.43	142.8	101.2	107.2	6.0	2.38	1061	2105.1	880.87
4	10.04.2025	M5	P010102	NaOH (50%)	0.68	7.01	8.47	143.0	101.3	107.0	5.7	2.30	1061	2240.2	879.38
4	10.04.2025	M5	P010200	NaOH (50%)	0.64	7.01	8.38	140.9	100.0	109.1	9.0	3.62	1040	2116.3	881.11
4	10.04.2025	M5	P010201	NaOH (50%)	0.6	7.02	8.34	141.0	100.1	109.0	8.9	3.56	1041	2139.5	883.72
4	10.04.2025	M5	P010202	NaOH (50%)	0.6	7.02	8.32	141.2	100.2	108.8	8.7	3.47	1048	2222.3	883.70
4	10.04.2025	M5	P010300	NaOH (50%)	0.68	7	8.49	141.9	100.7	108.1	7.4	2.96	1034	2100.9	874.97
4	10.04.2025	M5	P010301	NaOH (50%)	0.64	7.04	8.38	142.0	100.7	108.0	7.3	2.93	1032	2108.5	875.30
4	10.04.2025	M5	P010302	NaOH (50%)	0.68	7.04	8.54	143.2	101.1	106.8	5.6	2.26	1066	2170.5	879.34
4	10.04.2025	M5	P010303	NaOH (50%)	0.64	7.06	8.44	142.0	100.7	108.0	7.3	2.90	1034	2124.5	877.50
4	10.04.2025	M5	P020100	NaOH (50%)	0.68	7.02	8.49	141.2	99.8	108.8	9.0	3.58	1021	2081.0	873.81
4	10.04.2025	M5	P020101	NaOH (50%)	0.64	7	8.4	141.1	100.1	108.9	8.8	3.51	1023	2104.5	876.26
4	10.04.2025	M5	P020102	NaOH (50%)	0.68	7.06	8.51	141.6	100.5	108.4	7.9	3.18	1030	2194.3	876.39
4	10.04.2025	M5	P020200	NaOH (50%)	0.6	7.05	8.35	140.6	99.9	109.4	9.5	3.81	1006	2049.1	873.74
4	10.04.2025	M5	P020201	NaOH (50%)	0.6	7.04	8.36	140.7	99.9	109.3	9.4	3.75	1007	2074.0	876.11
4	10.04.2025	M5	P020202	NaOH (50%)	0.6	7.04	8.33	140.9	100.0	109.1	9.2	3.66	1011	2162.4	876.72
4	10.04.2025	M6	P010100	pH adjustment was not performed	-	7.01	-	143.1	101.0	106.9	5.9	2.38	1056	2148.7	885.56
4	10.04.2025	M6	P010101	pH adjustment was not performed	-	7.06	-	143.2	101.0	106.8	5.8	2.32	1057	2170.9	888.36
4	10.04.2025	M6	P010102	pH adjustment was not performed	-	7.06	-	143.3	101.1	106.7	5.6	2.23	1061	2252.6	886.86
4	10.04.2025	M6	P010200	pH adjustment was not performed	-	7	-	141.2	99.9	108.8	8.9	3.55	1040	2120.4	888.60
4	10.04.2025	M6	P010201	pH adjustment was not performed	-	7	-	141.3	99.9	108.7	8.7	3.49	1041	2143.5	891.23
4	10.04.2025	M6	P010202	pH adjustment was not performed	-	7.02	-	141.5	100.0	108.5	8.5	3.41	1044	2252.6	891.21
4	10.04.2025	M6	P010300	pH adjustment was not performed	-	7.04	-	142.3	100.5	107.7	7.2	2.90	1034	2105.1	882.40
4	10.04.2025	M6	P010301	pH adjustment was not performed	-	7.05	-	142.3	100.5	107.7	7.2	2.86	1032	2112.6	882.74
4	10.04.2025	M6	P010302	pH adjustment was not performed	-	7.01	-	143.6	101.0	106.4	5.5	2.19	1066	2174.6	886.82
4	10.04.2025	M6	P010303	pH adjustment was not performed	-	7.05	-	142.4	100.6	107.6	7.1	2.84	1034	2128.7	884.96
4	10.04.2025	M6	P020100	pH adjustment was not performed	-	7.02	-	141.5	99.7	108.5	8.8	3.52	1018	2085.1	881.24
4	10.04.2025	M6	P020101	pH adjustment was not performed	-	7.05	-	141.4	100.0	108.6	8.6	3.45	1021	2108.7	883.71
4	10.04.2025	M6	P020102	pH adjustment was not performed	-	7.01	-	141.9	100.3	108.1	7.8	3.11	1030	2198.2	883.84
4	10.04.2025	M6	P020200	pH adjustment was not performed	-	7.01	-	140.9	99.7	109.1	9.4	3.75	1006	2053.2	881.17
4	10.04.2025	M6	P020201	pH adjustment was not performed	-	7.06	-	141.0	99.8	109.0	9.2	3.69	1007	2078.2	883.56
4	10.04.2025	M6	P020202	pH adjustment was not performed	-	7.06	-	141.2	99.8	108.8	9.0	3.60	1011	2166.0	884.17

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
5	14.04.2025	M1	-	-	-	7.62	-	-	-	-	-	-	1100>	1839.0	1325.00
5	14.04.2025	M2	P040102	Lime (10%)	2.8	7.61	8.43	123.2	113.6	126.8	13.2	5.30	1100>	1664.4	1078.83
5	14.04.2025	M3	P040102	NaOH (50%)	0.44	7.63	8.55	127.2	111.6	122.8	11.3	4.50	1100>	1698.5	1087.34
5	14.04.2025	M4	P040100	NaOH (50%)	0.4	7.63	8.5	128.4	113.2	121.6	8.4	3.36	1100>	1484.0	945.94
5	14.04.2025	M5	P010100	NaOH (50%)	0.36	7.65	8.44	129.5	113.7	120.5	6.8	2.71	1100>	1453.6	964.87
5	14.04.2025	M5	P010101	NaOH (50%)	0.36	7.65	8.42	129.6	113.7	120.4	6.6	2.64	1100>	1474.2	967.91
5	14.04.2025	M5	P010102	NaOH (50%)	0.32	7.63	8.35	129.8	113.8	120.2	6.4	2.54	1100>	1568.8	966.27
5	14.04.2025	M5	P010200	NaOH (50%)	0.36	7.59	8.37	127.5	112.4	122.5	10.1	4.03	1100>	1482.0	968.18
5	14.04.2025	M5	P010201	NaOH (50%)	0.32	7.65	8.37	127.6	112.5	122.4	9.9	3.96	1100>	1498.3	971.04
5	14.04.2025	M5	P010202	NaOH (50%)	0.44	7.61	8.55	127.7	112.6	122.3	9.7	3.88	1100>	1556.3	971.02
5	14.04.2025	M5	P010300	NaOH (50%)	0.4	7.63	8.49	128.6	113.1	121.4	8.2	3.30	1100>	1471.3	961.42
5	14.04.2025	M5	P010301	NaOH (50%)	0.4	7.6	8.49	128.7	113.2	121.3	8.2	3.26	1100>	1476.6	961.80
5	14.04.2025	M5	P010302	NaOH (50%)	0.4	7.63	8.51	130.1	113.7	119.9	6.3	2.50	1100>	1520.0	966.24
5	14.04.2025	M5	P010303	NaOH (50%)	0.36	7.6	8.36	128.7	113.2	121.3	8.1	3.23	1100>	1487.8	964.22
5	14.04.2025	M5	P020100	NaOH (50%)	0.36	7.6	8.4	127.8	112.2	122.2	10.0	3.99	1100>	1457.3	960.16
5	14.04.2025	M5	P020101	NaOH (50%)	0.4	7.64	8.46	127.7	112.6	122.3	9.8	3.92	1100>	1473.8	962.84
5	14.04.2025	M5	P020102	NaOH (50%)	0.4	7.6	8.48	128.2	112.9	121.8	8.9	3.54	1100>	1536.7	962.99
5	14.04.2025	M5	P020200	NaOH (50%)	0.32	7.64	8.33	127.2	112.2	122.8	10.6	4.24	1100>	1435.0	960.08
5	14.04.2025	M5	P020201	NaOH (50%)	0.36	7.65	8.44	127.2	112.3	122.8	10.5	4.19	1100>	1452.4	962.69
5	14.04.2025	M5	P020202	NaOH (50%)	0.32	7.63	8.35	127.4	112.4	122.6	10.2	4.08	1100>	1514.3	963.35
5	14.04.2025	M6	P010100	pH adjustment was not performed	-	7.61	-	129.7	113.6	120.3	6.7	2.67	1100>	1504.7	970.56
5	14.04.2025	M6	P010101	pH adjustment was not performed	-	7.59	-	129.8	113.7	120.2	6.5	2.61	1100>	1520.3	973.62
5	14.04.2025	M6	P010102	pH adjustment was not performed	-	7.61	-	130.0	113.7	120.0	6.3	2.51	1100>	1577.5	971.97
5	14.04.2025	M6	P010200	pH adjustment was not performed	-	7.63	-	127.7	112.3	122.3	10.0	3.99	1100>	1484.9	973.89
5	14.04.2025	M6	P010201	pH adjustment was not performed	-	7.61	-	127.8	112.4	122.2	9.8	3.93	1100>	1501.1	976.77
5	14.04.2025	M6	P010202	pH adjustment was not performed	-	7.59	-	127.9	112.5	122.1	9.6	3.83	1100>	1577.5	976.75
5	14.04.2025	M6	P010300	pH adjustment was not performed	-	7.61	-	128.8	113.0	121.2	8.1	3.26	1100>	1474.2	967.09
5	14.04.2025	M6	P010301	pH adjustment was not performed	-	7.6	-	128.9	113.1	121.1	8.1	3.22	1100>	1479.4	967.47
5	14.04.2025	M6	P010302	pH adjustment was not performed	-	7.63	-	130.3	113.6	119.7	6.1	2.46	1100>	1522.9	971.94
5	14.04.2025	M6	P010303	pH adjustment was not performed	-	7.64	-	128.9	113.1	121.1	8.0	3.19	1100>	1490.7	969.91
5	14.04.2025	M6	P020100	pH adjustment was not performed	-	7.64	-	128.0	112.1	122.0	9.9	3.96	1100>	1460.2	965.82
5	14.04.2025	M6	P020101	pH adjustment was not performed	-	7.61	-	127.8	112.5	122.2	9.7	3.88	1100>	1476.7	968.52
5	14.04.2025	M6	P020102	pH adjustment was not performed	-	7.64	-	128.4	112.8	121.6	8.7	3.50	1100>	1539.4	968.67
5	14.04.2025	M6	P020200	pH adjustment was not performed	-	7.6	-	127.3	112.1	122.7	10.5	4.21	1100>	1437.8	965.74
5	14.04.2025	M6	P020201	pH adjustment was not performed	-	7.6	-	127.4	112.2	122.6	10.4	4.15	1100>	1455.3	968.37
5	14.04.2025	M6	P020202	pH adjustment was not performed	-	7.6	-	127.6	112.3	122.4	10.1	4.05	1100>	1516.9	969.03
6	16.04.2025	M1	-	-	-	7.52	-	-	-	-	-	-	1100>	1819.5	1186.00
6	16.04.2025	M2	P040102	Lime (10%)	3.28	7.5	8.46	135.3	102.2	114.7	12.4	4.97	1094	1690.8	976.29

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
6	16.04.2025	M3	P040102	NaOH (50%)	0.44	7.5	8.41	140.1	99.9	109.9	10.1	4.03	1085	1725.5	984.00
6	16.04.2025	M4	P040100	NaOH (50%)	0.4	7.53	8.42	141.2	101.3	108.8	7.5	3.01	1067	1507.5	856.04
6	16.04.2025	M5	P010100	NaOH (50%)	0.44	7.51	8.48	142.1	101.8	107.9	6.1	2.44	1068	1476.7	873.17
6	16.04.2025	M5	P010101	NaOH (50%)	0.48	7.55	8.54	142.2	101.8	107.8	6.0	2.38	1068	1497.6	875.92
6	16.04.2025	M5	P010102	NaOH (50%)	0.4	7.55	8.42	142.4	101.9	107.6	5.7	2.29	1069	1593.7	874.43
6	16.04.2025	M5	P010200	NaOH (50%)	0.4	7.49	8.37	140.3	100.7	109.7	9.0	3.62	1047	1505.6	876.16
6	16.04.2025	M5	P010201	NaOH (50%)	0.4	7.54	8.42	140.4	100.7	109.6	8.9	3.56	1048	1522.1	878.75
6	16.04.2025	M5	P010202	NaOH (50%)	0.44	7.55	8.5	140.5	100.8	109.5	8.7	3.47	1055	1581.0	878.74
6	16.04.2025	M5	P010300	NaOH (50%)	0.44	7.53	8.5	141.3	101.3	108.7	7.4	2.96	1041	1494.6	870.04
6	16.04.2025	M5	P010301	NaOH (50%)	0.44	7.55	8.49	141.4	101.3	108.6	7.3	2.93	1039	1500.0	870.38
6	16.04.2025	M5	P010302	NaOH (50%)	0.4	7.49	8.39	142.6	101.7	107.4	5.6	2.24	1073	1544.1	874.40
6	16.04.2025	M5	P010303	NaOH (50%)	0.4	7.49	8.37	141.4	101.3	108.6	7.2	2.90	1042	1511.4	872.58
6	16.04.2025	M5	P020100	NaOH (50%)	0.44	7.53	8.49	140.6	100.5	109.4	9.0	3.59	1028	1480.4	868.90
6	16.04.2025	M5	P020101	NaOH (50%)	0.4	7.53	8.41	140.5	100.8	109.5	8.8	3.51	1030	1497.2	871.33
6	16.04.2025	M5	P020102	NaOH (50%)	0.48	7.49	8.53	141.0	101.1	109.0	8.0	3.18	1037	1561.1	871.47
6	16.04.2025	M5	P020200	NaOH (50%)	0.48	7.53	8.54	140.0	100.5	110.0	9.5	3.82	1013	1457.8	868.82
6	16.04.2025	M5	P020201	NaOH (50%)	0.4	7.55	8.37	140.1	100.5	109.9	9.4	3.75	1014	1475.5	871.19
6	16.04.2025	M5	P020202	NaOH (50%)	0.44	7.53	8.44	140.2	100.6	109.8	9.2	3.67	1018	1538.4	871.79
6	16.04.2025	M6	P010100	pH adjustment was not performed	-	7.53	-	142.3	101.7	107.7	6.0	2.39	1063	1528.6	880.50
6	16.04.2025	M6	P010101	pH adjustment was not performed	-	7.5	-	142.4	101.7	107.6	5.8	2.33	1064	1544.4	883.28
6	16.04.2025	M6	P010102	pH adjustment was not performed	-	7.53	-	142.6	101.8	107.4	5.6	2.25	1069	1602.6	881.78
6	16.04.2025	M6	P010200	pH adjustment was not performed	-	7.5	-	140.5	100.6	109.5	8.9	3.58	1047	1508.5	883.52
6	16.04.2025	M6	P010201	pH adjustment was not performed	-	7.53	-	140.6	100.6	109.4	8.8	3.52	1048	1524.9	886.13
6	16.04.2025	M6	P010202	pH adjustment was not performed	-	7.53	-	140.7	100.7	109.3	8.6	3.43	1051	1602.6	886.12
6	16.04.2025	M6	P010300	pH adjustment was not performed	-	7.53	-	141.5	101.2	108.5	7.3	2.92	1041	1497.6	877.35
6	16.04.2025	M6	P010301	pH adjustment was not performed	-	7.49	-	141.6	101.2	108.4	7.2	2.88	1039	1502.9	877.69
6	16.04.2025	M6	P010302	pH adjustment was not performed	-	7.53	-	142.9	101.6	107.1	5.5	2.20	1073	1547.1	881.75
6	16.04.2025	M6	P010303	pH adjustment was not performed	-	7.49	-	141.6	101.2	108.4	7.1	2.86	1042	1514.4	879.91
6	16.04.2025	M6	P020100	pH adjustment was not performed	-	7.54	-	140.8	100.4	109.2	8.9	3.54	1025	1483.4	876.20
6	16.04.2025	M6	P020101	pH adjustment was not performed	-	7.49	-	140.7	100.7	109.3	8.7	3.47	1028	1500.2	878.65
6	16.04.2025	M6	P020102	pH adjustment was not performed	-	7.53	-	141.2	101.0	108.8	7.8	3.13	1037	1563.9	878.79
6	16.04.2025	M6	P020200	pH adjustment was not performed	-	7.53	-	140.2	100.4	109.8	9.4	3.77	1013	1460.7	876.12
6	16.04.2025	M6	P020201	pH adjustment was not performed	-	7.55	-	140.3	100.4	109.7	9.3	3.71	1014	1478.4	878.51
6	16.04.2025	M6	P020202	pH adjustment was not performed	-	7.55	-	140.4	100.5	109.6	9.1	3.62	1018	1541.0	879.11
7	18.04.2025	M1	-	-	-	7.68	-	-	-	-	-	-	1100>	1797.4	860.00
7	18.04.2025	M2	P040102	Lime (10%)	2.48	7.66	8.39	166.7	74.2	83.3	9.1	3.64	793	1659.7	695.94
7	18.04.2025	M3	P040102	NaOH (50%)	0.4	7.7	8.53	170.2	72.4	79.8	7.3	2.93	787	1693.7	701.44
7	18.04.2025	M4	P040100	NaOH (50%)	0.4	7.67	8.54	171.0	73.5	79.0	5.5	2.19	774	1479.8	610.22

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
7	18.04.2025	M5	P010100	NaOH (50%)	0.36	7.66	8.42	171.8	73.8	78.2	4.4	1.77	775	1449.5	622.43
7	18.04.2025	M5	P010101	NaOH (50%)	0.36	7.69	8.48	171.8	73.9	78.2	4.3	1.73	775	1470.0	624.39
7	18.04.2025	M5	P010102	NaOH (50%)	0.36	7.65	8.42	171.9	73.9	78.1	4.2	1.66	775	1564.4	623.33
7	18.04.2025	M5	P010200	NaOH (50%)	0.36	7.7	8.49	170.4	73.0	79.6	6.6	2.63	759	1477.8	624.57
7	18.04.2025	M5	P010201	NaOH (50%)	0.36	7.66	8.45	170.5	73.1	79.5	6.5	2.59	760	1494.1	626.42
7	18.04.2025	M5	P010202	NaOH (50%)	0.36	7.71	8.46	170.6	73.1	79.4	6.3	2.52	765	1551.9	626.40
7	18.04.2025	M5	P010300	NaOH (50%)	0.36	7.66	8.41	171.2	73.5	78.8	5.4	2.15	755	1467.1	620.20
7	18.04.2025	M5	P010301	NaOH (50%)	0.28	7.69	8.33	171.2	73.5	78.8	5.3	2.12	753	1472.4	620.45
7	18.04.2025	M5	P010302	NaOH (50%)	0.32	7.65	8.35	172.1	73.8	77.9	4.1	1.63	778	1515.7	623.31
7	18.04.2025	M5	P010303	NaOH (50%)	0.36	7.69	8.46	171.2	73.5	78.8	5.3	2.11	755	1483.6	622.01
7	18.04.2025	M5	P020100	NaOH (50%)	0.32	7.66	8.33	170.7	72.8	79.3	6.5	2.60	745	1453.2	619.39
7	18.04.2025	M5	P020101	NaOH (50%)	0.36	7.7	8.44	170.5	73.1	79.5	6.4	2.55	747	1469.6	621.13
7	18.04.2025	M5	P020102	NaOH (50%)	0.32	7.7	8.41	170.9	73.3	79.1	5.8	2.30	752	1532.3	621.22
7	18.04.2025	M5	P020200	NaOH (50%)	0.36	7.7	8.43	170.2	72.9	79.8	6.9	2.77	734	1430.9	619.34
7	18.04.2025	M5	P020201	NaOH (50%)	0.32	7.7	8.39	170.3	72.9	79.7	6.8	2.72	735	1448.3	621.02
7	18.04.2025	M5	P020202	NaOH (50%)	0.36	7.66	8.46	170.4	73.0	79.6	6.7	2.67	738	1510.1	621.45
7	18.04.2025	M6	P010100	pH adjustment was not performed	-	7.67	-	171.9	73.7	78.1	4.3	1.74	771	1500.5	628.53
7	18.04.2025	M6	P010101	pH adjustment was not performed	-	7.67	-	172.0	73.8	78.0	4.2	1.69	772	1516.0	630.51
7	18.04.2025	M6	P010102	pH adjustment was not performed	-	7.65	-	172.1	73.8	77.9	4.1	1.63	775	1573.1	629.44
7	18.04.2025	M6	P010200	pH adjustment was not performed	-	7.71	-	170.6	72.9	79.4	6.5	2.59	759	1480.7	630.69
7	18.04.2025	M6	P010201	pH adjustment was not performed	-	7.7	-	170.7	73.0	79.3	6.4	2.55	760	1496.8	632.56
7	18.04.2025	M6	P010202	pH adjustment was not performed	-	7.65	-	170.8	73.0	79.2	6.2	2.49	762	1573.1	632.54
7	18.04.2025	M6	P010300	pH adjustment was not performed	-	7.67	-	171.4	73.4	78.6	5.3	2.11	755	1470.0	626.28
7	18.04.2025	M6	P010301	pH adjustment was not performed	-	7.71	-	171.4	73.4	78.6	5.2	2.09	753	1475.2	626.53
7	18.04.2025	M6	P010302	pH adjustment was not performed	-	7.66	-	172.3	73.7	77.7	4.0	1.60	778	1518.6	629.42
7	18.04.2025	M6	P010303	pH adjustment was not performed	-	7.69	-	171.4	73.4	78.6	5.2	2.07	755	1486.5	628.10
7	18.04.2025	M6	P020100	pH adjustment was not performed	-	7.65	-	170.8	72.8	79.2	6.4	2.57	743	1456.1	625.46
7	18.04.2025	M6	P020101	pH adjustment was not performed	-	7.7	-	170.7	73.0	79.3	6.3	2.52	745	1472.6	627.21
7	18.04.2025	M6	P020102	pH adjustment was not performed	-	7.65	-	171.1	73.2	78.9	5.7	2.27	752	1535.1	627.31
7	18.04.2025	M6	P020200	pH adjustment was not performed	-	7.67	-	170.4	72.8	79.6	6.8	2.73	734	1433.8	625.41
7	18.04.2025	M6	P020201	pH adjustment was not performed	-	7.7	-	170.4	72.8	79.6	6.7	2.69	735	1451.2	627.10
7	18.04.2025	M6	P020202	pH adjustment was not performed	-	7.7	-	170.5	72.9	79.5	6.6	2.63	738	1512.6	627.54
8	22.04.2025	M1	-	-	-	7.85	-	-	-	-	-	-	1100>	1050.4	525.00
8	22.04.2025	M2	P040102	Lime (10%)	2.04	7.84	8.44	198.3	45.7	51.7	6.0	2.38	484	970.6	426.77
8	22.04.2025	M3	P040102	NaOH (50%)	0.32	7.87	8.55	201.3	44.2	48.7	4.5	1.80	480	990.5	430.13
8	22.04.2025	M4	P040100	NaOH (50%)	0.24	7.83	8.35	201.8	44.9	48.2	3.3	1.34	472	865.4	374.19
8	22.04.2025	M5	P010100	NaOH (50%)	0.24	7.82	8.36	202.2	45.1	47.8	2.7	1.08	473	847.7	381.68
8	22.04.2025	M5	P010101	NaOH (50%)	0.28	7.84	8.46	202.2	45.1	47.8	2.7	1.06	473	859.7	382.89

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
8	22.04.2025	M5	P010102	NaOH (50%)	0.28	7.82	8.44	202.3	45.1	47.7	2.6	1.02	473	914.9	382.24
8	22.04.2025	M5	P010200	NaOH (50%)	0.24	7.83	8.36	201.4	44.6	48.6	4.0	1.61	464	864.3	382.99
8	22.04.2025	M5	P010201	NaOH (50%)	0.28	7.88	8.51	201.4	44.6	48.6	4.0	1.59	464	873.8	384.12
8	22.04.2025	M5	P010202	NaOH (50%)	0.32	7.83	8.54	201.5	44.7	48.5	3.9	1.55	467	907.6	384.11
8	22.04.2025	M5	P010300	NaOH (50%)	0.28	7.88	8.49	201.8	44.9	48.2	3.3	1.32	461	858.0	380.32
8	22.04.2025	M5	P010301	NaOH (50%)	0.24	7.88	8.4	201.9	44.9	48.1	3.3	1.30	460	861.1	380.47
8	22.04.2025	M5	P010302	NaOH (50%)	0.28	7.84	8.41	202.4	45.1	47.6	2.5	1.00	475	886.4	382.22
8	22.04.2025	M5	P010303	NaOH (50%)	0.28	7.88	8.48	201.9	44.9	48.1	3.2	1.29	461	867.7	381.42
8	22.04.2025	M5	P020100	NaOH (50%)	0.24	7.86	8.41	201.5	44.5	48.5	4.0	1.59	455	849.9	379.81
8	22.04.2025	M5	P020101	NaOH (50%)	0.28	7.84	8.4	201.5	44.6	48.5	3.9	1.56	456	859.5	380.88
8	22.04.2025	M5	P020102	NaOH (50%)	0.28	7.84	8.4	201.7	44.8	48.3	3.5	1.41	459	896.1	380.94
8	22.04.2025	M5	P020200	NaOH (50%)	0.28	7.82	8.45	201.2	44.5	48.8	4.2	1.70	448	836.8	379.78
8	22.04.2025	M5	P020201	NaOH (50%)	0.24	7.86	8.41	201.3	44.5	48.7	4.2	1.67	449	847.0	380.82
8	22.04.2025	M5	P020202	NaOH (50%)	0.28	7.83	8.42	201.4	44.6	48.6	4.1	1.63	451	883.1	381.08
8	22.04.2025	M6	P010100	pH adjustment was not performed	-	7.82	-	202.3	45.0	47.7	2.6	1.06	471	877.5	384.12
8	22.04.2025	M6	P010101	pH adjustment was not performed	-	7.84	-	202.4	45.0	47.6	2.6	1.03	471	886.6	385.34
8	22.04.2025	M6	P010102	pH adjustment was not performed	-	7.86	-	202.4	45.1	47.6	2.5	0.99	473	920.0	384.69
8	22.04.2025	M6	P010200	pH adjustment was not performed	-	7.83	-	201.5	44.5	48.5	4.0	1.58	464	866.0	385.44
8	22.04.2025	M6	P010201	pH adjustment was not performed	-	7.84	-	201.6	44.5	48.4	3.9	1.56	464	875.4	386.58
8	22.04.2025	M6	P010202	pH adjustment was not performed	-	7.82	-	201.6	44.6	48.4	3.8	1.52	465	920.0	386.57
8	22.04.2025	M6	P010300	pH adjustment was not performed	-	7.87	-	202.0	44.8	48.0	3.2	1.29	461	859.7	382.75
8	22.04.2025	M6	P010301	pH adjustment was not performed	-	7.82	-	202.0	44.8	48.0	3.2	1.28	460	862.8	382.90
8	22.04.2025	M6	P010302	pH adjustment was not performed	-	7.83	-	202.6	45.0	47.4	2.4	0.97	475	888.1	384.67
8	22.04.2025	M6	P010303	pH adjustment was not performed	-	7.86	-	202.0	44.8	48.0	3.2	1.26	461	869.4	383.86
8	22.04.2025	M6	P020100	pH adjustment was not performed	-	7.88	-	201.7	44.4	48.3	3.9	1.57	454	851.6	382.24
8	22.04.2025	M6	P020101	pH adjustment was not performed	-	7.86	-	201.6	44.6	48.4	3.8	1.54	455	861.2	383.32
8	22.04.2025	M6	P020102	pH adjustment was not performed	-	7.83	-	201.8	44.7	48.2	3.5	1.39	459	897.8	383.38
8	22.04.2025	M6	P020200	pH adjustment was not performed	-	7.86	-	201.4	44.4	48.6	4.2	1.67	448	838.5	382.22
8	22.04.2025	M6	P020201	pH adjustment was not performed	-	7.82	-	201.4	44.5	48.6	4.1	1.64	449	848.7	383.26
8	22.04.2025	M6	P020202	pH adjustment was not performed	-	7.83	-	201.5	44.5	48.5	4.0	1.60	451	884.6	383.52
9	24.04.2025	M1	-	-	-	7.9	-	-	-	-	-	-	1100>	2007.6	1435.00
9	24.04.2025	M2	P040102	Lime (10%)	2.12	7.89	8.51	114.1	122.3	135.9	13.7	5.46	1100>	1818.8	1191.50
9	24.04.2025	M3	P040102	NaOH (50%)	0.24	7.89	8.38	117.1	120.8	132.9	12.1	4.85	1100>	1856.1	1200.91
9	24.04.2025	M4	P040100	NaOH (50%)	0.2	7.88	8.35	118.5	122.5	131.5	9.0	3.62	1100>	1621.7	1044.74
9	24.04.2025	M5	P010100	NaOH (50%)	0.24	7.91	8.43	119.6	123.1	130.4	7.3	2.92	1100>	1588.5	1065.64
9	24.04.2025	M5	P010101	NaOH (50%)	0.32	7.87	8.53	119.7	123.2	130.3	7.1	2.86	1100>	1611.0	1069.00
9	24.04.2025	M5	P010102	NaOH (50%)	0.24	7.92	8.43	119.9	123.2	130.1	6.9	2.74	1100>	1714.4	1067.19
9	24.04.2025	M5	P010200	NaOH (50%)	0.24	7.89	8.44	117.4	121.7	132.6	10.9	4.35	1100>	1619.6	1069.30

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
9	24.04.2025	M5	P010201	NaOH (50%)	0.28	7.92	8.5	117.5	121.8	132.5	10.7	4.28	1100>	1637.4	1072.46
9	24.04.2025	M5	P010202	NaOH (50%)	0.24	7.93	8.45	117.7	121.9	132.3	10.4	4.17	1100>	1700.7	1072.44
9	24.04.2025	M5	P010300	NaOH (50%)	0.2	7.89	8.33	118.7	122.5	131.3	8.9	3.55	1100>	1607.8	1061.83
9	24.04.2025	M5	P010301	NaOH (50%)	0.24	7.87	8.36	118.7	122.5	131.3	8.8	3.51	1100>	1613.6	1062.24
9	24.04.2025	M5	P010302	NaOH (50%)	0.28	7.93	8.51	120.2	123.0	129.8	6.7	2.69	1100>	1661.0	1067.16
9	24.04.2025	M5	P010303	NaOH (50%)	0.28	7.88	8.52	118.7	122.6	131.3	8.7	3.48	1100>	1625.9	1064.92
9	24.04.2025	M5	P020100	NaOH (50%)	0.24	7.91	8.43	117.8	121.5	132.2	10.8	4.31	1100>	1592.5	1060.44
9	24.04.2025	M5	P020101	NaOH (50%)	0.2	7.87	8.34	117.6	121.8	132.4	10.6	4.22	1100>	1610.6	1063.40
9	24.04.2025	M5	P020102	NaOH (50%)	0.2	7.93	8.33	118.3	122.2	131.7	9.5	3.81	1100>	1679.3	1063.57
9	24.04.2025	M5	P020200	NaOH (50%)	0.28	7.88	8.48	117.0	121.5	133.0	11.5	4.59	1100>	1568.1	1060.35
9	24.04.2025	M5	P020201	NaOH (50%)	0.24	7.93	8.42	117.1	121.6	132.9	11.3	4.52	1100>	1587.2	1063.22
9	24.04.2025	M5	P020202	NaOH (50%)	0.24	7.91	8.42	117.3	121.7	132.7	11.0	4.41	1100>	1654.9	1063.96
9	24.04.2025	M6	P010100	pH adjustment was not performed	-	7.89	-	119.7	123.0	130.3	7.2	2.90	1100>	1644.4	1074.27
9	24.04.2025	M6	P010101	pH adjustment was not performed	-	7.87	-	119.9	123.1	130.1	7.1	2.82	1100>	1661.4	1077.66
9	24.04.2025	M6	P010102	pH adjustment was not performed	-	7.88	-	120.0	123.2	130.0	6.8	2.72	1100>	1723.9	1075.83
9	24.04.2025	M6	P010200	pH adjustment was not performed	-	7.87	-	117.5	121.7	132.5	10.8	4.33	1100>	1622.7	1077.96
9	24.04.2025	M6	P010201	pH adjustment was not performed	-	7.91	-	117.6	121.7	132.4	10.6	4.26	1100>	1640.4	1081.14
9	24.04.2025	M6	P010202	pH adjustment was not performed	-	7.88	-	117.8	121.8	132.2	10.4	4.15	1100>	1723.9	1081.12
9	24.04.2025	M6	P010300	pH adjustment was not performed	-	7.87	-	118.8	122.4	131.2	8.8	3.53	1100>	1611.0	1070.43
9	24.04.2025	M6	P010301	pH adjustment was not performed	-	7.93	-	118.8	122.5	131.2	8.7	3.49	1100>	1616.7	1070.85
9	24.04.2025	M6	P010302	pH adjustment was not performed	-	7.91	-	120.4	123.0	129.6	6.7	2.66	1100>	1664.2	1075.80
9	24.04.2025	M6	P010303	pH adjustment was not performed	-	7.87	-	118.9	122.5	131.1	8.6	3.45	1100>	1629.1	1073.55
9	24.04.2025	M6	P020100	pH adjustment was not performed	-	7.92	-	117.9	121.4	132.1	10.7	4.28	1100>	1595.7	1069.03
9	24.04.2025	M6	P020101	pH adjustment was not performed	-	7.93	-	117.7	121.8	132.3	10.5	4.20	1100>	1613.8	1072.01
9	24.04.2025	M6	P020102	pH adjustment was not performed	-	7.89	-	118.3	122.2	131.7	9.5	3.79	1100>	1682.3	1072.19
9	24.04.2025	M6	P020200	pH adjustment was not performed	-	7.89	-	117.1	121.5	132.9	11.4	4.56	1100>	1571.3	1068.94
9	24.04.2025	M6	P020201	pH adjustment was not performed	-	7.89	-	117.2	121.5	132.8	11.2	4.49	1100>	1590.4	1071.83
9	24.04.2025	M6	P020202	pH adjustment was not performed	-	7.91	-	117.4	121.6	132.6	11.0	4.39	1100>	1657.6	1072.58
10	28.04.2025	M1	-	-	-	8.31	-	-	-	-	-	-	1100>	2465.3	2640.00
10	28.04.2025	M2	P040102	pH adjustment was not performed	-	8.32	-	156.03	71.77	94.0	22.21	8.88	1100>	2255.3	2197.40
10	28.04.2025	M4	P040100	pH adjustment was not performed	-	8.28	-	158.28	75.19	91.7	16.53	6.61	1100>	2010.9	1926.74
10	28.04.2025	M6	P010100	pH adjustment was not performed	-	8.3	-	159.02	79.52	91.0	11.46	4.58	1100>	2039.0	1867.84
10	28.04.2025	M6	P010101	pH adjustment was not performed	-	8.3	-	159.11	79.71	90.9	11.17	4.47	1100>	2060.1	1874.35
10	28.04.2025	M6	P010102	pH adjustment was not performed	-	8.33	-	159.24	80.02	90.8	10.75	4.30	1100>	2137.6	1869.25
10	28.04.2025	M6	P010200	pH adjustment was not performed	-	8.33	-	157.28	75.6	92.7	17.11	6.84	1100>	2012.1	1875.61
10	28.04.2025	M6	P010201	pH adjustment was not performed	-	8.3	-	157.37	75.79	92.6	16.84	6.74	1100>	2034.1	1881.68
10	28.04.2025	M6	P010202	pH adjustment was not performed	-	8.3	-	157.5	76.09	92.5	16.41	6.56	1100>	2137.6	1880.38
10	28.04.2025	M6	P010300	pH adjustment was not performed	-	8.33	-	158.25	77.8	91.8	13.95	5.58	1100>	1997.7	1859.77

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
10	28.04.2025	M6	P010301	pH adjustment was not performed	-	8.34	-	158.3	77.9	91.7	13.8	5.52	1100>	2004.7	1860.64
10	28.04.2025	M6	P010302	pH adjustment was not performed	-	8.3	-	158.98	80.49	91.0	10.54	4.22	1100>	2063.6	1871.05
10	28.04.2025	M6	P010303	pH adjustment was not performed	-	8.29	-	158.34	77.99	91.7	13.66	5.46	1100>	2020.0	1865.68
10	28.04.2025	M6	P020100	pH adjustment was not performed	-	8.28	-	156.96	76.1	93.0	16.94	6.78	1100>	1978.7	1856.81
10	28.04.2025	M6	P020101	pH adjustment was not performed	-	8.3	-	157.44	75.94	92.6	16.61	6.64	1100>	2001.1	1862.47
10	28.04.2025	M6	P020102	pH adjustment was not performed	-	8.34	-	157.94	77.07	92.1	14.99	6.00	1100>	2086.0	1861.57
10	28.04.2025	M6	P020200	pH adjustment was not performed	-	8.28	-	157	74.95	93.0	18.05	7.22	1100>	1948.3	1856.61
10	28.04.2025	M6	P020201	pH adjustment was not performed	-	8.3	-	157.09	75.14	92.9	17.77	7.11	1100>	1972.1	1862.09
10	28.04.2025	M6	P020202	pH adjustment was not performed	-	8.29	-	157.21	75.45	92.8	17.35	6.94	1100>	2055.5	1862.41
11	30.04.2025	M1	-	-	-	8.37	-	-	-	-	-	-	1100>	2853.7	2020.00
11	30.04.2025	M2	P040102	pH adjustment was not performed	-	8.34	-	129.95	103.06	120.1	16.99	6.80	1100>	2604.4	1696.18
11	30.04.2025	M4	P040100	pH adjustment was not performed	-	8.39	-	131.83	105.52	118.2	12.65	5.06	1100>	2322.1	1487.25
11	30.04.2025	M6	P010100	pH adjustment was not performed	-	8.34	-	132.44	108.79	117.6	8.77	3.51	1100>	2354.6	1441.79
11	30.04.2025	M6	P010101	pH adjustment was not performed	-	8.4	-	132.52	108.93	117.5	8.55	3.42	1100>	2379.0	1446.82
11	30.04.2025	M6	P010102	pH adjustment was not performed	-	8.38	-	132.62	109.15	117.4	8.22	3.29	1100>	2468.5	1442.89
11	30.04.2025	M6	P010200	pH adjustment was not performed	-	8.39	-	131	105.91	119.0	13.09	5.24	1100>	2323.5	1447.79
11	30.04.2025	M6	P010201	pH adjustment was not performed	-	8.39	-	131.07	106.04	118.9	12.88	5.15	1100>	2348.9	1452.47
11	30.04.2025	M6	P010202	pH adjustment was not performed	-	8.39	-	131.18	106.26	118.8	12.56	5.02	1100>	2468.5	1451.47
11	30.04.2025	M6	P010300	pH adjustment was not performed	-	8.34	-	131.8	107.52	118.2	10.67	4.27	1100>	2306.8	1435.56
11	30.04.2025	M6	P010301	pH adjustment was not performed	-	8.39	-	131.84	107.59	118.2	10.56	4.22	1100>	2315.0	1436.24
11	30.04.2025	M6	P010302	pH adjustment was not performed	-	8.34	-	132.41	109.53	117.6	8.06	3.22	1100>	2383.0	1444.27
11	30.04.2025	M6	P010303	pH adjustment was not performed	-	8.34	-	131.88	107.66	118.1	10.46	4.18	1100>	2332.7	1440.13
11	30.04.2025	M6	P020100	pH adjustment was not performed	-	8.36	-	130.73	106.31	119.3	12.96	5.18	1100>	2284.9	1433.28
11	30.04.2025	M6	P020101	pH adjustment was not performed	-	8.35	-	131.13	106.16	118.9	12.71	5.08	1100>	2310.8	1437.65
11	30.04.2025	M6	P020102	pH adjustment was not performed	-	8.39	-	131.54	106.99	118.5	11.47	4.59	1100>	2408.9	1436.95
11	30.04.2025	M6	P020200	pH adjustment was not performed	-	8.34	-	130.76	105.43	119.2	13.81	5.52	1100>	2249.9	1433.13
11	30.04.2025	M6	P020201	pH adjustment was not performed	-	8.35	-	130.83	105.57	119.2	13.6	5.44	1100>	2277.3	1437.36
11	30.04.2025	M6	P020202	pH adjustment was not performed	-	8.36	-	130.94	105.79	119.1	13.27	5.31	1100>	2373.6	1437.60
12	2.05.2025	M1	-	-	-	8.02	-	-	-	-	-	-	1100>	3296.4	2053.00
12	2.05.2025	M2	P040102	Lime (10%)	3	8.05	8.37	58.4	173.5	191.6	18.1	7.24	1100>	3058.8	1680.45
12	2.05.2025	M3	P040102	NaOH (50%)	0.48	8	8.38	60.0	172.7	190.0	17.3	6.92	1100>	3121.5	1693.72
12	2.05.2025	M4	P040100	NaOH (50%)	0.44	8	8.5	61.9	175.2	188.1	12.9	5.17	1100>	2727.3	1473.46
12	2.05.2025	M5	P010100	NaOH (50%)	0.4	8.04	8.34	63.6	176.0	186.4	10.4	4.16	1100>	2671.5	1502.95
12	2.05.2025	M5	P010101	NaOH (50%)	0.48	7.99	8.36	63.7	176.1	186.3	10.1	4.06	1100>	2709.3	1507.69
12	2.05.2025	M5	P010102	NaOH (50%)	0.48	8.05	8.35	64.0	176.3	186.0	9.8	3.90	1100>	2883.2	1505.13
12	2.05.2025	M5	P010200	NaOH (50%)	0.4	8	8.34	60.4	174.1	189.6	15.5	6.21	1100>	2723.7	1508.10
12	2.05.2025	M5	P010201	NaOH (50%)	0.48	8.03	8.46	60.5	174.2	189.5	15.3	6.11	1100>	2753.6	1512.56

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
12	2.05.2025	M5	P010202	NaOH (50%)	0.48	8.01	8.49	60.7	174.4	189.3	14.9	5.96	1100>	2860.1	1512.53
12	2.05.2025	M5	P010300	NaOH (50%)	0.48	8.01	8.4	62.2	175.2	187.8	12.7	5.06	1100>	2703.9	1497.57
12	2.05.2025	M5	P010301	NaOH (50%)	0.48	8.03	8.48	62.2	175.2	187.8	12.5	5.01	1100>	2713.7	1498.15
12	2.05.2025	M5	P010302	NaOH (50%)	0.44	8	8.39	64.4	176.0	185.6	9.6	3.83	1100>	2793.4	1505.08
12	2.05.2025	M5	P010303	NaOH (50%)	0.44	8.03	8.46	62.3	175.3	187.7	12.4	4.96	1100>	2734.3	1501.92
12	2.05.2025	M5	P020100	NaOH (50%)	0.52	8.01	8.55	60.8	173.8	189.2	15.4	6.15	1100>	2678.2	1495.61
12	2.05.2025	M5	P020101	NaOH (50%)	0.4	8	8.4	60.6	174.3	189.4	15.1	6.03	1100>	2708.6	1499.79
12	2.05.2025	M5	P020102	NaOH (50%)	0.44	7.99	8.4	61.6	174.8	188.4	13.6	5.44	1100>	2824.1	1500.02
12	2.05.2025	M5	P020200	NaOH (50%)	0.44	8.05	8.32	59.9	173.8	190.1	16.3	6.54	1100>	2637.2	1495.48
12	2.05.2025	M5	P020201	NaOH (50%)	0.48	8.05	8.47	60.0	173.9	190.0	16.1	6.45	1100>	2669.2	1499.54
12	2.05.2025	M5	P020202	NaOH (50%)	0.44	8	8.35	60.2	174.0	189.8	15.7	6.29	1100>	2783.1	1500.57
12	2.05.2025	M6	P010100	pH adjustment was not performed	-	7.99	-	63.6	176.0	186.4	10.4	4.14	1100>	2765.4	1511.51
12	2.05.2025	M6	P010101	pH adjustment was not performed	-	8.04	-	63.8	176.1	186.2	10.1	4.04	1100>	2794.0	1516.29
12	2.05.2025	M6	P010102	pH adjustment was not performed	-	8.01	-	64.1	176.2	185.9	9.7	3.89	1100>	2899.2	1513.71
12	2.05.2025	M6	P010200	pH adjustment was not performed	-	8.04	-	60.5	174.1	189.5	15.5	6.19	1100>	2728.9	1516.70
12	2.05.2025	M6	P010201	pH adjustment was not performed	-	7.99	-	60.6	174.2	189.4	15.2	6.09	1100>	2758.7	1521.18
12	2.05.2025	M6	P010202	pH adjustment was not performed	-	7.99	-	60.8	174.3	189.2	14.8	5.94	1100>	2899.2	1521.15
12	2.05.2025	M6	P010300	pH adjustment was not performed	-	8.05	-	62.2	175.1	187.8	12.6	5.05	1100>	2709.3	1506.11
12	2.05.2025	M6	P010301	pH adjustment was not performed	-	8.04	-	62.3	175.2	187.7	12.5	4.99	1100>	2718.9	1506.69
12	2.05.2025	M6	P010302	pH adjustment was not performed	-	8.05	-	64.5	175.9	185.5	9.5	3.81	1100>	2798.8	1513.66
12	2.05.2025	M6	P010303	pH adjustment was not performed	-	8.04	-	62.4	175.2	187.6	12.4	4.94	1100>	2739.7	1510.48
12	2.05.2025	M6	P020100	pH adjustment was not performed	-	8.01	-	61.0	173.7	189.0	15.3	6.13	1100>	2683.6	1504.13
12	2.05.2025	M6	P020101	pH adjustment was not performed	-	8.01	-	60.7	174.2	189.3	15.0	6.01	1100>	2714.0	1508.34
12	2.05.2025	M6	P020102	pH adjustment was not performed	-	8.01	-	61.7	174.8	188.3	13.6	5.42	1100>	2829.2	1508.57
12	2.05.2025	M6	P020200	pH adjustment was not performed	-	8.01	-	59.9	173.8	190.1	16.3	6.53	1100>	2642.5	1504.00
12	2.05.2025	M6	P020201	pH adjustment was not performed	-	8.04	-	60.1	173.9	189.9	16.1	6.43	1100>	2674.6	1508.09
12	2.05.2025	M6	P020202	pH adjustment was not performed	-	7.99	-	60.3	174.0	189.7	15.7	6.27	1100>	2787.7	1509.13
13	5.05.2025	M1	-	-	-	7.46	-	-	-	-	-	-	1100>	2265.8	1630.00
13	5.05.2025	M2	P040102	Lime (10%)	3.52	7.48	8.36	94.7	139.4	155.3	16.0	6.39	1100>	2084.9	1336.61
13	5.05.2025	M3	P040102	NaOH (50%)	0.48	7.43	8.46	98.9	137.2	151.1	13.8	5.53	1100>	2127.6	1347.16
13	5.05.2025	M4	P040100	NaOH (50%)	0.52	7.44	8.35	100.5	139.2	149.5	10.3	4.13	1100>	1858.9	1171.98
13	5.05.2025	M5	P010100	NaOH (50%)	0.44	7.47	8.37	101.8	139.8	148.2	8.3	3.33	1100>	1820.9	1195.42
13	5.05.2025	M5	P010101	NaOH (50%)	0.48	7.47	8.54	101.9	139.9	148.1	8.1	3.26	1100>	1846.7	1199.19
13	5.05.2025	M5	P010102	NaOH (50%)	0.44	7.47	8.49	102.1	140.0	147.9	7.8	3.13	1100>	1965.2	1197.16
13	5.05.2025	M5	P010200	NaOH (50%)	0.4	7.49	8.33	99.3	138.3	150.7	12.4	4.95	1100>	1856.5	1199.52
13	5.05.2025	M5	P010201	NaOH (50%)	0.44	7.45	8.51	99.4	138.4	150.6	12.2	4.88	1100>	1876.9	1203.07
13	5.05.2025	M5	P010202	NaOH (50%)	0.48	7.45	8.49	99.6	138.5	150.4	11.9	4.76	1100>	1949.5	1203.04
13	5.05.2025	M5	P010300	NaOH (50%)	0.48	7.48	8.48	100.7	139.2	149.3	10.1	4.05	1100>	1843.0	1191.15

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
13	5.05.2025	M5	P010301	NaOH (50%)	0.48	7.49	8.54	100.7	139.2	149.3	10.0	4.01	1100>	1849.6	1191.61
13	5.05.2025	M5	P010302	NaOH (50%)	0.44	7.49	8.43	102.5	139.8	147.5	7.7	3.07	1100>	1904.0	1197.13
13	5.05.2025	M5	P010303	NaOH (50%)	0.4	7.49	8.45	100.8	139.2	149.2	9.9	3.97	1100>	1863.7	1194.61
13	5.05.2025	M5	P020100	NaOH (50%)	0.44	7.44	8.54	99.7	138.0	150.3	12.3	4.92	1100>	1825.5	1189.58
13	5.05.2025	M5	P020101	NaOH (50%)	0.44	7.43	8.33	99.5	138.4	150.5	12.0	4.81	1100>	1846.2	1192.92
13	5.05.2025	M5	P020102	NaOH (50%)	0.52	7.44	8.39	100.2	138.9	149.8	10.9	4.35	1100>	1924.9	1193.10
13	5.05.2025	M5	P020200	NaOH (50%)	0.48	7.43	8.35	98.9	138.1	151.1	13.1	5.23	1100>	1797.5	1189.48
13	5.05.2025	M5	P020201	NaOH (50%)	0.44	7.44	8.48	99.0	138.2	151.0	12.9	5.15	1100>	1819.3	1192.71
13	5.05.2025	M5	P020202	NaOH (50%)	0.52	7.45	8.36	99.2	138.2	150.8	12.6	5.02	1100>	1896.9	1193.54
13	5.05.2025	M6	P010100	pH adjustment was not performed	-	7.44	-	102.0	139.7	148.0	8.2	3.29	1100>	1884.9	1207.38
13	5.05.2025	M6	P010101	pH adjustment was not performed	-	7.49	-	102.2	139.8	147.8	8.0	3.21	1100>	1904.4	1211.19
13	5.05.2025	M6	P010102	pH adjustment was not performed	-	7.47	-	102.4	139.9	147.6	7.7	3.09	1100>	1976.1	1209.14
13	5.05.2025	M6	P010200	pH adjustment was not performed	-	7.44	-	99.5	138.2	150.5	12.3	4.91	1100>	1860.0	1211.52
13	5.05.2025	M6	P010201	pH adjustment was not performed	-	7.49	-	99.6	138.3	150.4	12.1	4.84	1100>	1880.3	1215.10
13	5.05.2025	M6	P010202	pH adjustment was not performed	-	7.49	-	99.8	138.4	150.2	11.8	4.71	1100>	1976.1	1215.07
13	5.05.2025	M6	P010300	pH adjustment was not performed	-	7.47	-	100.9	139.1	149.1	10.0	4.01	1100>	1846.7	1203.06
13	5.05.2025	M6	P010301	pH adjustment was not performed	-	7.49	-	101.0	139.1	149.0	9.9	3.96	1100>	1853.2	1203.53
13	5.05.2025	M6	P010302	pH adjustment was not performed	-	7.45	-	102.7	139.7	147.3	7.6	3.03	1100>	1907.7	1209.10
13	5.05.2025	M6	P010303	pH adjustment was not performed	-	7.49	-	101.1	139.1	148.9	9.8	3.92	1100>	1867.4	1206.55
13	5.05.2025	M6	P020100	pH adjustment was not performed	-	7.45	-	99.9	137.9	150.1	12.2	4.87	1100>	1829.1	1201.48
13	5.05.2025	M6	P020101	pH adjustment was not performed	-	7.47	-	99.7	138.3	150.3	11.9	4.77	1100>	1849.8	1204.85
13	5.05.2025	M6	P020102	pH adjustment was not performed	-	7.47	-	100.5	138.8	149.5	10.8	4.31	1100>	1928.4	1205.03
13	5.05.2025	M6	P020200	pH adjustment was not performed	-	7.48	-	99.1	138.0	150.9	13.0	5.18	1100>	1801.1	1201.38
13	5.05.2025	M6	P020201	pH adjustment was not performed	-	7.47	-	99.2	138.0	150.8	12.8	5.10	1100>	1823.0	1204.63
13	5.05.2025	M6	P020202	pH adjustment was not performed	-	7.43	-	99.4	138.1	150.6	12.5	4.98	1100>	1900.1	1205.48
14	7.05.2025	M1	-	-	-	7.36	-	-	-	-	-	-	1100>	2231.5	1070.00
14	7.05.2025	M2	P040102	Lime (10%)	2.96	7.35	8.37	150.0	90.0	100.0	10.0	4.00	987	2044.5	881.98
14	7.05.2025	M3	P040102	NaOH (50%)	0.36	7.33	8.36	152.0	90.0	98.0	8.0	3.20	979	2086.4	888.94
14	7.05.2025	M4	P040100	NaOH (50%)	0.36	7.38	8.5	152.0	91.3	98.0	6.7	2.68	963	1822.9	773.34
14	7.05.2025	M5	P010100	NaOH (50%)	0.4	7.37	8.35	152.2	91.3	97.8	6.5	2.59	964	1785.6	788.81
14	7.05.2025	M5	P010101	NaOH (50%)	0.36	7.35	8.39	152.3	91.4	97.7	6.3	2.53	964	1810.9	791.30
14	7.05.2025	M5	P010102	NaOH (50%)	0.36	7.38	8.34	152.4	91.5	97.6	6.1	2.45	964	1927.1	789.96
14	7.05.2025	M5	P010200	NaOH (50%)	0.4	7.37	8.26	150.5	90.3	99.5	9.1	3.65	945	1820.5	791.52
14	7.05.2025	M5	P010201	NaOH (50%)	0.36	7.33	8.25	150.6	90.4	99.4	9.0	3.60	946	1840.5	793.86
14	7.05.2025	M5	P010202	NaOH (50%)	0.44	7.34	8.39	150.8	90.5	99.3	8.8	3.52	952	1911.7	793.84
14	7.05.2025	M5	P010300	NaOH (50%)	0.44	7.35	8.38	151.5	90.9	98.5	7.6	3.06	939	1807.3	785.99
14	7.05.2025	M5	P010301	NaOH (50%)	0.36	7.33	8.35	151.5	90.9	98.5	7.6	3.03	937	1813.8	786.30
14	7.05.2025	M5	P010302	NaOH (50%)	0.4	7.33	8.25	152.7	91.6	97.3	5.7	2.29	968	1867.1	789.93

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
14	7.05.2025	M5	P010303	NaOH (50%)	0.44	7.37	8.26	151.6	90.9	98.4	7.5	3.00	940	1827.6	788.28
14	7.05.2025	M5	P020100	NaOH (50%)	0.36	7.35	8.28	151.0	90.6	99.0	8.5	3.39	927	1790.1	784.96
14	7.05.2025	M5	P020101	NaOH (50%)	0.4	7.34	8.3	151.0	90.6	99.0	8.3	3.33	929	1810.4	787.16
14	7.05.2025	M5	P020102	NaOH (50%)	0.4	7.37	8.5	151.2	90.7	98.8	8.1	3.25	935	1887.6	787.28
14	7.05.2025	M5	P020200	NaOH (50%)	0.36	7.35	8.36	150.3	90.2	99.7	9.6	3.83	914	1762.7	784.89
14	7.05.2025	M5	P020201	NaOH (50%)	0.44	7.38	8.29	150.4	90.2	99.7	9.4	3.78	915	1784.1	787.02
14	7.05.2025	M5	P020202	NaOH (50%)	0.36	7.34	8.41	150.5	90.3	99.5	9.2	3.70	918	1860.2	787.57
14	7.05.2025	M6	P010100	pH adjustment was not performed	-	7.38	-	153.5	92.1	96.5	4.3	1.73	959	1848.4	794.96
14	7.05.2025	M6	P010101	pH adjustment was not performed	-	7.38	-	153.6	92.2	96.4	4.2	1.68	960	1867.5	797.47
14	7.05.2025	M6	P010102	pH adjustment was not performed	-	7.35	-	153.8	92.3	96.3	4.0	1.60	964	1937.8	796.12
14	7.05.2025	M6	P010200	pH adjustment was not performed	-	7.33	-	151.9	91.1	98.1	7.0	2.80	945	1824.0	797.69
14	7.05.2025	M6	P010201	pH adjustment was not performed	-	7.38	-	152.0	91.2	98.0	6.9	2.75	946	1843.9	800.05
14	7.05.2025	M6	P010202	pH adjustment was not performed	-	7.38	-	152.1	91.3	97.9	6.7	2.67	948	1937.8	800.03
14	7.05.2025	M6	P010300	pH adjustment was not performed	-	7.38	-	152.8	91.7	97.2	5.5	2.20	939	1810.9	792.12
14	7.05.2025	M6	P010301	pH adjustment was not performed	-	7.33	-	152.9	91.7	97.2	5.4	2.18	937	1817.3	792.43
14	7.05.2025	M6	P010302	pH adjustment was not performed	-	7.33	-	154.0	91.8	96.0	4.2	1.68	968	1870.7	796.09
14	7.05.2025	M6	P010303	pH adjustment was not performed	-	7.37	-	152.9	91.7	97.1	5.4	2.15	940	1831.2	794.43
14	7.05.2025	M6	P020100	pH adjustment was not performed	-	7.34	-	152.0	90.5	98.0	7.5	3.00	925	1793.7	791.08
14	7.05.2025	M6	P020101	pH adjustment was not performed	-	7.33	-	151.7	91.0	98.3	7.3	2.93	927	1814.0	793.30
14	7.05.2025	M6	P020102	pH adjustment was not performed	-	7.35	-	152.5	91.5	97.5	6.0	2.40	935	1891.0	793.42
14	7.05.2025	M6	P020200	pH adjustment was not performed	-	7.39	-	151.6	91.0	98.4	7.4	2.98	914	1766.2	791.01
14	7.05.2025	M6	P020201	pH adjustment was not performed	-	7.38	-	151.7	91.0	98.3	7.3	2.92	915	1787.7	793.16
14	7.05.2025	M6	P020202	pH adjustment was not performed	-	7.39	-	151.8	91.1	98.2	7.1	2.84	918	1863.3	793.71
15	9.05.2025	M1	-	-	-	7.59	-	-	-	-	-	-	1100>	2360.0	555.00
15	9.05.2025	M2	P040102	Lime (10%)	1.68	7.56	8.43	194.2	48.9	55.8	6.9	2.76	512	2183.2	456.91
15	9.05.2025	M3	P040102	NaOH (50%)	0.28	7.58	8.37	198.5	46.8	51.5	4.8	1.90	508	2227.9	460.53
15	9.05.2025	M4	P040100	NaOH (50%)	0.24	7.56	8.34	199.0	47.4	51.0	3.6	1.43	500	1946.5	400.64
15	9.05.2025	M5	P010100	NaOH (50%)	0.24	7.61	8.47	199.4	47.7	50.6	2.9	1.16	500	1906.7	408.65
15	9.05.2025	M5	P010101	NaOH (50%)	0.24	7.57	8.33	199.5	47.7	50.5	2.8	1.13	500	1933.7	409.94
15	9.05.2025	M5	P010102	NaOH (50%)	0.2	7.62	8.42	199.5	47.7	50.5	2.7	1.09	500	2057.8	409.25
15	9.05.2025	M5	P010200	NaOH (50%)	0.28	7.6	8.44	198.6	47.2	51.4	4.3	1.71	490	1944.0	410.06
15	9.05.2025	M5	P010201	NaOH (50%)	0.2	7.58	8.37	198.6	47.2	51.4	4.2	1.68	491	1965.3	411.27
15	9.05.2025	M5	P010202	NaOH (50%)	0.24	7.6	8.54	198.6	47.2	51.4	4.1	1.65	494	2041.4	411.26
15	9.05.2025	M5	P010300	NaOH (50%)	0.2	7.6	8.53	199.0	47.5	51.0	3.5	1.41	487	1929.9	407.19
15	9.05.2025	M5	P010301	NaOH (50%)	0.28	7.62	8.4	199.1	47.5	50.9	3.5	1.39	486	1936.8	407.35
15	9.05.2025	M5	P010302	NaOH (50%)	0.28	7.57	8.46	199.7	47.7	50.3	2.7	1.07	502	1993.7	409.23
15	9.05.2025	M5	P010303	NaOH (50%)	0.24	7.56	8.48	199.1	47.5	50.9	3.4	1.38	487	1951.6	408.37
15	9.05.2025	M5	P020100	NaOH (50%)	0.24	7.61	8.37	198.7	47.0	51.3	4.2	1.69	481	1911.5	406.65

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
15	9.05.2025	M5	P020101	NaOH (50%)	0.24	7.6	8.45	198.6	47.2	51.4	4.2	1.66	482	1933.2	407.79
15	9.05.2025	M5	P020102	NaOH (50%)	0.28	7.58	8.42	198.9	47.4	51.1	3.8	1.50	485	2015.6	407.85
15	9.05.2025	M5	P020200	NaOH (50%)	0.28	7.58	8.39	198.4	47.1	51.6	4.5	1.80	474	1882.3	406.62
15	9.05.2025	M5	P020201	NaOH (50%)	0.2	7.6	8.51	198.4	47.1	51.6	4.5	1.78	474	1905.1	407.72
15	9.05.2025	M5	P020202	NaOH (50%)	0.2	7.61	8.4	198.5	47.1	51.5	4.3	1.73	476	1986.4	408.01
15	9.05.2025	M6	P010100	pH adjustment was not performed	-	7.61	-	199.6	47.6	50.4	2.8	1.12	497	1973.8	412.62
15	9.05.2025	M6	P010101	pH adjustment was not performed	-	7.62	-	199.7	47.6	50.3	2.7	1.09	498	1994.2	413.92
15	9.05.2025	M6	P010102	pH adjustment was not performed	-	7.56	-	199.7	47.6	50.3	2.6	1.05	500	2069.2	413.22
15	9.05.2025	M6	P010200	pH adjustment was not performed	-	7.56	-	198.8	47.1	51.2	4.2	1.67	490	1947.7	414.04
15	9.05.2025	M6	P010201	pH adjustment was not performed	-	7.57	-	198.8	47.1	51.2	4.1	1.65	491	1969.0	415.26
15	9.05.2025	M6	P010202	pH adjustment was not performed	-	7.57	-	198.9	47.1	51.1	4.0	1.60	492	2069.2	415.25
15	9.05.2025	M6	P010300	pH adjustment was not performed	-	7.56	-	199.2	47.3	50.8	3.4	1.36	487	1933.7	411.14
15	9.05.2025	M6	P010301	pH adjustment was not performed	-	7.57	-	199.3	47.4	50.7	3.4	1.35	486	1940.6	411.30
15	9.05.2025	M6	P010302	pH adjustment was not performed	-	7.62	-	199.9	47.6	50.1	2.6	1.03	502	1997.6	413.20
15	9.05.2025	M6	P010303	pH adjustment was not performed	-	7.6	-	199.3	47.4	50.7	3.3	1.34	487	1955.4	412.33
15	9.05.2025	M6	P020100	pH adjustment was not performed	-	7.56	-	198.9	47.0	51.1	4.1	1.66	480	1915.4	410.60
15	9.05.2025	M6	P020101	pH adjustment was not performed	-	7.6	-	198.8	47.1	51.2	4.1	1.62	481	1937.0	411.75
15	9.05.2025	M6	P020102	pH adjustment was not performed	-	7.57	-	199.1	47.3	50.9	3.7	1.47	485	2019.3	411.81
15	9.05.2025	M6	P020200	pH adjustment was not performed	-	7.6	-	198.6	47.0	51.4	4.4	1.76	474	1886.0	410.57
15	9.05.2025	M6	P020201	pH adjustment was not performed	-	7.56	-	198.7	47.0	51.3	4.3	1.74	474	1909.0	411.68
15	9.05.2025	M6	P020202	pH adjustment was not performed	-	7.62	-	198.7	47.0	51.3	4.2	1.70	476	1989.7	411.97
16	13.05.2025	M1	-	-	-	7.92	-	-	-	-	-	-	1100>	2445.6	1785.00
16	13.05.2025	M2	P040102	Lime (10%)	2.28	7.94	8.43	82.3	151.4	167.7	16.3	6.51	1100>	2236.9	1453.06
16	13.05.2025	M3	P040102	NaOH (50%)	0.32	7.9	8.51	84.7	150.2	165.3	15.1	6.03	1100>	2282.7	1464.53
16	13.05.2025	M4	P040100	NaOH (50%)	0.32	7.9	8.39	86.4	152.4	163.6	11.2	4.49	1100>	1994.4	1274.09
16	13.05.2025	M5	P010100	NaOH (50%)	0.36	7.89	8.43	87.8	153.1	162.2	9.1	3.63	1100>	1953.6	1299.57
16	13.05.2025	M5	P010101	NaOH (50%)	0.36	7.91	8.46	88.0	153.2	162.0	8.8	3.54	1100>	1981.3	1303.67
16	13.05.2025	M5	P010102	NaOH (50%)	0.4	7.94	8.36	88.2	153.3	161.8	8.5	3.40	1100>	2108.4	1301.46
16	13.05.2025	M5	P010200	NaOH (50%)	0.28	7.91	8.52	85.1	151.4	164.9	13.5	5.41	1100>	1991.8	1304.03
16	13.05.2025	M5	P010201	NaOH (50%)	0.36	7.94	8.35	85.2	151.5	164.8	13.3	5.31	1100>	2013.7	1307.89
16	13.05.2025	M5	P010202	NaOH (50%)	0.4	7.89	8.39	85.4	151.6	164.6	13.0	5.18	1100>	2091.6	1307.86
16	13.05.2025	M5	P010300	NaOH (50%)	0.28	7.94	8.33	86.7	152.3	163.3	11.0	4.41	1100>	1977.3	1294.92
16	13.05.2025	M5	P010301	NaOH (50%)	0.36	7.9	8.49	86.7	152.4	163.3	10.9	4.37	1100>	1984.4	1295.43
16	13.05.2025	M5	P010302	NaOH (50%)	0.36	7.9	8.47	88.6	153.0	161.4	8.3	3.34	1100>	2042.8	1301.42
16	13.05.2025	M5	P010303	NaOH (50%)	0.28	7.93	8.47	86.8	152.4	163.2	10.8	4.32	1100>	1999.5	1298.69
16	13.05.2025	M5	P020100	NaOH (50%)	0.32	7.93	8.45	85.5	151.1	164.5	13.4	5.35	1100>	1958.5	1293.23
16	13.05.2025	M5	P020101	NaOH (50%)	0.32	7.9	8.38	85.3	151.6	164.7	13.1	5.25	1100>	1980.7	1296.84
16	13.05.2025	M5	P020102	NaOH (50%)	0.36	7.9	8.52	86.1	152.0	163.9	11.9	4.74	1100>	2065.2	1297.05

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
16	13.05.2025	M5	P020200	NaOH (50%)	0.36	7.89	8.46	84.6	151.1	165.4	14.3	5.70	1100>	1928.5	1293.12
16	13.05.2025	M5	P020201	NaOH (50%)	0.36	7.89	8.32	84.8	151.2	165.2	14.0	5.61	1100>	1952.0	1296.62
16	13.05.2025	M5	P020202	NaOH (50%)	0.32	7.89	8.32	85.0	151.3	165.0	13.7	5.48	1100>	2035.2	1297.52
16	13.05.2025	M6	P010100	pH adjustment was not performed	-	7.89	-	88.0	153.0	162.0	9.0	3.60	1100>	2022.3	1307.62
16	13.05.2025	M6	P010101	pH adjustment was not performed	-	7.91	-	88.1	153.1	161.9	8.8	3.51	1100>	2043.2	1311.76
16	13.05.2025	M6	P010102	pH adjustment was not performed	-	7.94	-	88.3	153.2	161.7	8.4	3.38	1100>	2120.1	1309.53
16	13.05.2025	M6	P010200	pH adjustment was not performed	-	7.89	-	85.2	151.3	164.8	13.5	5.38	1100>	1995.6	1312.11
16	13.05.2025	M6	P010201	pH adjustment was not performed	-	7.93	-	85.3	151.4	164.7	13.2	5.29	1100>	2017.4	1316.00
16	13.05.2025	M6	P010202	pH adjustment was not performed	-	7.95	-	85.5	151.6	164.5	12.9	5.16	1100>	2120.1	1315.97
16	13.05.2025	M6	P010300	pH adjustment was not performed	-	7.91	-	86.8	152.3	163.2	11.0	4.39	1100>	1981.3	1302.95
16	13.05.2025	M6	P010301	pH adjustment was not performed	-	7.89	-	86.8	152.3	163.2	10.9	4.34	1100>	1988.3	1303.46
16	13.05.2025	M6	P010302	pH adjustment was not performed	-	7.93	-	88.7	153.0	161.3	8.3	3.31	1100>	2046.7	1309.49
16	13.05.2025	M6	P010303	pH adjustment was not performed	-	7.9	-	86.9	152.4	163.1	10.7	4.30	1100>	2003.5	1306.74
16	13.05.2025	M6	P020100	pH adjustment was not performed	-	7.91	-	85.6	151.0	164.4	13.3	5.33	1100>	1962.5	1301.24
16	13.05.2025	M6	P020101	pH adjustment was not performed	-	7.94	-	85.4	151.5	164.6	13.1	5.22	1100>	1984.7	1304.88
16	13.05.2025	M6	P020102	pH adjustment was not performed	-	7.93	-	86.2	152.0	163.8	11.8	4.71	1100>	2068.9	1305.09
16	13.05.2025	M6	P020200	pH adjustment was not performed	-	7.95	-	84.7	151.1	165.3	14.2	5.68	1100>	1932.4	1301.13
16	13.05.2025	M6	P020201	pH adjustment was not performed	-	7.89	-	84.9	151.2	165.1	14.0	5.59	1100>	1955.9	1304.66
16	13.05.2025	M6	P020202	pH adjustment was not performed	-	7.9	-	85.1	151.3	164.9	13.6	5.46	1100>	2038.6	1305.57
17	15.05.2025	M1	-	-	-	7.72	-	-	-	-	-	-	1100>	1983.7	1006.00
17	15.05.2025	M2	P040102	Lime (10%)	2.3	7.73	8.4	153.5	86.3	96.5	10.2	4.07	928	1802.6	816.94
17	15.05.2025	M3	P040102	NaOH (50%)	0.32	7.7	8.39	156.8	84.7	93.2	8.5	3.42	920	1839.5	823.40
17	15.05.2025	M4	P040100	NaOH (50%)	0.34	7.7	8.42	157.7	85.9	92.3	6.4	2.55	905	1607.2	716.33
17	15.05.2025	M5	P010100	NaOH (50%)	0.35	7.7	8.43	158.5	86.3	91.5	5.2	2.06	906	1574.3	730.65
17	15.05.2025	M5	P010101	NaOH (50%)	0.33	7.69	8.42	158.6	86.4	91.4	5.0	2.01	906	1596.6	732.96
17	15.05.2025	M5	P010102	NaOH (50%)	0.4	7.7	8.52	158.7	86.5	91.3	4.9	1.94	906	1699.1	731.72
17	15.05.2025	M5	P010200	NaOH (50%)	0.28	7.71	8.34	157.0	85.4	93.0	7.7	3.06	888	1605.1	733.16
17	15.05.2025	M5	P010201	NaOH (50%)	0.36	7.7	8.51	157.0	85.4	93.0	7.6	3.02	889	1622.7	735.33
17	15.05.2025	M5	P010202	NaOH (50%)	0.4	7.71	8.54	157.1	85.5	92.9	7.4	2.95	895	1685.5	735.31
17	15.05.2025	M5	P010300	NaOH (50%)	0.3	7.73	8.36	157.9	85.9	92.1	6.3	2.50	883	1593.5	728.04
17	15.05.2025	M5	P010301	NaOH (50%)	0.35	7.7	8.46	157.9	85.9	92.1	6.2	2.48	881	1599.2	728.33
17	15.05.2025	M5	P010302	NaOH (50%)	0.36	7.69	8.48	158.9	86.3	91.1	4.8	1.90	910	1646.2	731.69
17	15.05.2025	M5	P010303	NaOH (50%)	0.28	7.71	8.33	157.9	85.9	92.1	6.1	2.45	883	1611.4	730.16
17	15.05.2025	M5	P020100	NaOH (50%)	0.32	7.73	8.45	157.2	85.2	92.8	7.6	3.04	872	1578.3	727.09
17	15.05.2025	M5	P020101	NaOH (50%)	0.32	7.75	8.43	157.1	85.5	92.9	7.4	2.98	873	1596.2	729.11
17	15.05.2025	M5	P020102	NaOH (50%)	0.36	7.7	8.49	157.5	85.7	92.5	6.7	2.69	880	1664.3	729.23
17	15.05.2025	M5	P020200	NaOH (50%)	0.35	7.71	8.46	156.7	85.2	93.3	8.1	3.23	859	1554.1	727.03
17	15.05.2025	M5	P020201	NaOH (50%)	0.36	7.75	8.52	156.8	85.3	93.2	8.0	3.19	860	1573.0	729.00

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
17	15.05.2025	M5	P020202	NaOH (50%)	0.31	7.7	8.42	156.9	85.3	93.1	7.8	3.11	864	1640.1	729.50
17	15.05.2025	M6	P010100	pH adjustment was not performed	-	7.73	-	158.7	86.2	91.3	5.1	2.03	902	1629.7	735.99
17	15.05.2025	M6	P010101	pH adjustment was not performed	-	7.69	-	158.8	86.3	91.2	5.0	1.98	903	1646.5	738.31
17	15.05.2025	M6	P010102	pH adjustment was not performed	-	7.74	-	158.9	86.4	91.1	4.8	1.90	906	1708.5	737.06
17	15.05.2025	M6	P010200	pH adjustment was not performed	-	7.74	-	157.1	85.3	92.9	7.6	3.03	888	1608.2	738.52
17	15.05.2025	M6	P010201	pH adjustment was not performed	-	7.71	-	157.2	85.3	92.8	7.5	2.98	889	1625.7	740.70
17	15.05.2025	M6	P010202	pH adjustment was not performed	-	7.75	-	157.3	85.4	92.7	7.3	2.91	892	1708.5	740.68
17	15.05.2025	M6	P010300	pH adjustment was not performed	-	7.71	-	158.0	85.8	92.0	6.2	2.47	883	1596.6	733.36
17	15.05.2025	M6	P010301	pH adjustment was not performed	-	7.75	-	158.0	85.8	92.0	6.1	2.45	881	1602.3	733.64
17	15.05.2025	M6	P010302	pH adjustment was not performed	-	7.69	-	159.1	86.2	90.9	4.7	1.87	910	1649.4	737.03
17	15.05.2025	M6	P010303	pH adjustment was not performed	-	7.71	-	158.1	85.9	91.9	6.1	2.42	883	1614.5	735.49
17	15.05.2025	M6	P020100	pH adjustment was not performed	-	7.7	-	157.4	85.1	92.6	7.5	3.00	869	1581.5	732.39
17	15.05.2025	M6	P020101	pH adjustment was not performed	-	7.7	-	157.3	85.4	92.7	7.4	2.94	872	1599.4	734.44
17	15.05.2025	M6	P020102	pH adjustment was not performed	-	7.73	-	157.7	85.7	92.3	6.6	2.66	880	1667.3	734.56
17	15.05.2025	M6	P020200	pH adjustment was not performed	-	7.74	-	156.9	85.1	93.1	8.0	3.20	859	1557.2	732.33
17	15.05.2025	M6	P020201	pH adjustment was not performed	-	7.69	-	156.9	85.2	93.1	7.9	3.15	860	1576.2	734.32
17	15.05.2025	M6	P020202	pH adjustment was not performed	-	7.69	-	157.1	85.3	92.9	7.7	3.07	864	1642.8	734.82
18	19.05.2025	M1	-	-	-	8.47	-	-	-	-	-	-	1100>	2375.6	855.00
18	19.05.2025	M2	P040102	pH adjustment was not performed	-	8.45	-	161.85	80.96	88.2	7.19	2.88	789	2180.1	704.08
18	19.05.2025	M4	P040100	pH adjustment was not performed	-	8.5	-	162.52	82.13	87.5	5.35	2.14	770	1943.8	617.35
18	19.05.2025	M6	P010100	pH adjustment was not performed	-	8.49	-	163.78	82.51	86.2	3.71	1.48	766	1971.0	598.48
18	19.05.2025	M6	P010101	pH adjustment was not performed	-	8.48	-	163.82	82.56	86.2	3.62	1.45	767	1991.4	600.57
18	19.05.2025	M6	P010102	pH adjustment was not performed	-	8.44	-	163.9	82.62	86.1	3.48	1.39	770	2066.3	598.93
18	19.05.2025	M6	P010200	pH adjustment was not performed	-	8.49	-	162.85	81.61	87.2	5.54	2.22	755	1945.0	600.97
18	19.05.2025	M6	P010201	pH adjustment was not performed	-	8.45	-	162.89	81.66	87.1	5.45	2.18	756	1966.2	602.91
18	19.05.2025	M6	P010202	pH adjustment was not performed	-	8.46	-	162.96	81.72	87.0	5.32	2.13	758	2066.3	602.49
18	19.05.2025	M6	P010300	pH adjustment was not performed	-	8.48	-	163.37	82.11	86.6	4.52	1.81	750	1931.0	595.89
18	19.05.2025	M6	P010301	pH adjustment was not performed	-	8.5	-	163.39	82.14	86.6	4.47	1.79	749	1937.8	596.17
18	19.05.2025	M6	P010302	pH adjustment was not performed	-	8.46	-	164.1	82.49	85.9	3.41	1.36	773	1994.8	599.51
18	19.05.2025	M6	P010303	pH adjustment was not performed	-	8.46	-	163.42	82.16	86.6	4.43	1.77	751	1952.6	597.79
18	19.05.2025	M6	P020100	pH adjustment was not performed	-	8.44	-	163.07	81.44	86.9	5.49	2.20	739	1912.7	594.94
18	19.05.2025	M6	P020101	pH adjustment was not performed	-	8.48	-	162.93	81.69	87.1	5.38	2.15	741	1934.3	596.76
18	19.05.2025	M6	P020102	pH adjustment was not performed	-	8.45	-	163.2	81.95	86.8	4.86	1.94	748	2016.4	596.47
18	19.05.2025	M6	P020200	pH adjustment was not performed	-	8.45	-	162.69	81.46	87.3	5.84	2.34	730	1883.3	594.88
18	19.05.2025	M6	P020201	pH adjustment was not performed	-	8.45	-	162.74	81.51	87.3	5.76	2.30	731	1906.3	596.64
18	19.05.2025	M6	P020202	pH adjustment was not performed	-	8.49	-	162.81	81.57	87.2	5.62	2.25	734	1986.9	596.74
19	21.05.2025	M1	-	-	-	7.95	-	-	-	-	-	-	1100>	1767.9	1596.00
19	21.05.2025	M2	P040102	Lime (10%)	2	7.93	8.51	99.4	135.7	150.6	14.9	5.96	1100>	1598.6	1301.18

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
19	21.05.2025	M3	P040102	NaOH (50%)	0.2	7.98	8.38	102.2	134.3	147.8	13.5	5.39	1100>	1631.3	1311.45
19	21.05.2025	M4	P040100	NaOH (50%)	0.22	7.92	8.38	103.7	136.2	146.3	10.0	4.02	1100>	1425.3	1140.91
19	21.05.2025	M5	P010100	NaOH (50%)	0.2	7.97	8.44	105.0	136.9	145.0	8.1	3.24	1100>	1396.1	1163.73
19	21.05.2025	M5	P010101	NaOH (50%)	0.28	7.96	8.53	105.1	137.0	144.9	7.9	3.17	1100>	1415.9	1167.41
19	21.05.2025	M5	P010102	NaOH (50%)	0.28	7.97	8.52	105.3	137.1	144.7	7.6	3.05	1100>	1506.8	1165.43
19	21.05.2025	M5	P010200	NaOH (50%)	0.2	7.92	8.38	102.5	135.4	147.5	12.1	4.83	1100>	1423.4	1167.72
19	21.05.2025	M5	P010201	NaOH (50%)	0.22	7.97	8.42	102.7	135.5	147.3	11.9	4.76	1100>	1439.1	1171.18
19	21.05.2025	M5	P010202	NaOH (50%)	0.30	7.98	8.55	102.8	135.6	147.2	11.6	4.64	1100>	1494.7	1171.16
19	21.05.2025	M5	P010300	NaOH (50%)	0.24	7.94	8.46	103.9	136.2	146.1	9.9	3.95	1100>	1413.1	1159.57
19	21.05.2025	M5	P010301	NaOH (50%)	0.2	7.96	8.39	104.0	136.2	146.0	9.8	3.90	1100>	1418.2	1160.02
19	21.05.2025	M5	P010302	NaOH (50%)	0.22	7.92	8.4	105.7	136.8	144.3	7.5	2.98	1100>	1459.8	1165.39
19	21.05.2025	M5	P010303	NaOH (50%)	0.24	7.93	8.48	104.0	136.3	146.0	9.7	3.87	1100>	1429.0	1162.95
19	21.05.2025	M5	P020100	NaOH (50%)	0.23	7.96	8.36	103.0	135.1	147.0	12.0	4.78	1100>	1399.6	1158.05
19	21.05.2025	M5	P020101	NaOH (50%)	0.2	7.96	8.37	102.8	135.5	147.2	11.7	4.69	1100>	1415.5	1161.28
19	21.05.2025	M5	P020102	NaOH (50%)	0.16	7.98	8.34	103.5	135.9	146.5	10.6	4.23	1100>	1475.9	1161.46
19	21.05.2025	M5	P020200	NaOH (50%)	0.21	7.92	8.37	102.1	135.1	147.9	12.7	5.10	1100>	1378.2	1157.95
19	21.05.2025	M5	P020201	NaOH (50%)	0.24	7.96	8.44	102.2	135.2	147.8	12.5	5.02	1100>	1395.0	1161.10
19	21.05.2025	M5	P020202	NaOH (50%)	0.2	7.92	8.36	102.4	135.3	147.6	12.2	4.90	1100>	1454.5	1161.90
19	21.05.2025	M6	P010100	pH adjustment was not performed	-	7.92	-	105.1	136.8	144.9	8.1	3.22	1100>	1445.2	1171.76
19	21.05.2025	M6	P010101	pH adjustment was not performed	-	7.94	-	105.2	136.9	144.8	7.9	3.14	1100>	1460.2	1175.46
19	21.05.2025	M6	P010102	pH adjustment was not performed	-	7.97	-	105.4	137.0	144.6	7.6	3.02	1100>	1515.1	1173.47
19	21.05.2025	M6	P010200	pH adjustment was not performed	-	7.97	-	102.6	135.3	147.4	12.0	4.81	1100>	1426.1	1175.78
19	21.05.2025	M6	P010201	pH adjustment was not performed	-	7.97	-	102.8	135.4	147.2	11.8	4.73	1100>	1441.7	1179.26
19	21.05.2025	M6	P010202	pH adjustment was not performed	-	7.92	-	103.0	135.5	147.0	11.5	4.61	1100>	1515.1	1179.24
19	21.05.2025	M6	P010300	pH adjustment was not performed	-	7.93	-	104.0	136.2	146.0	9.8	3.92	1100>	1415.9	1167.57
19	21.05.2025	M6	P010301	pH adjustment was not performed	-	7.92	-	104.1	136.2	145.9	9.7	3.88	1100>	1420.9	1168.02
19	21.05.2025	M6	P010302	pH adjustment was not performed	-	7.97	-	105.8	136.8	144.2	7.4	2.96	1100>	1462.7	1173.43
19	21.05.2025	M6	P010303	pH adjustment was not performed	-	7.94	-	104.2	136.2	145.8	9.6	3.84	1100>	1431.8	1170.97
19	21.05.2025	M6	P020100	pH adjustment was not performed	-	7.94	-	103.0	135.0	147.0	11.9	4.76	1100>	1402.5	1166.04
19	21.05.2025	M6	P020101	pH adjustment was not performed	-	7.93	-	102.9	135.5	147.1	11.7	4.67	1100>	1418.3	1169.30
19	21.05.2025	M6	P020102	pH adjustment was not performed	-	7.92	-	103.6	135.9	146.4	10.5	4.22	1100>	1478.5	1169.48
19	21.05.2025	M6	P020200	pH adjustment was not performed	-	7.92	-	102.2	135.1	147.8	12.7	5.07	1100>	1381.0	1165.94
19	21.05.2025	M6	P020201	pH adjustment was not performed	-	7.97	-	102.4	135.2	147.6	12.5	5.00	1100>	1397.8	1169.11
19	21.05.2025	M6	P020202	pH adjustment was not performed	-	7.93	-	102.5	135.3	147.5	12.2	4.88	1100>	1456.9	1169.91
20	23.05.2025	M1	-	-	-	8.41	-	-	-	-	-	-	1100>	1730.8	805.00
20	23.05.2025	M2	P040102	pH adjustment was not performed	-	8.39	-	164.37	78.86	85.6	6.77	2.71	743	1601.3	668.05
20	23.05.2025	M4	P040100	pH adjustment was not performed	-	8.39	-	164.97	79.99	85.0	5.04	2.02	724	1427.8	585.76
20	23.05.2025	M6	P010100	pH adjustment was not performed	-	8.44	-	166.14	80.37	83.9	3.49	1.40	721	1447.8	567.86

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
20	23.05.2025	M6	P010101	pH adjustment was not performed	-	8.42	-	166.18	80.41	83.8	3.41	1.36	722	1462.7	569.83
20	23.05.2025	M6	P010102	pH adjustment was not performed	-	8.4	-	166.25	80.48	83.8	3.28	1.31	725	1517.8	568.28
20	23.05.2025	M6	P010200	pH adjustment was not performed	-	8.44	-	165.29	79.49	84.7	5.22	2.09	711	1428.6	570.22
20	23.05.2025	M6	P010201	pH adjustment was not performed	-	8.44	-	165.33	79.53	84.7	5.13	2.05	711	1444.2	572.07
20	23.05.2025	M6	P010202	pH adjustment was not performed	-	8.4	-	165.4	79.6	84.6	5	2.00	714	1517.8	571.67
20	23.05.2025	M6	P010300	pH adjustment was not performed	-	8.38	-	165.77	79.98	84.2	4.25	1.70	706	1418.4	565.40
20	23.05.2025	M6	P010301	pH adjustment was not performed	-	8.42	-	165.79	80	84.2	4.21	1.68	705	1423.4	565.67
20	23.05.2025	M6	P010302	pH adjustment was not performed	-	8.42	-	166.44	80.34	83.6	3.21	1.28	728	1465.2	568.84
20	23.05.2025	M6	P010303	pH adjustment was not performed	-	8.43	-	165.81	80.02	84.2	4.17	1.67	707	1434.3	567.21
20	23.05.2025	M6	P020100	pH adjustment was not performed	-	8.43	-	165.51	79.32	84.5	5.17	2.07	696	1404.9	564.51
20	23.05.2025	M6	P020101	pH adjustment was not performed	-	8.38	-	165.36	79.57	84.6	5.07	2.03	698	1420.8	566.23
20	23.05.2025	M6	P020102	pH adjustment was not performed	-	8.43	-	165.61	79.82	84.4	4.57	1.83	704	1481.1	565.95
20	23.05.2025	M6	P020200	pH adjustment was not performed	-	8.4	-	165.15	79.35	84.9	5.5	2.20	687	1383.4	564.45
20	23.05.2025	M6	P020201	pH adjustment was not performed	-	8.44	-	165.19	79.39	84.8	5.42	2.17	688	1400.2	566.11
20	23.05.2025	M6	P020202	pH adjustment was not performed	-	8.39	-	165.26	79.45	84.7	5.29	2.12	691	1459.4	566.21
21	27.05.2025	M1	-	-	-	8	-	-	-	-	-	-	1100>	2132.7	1505.00
21	27.05.2025	M2	P040102	Lime (10%)	1.68	7.97	8.42	108.4	127.7	141.6	13.8	5.52	1100>	1961.7	1237.42
21	27.05.2025	M3	P040102	NaOH (50%)	0.16	7.99	8.41	110.7	126.6	139.3	12.7	5.08	1100>	2001.9	1247.19
21	27.05.2025	M4	P040100	NaOH (50%)	0.16	7.98	8.42	112.1	128.5	137.9	9.5	3.79	1100>	1749.1	1085.01
21	27.05.2025	M5	P010100	NaOH (50%)	0.24	7.97	8.36	113.3	129.1	136.7	7.6	3.06	1100>	1713.3	1106.71
21	27.05.2025	M5	P010101	NaOH (50%)	0.16	8.01	8.39	113.4	129.1	136.6	7.4	2.98	1100>	1737.6	1110.20
21	27.05.2025	M5	P010102	NaOH (50%)	0.16	8.02	8.33	113.6	129.2	136.4	7.2	2.86	1100>	1849.1	1108.32
21	27.05.2025	M5	P010200	NaOH (50%)	0.16	7.99	8.33	111.0	127.6	139.0	11.4	4.55	1100>	1746.8	1110.51
21	27.05.2025	M5	P010201	NaOH (50%)	0.2	7.98	8.51	111.0	127.7	139.0	11.2	4.49	1100>	1766.0	1113.79
21	27.05.2025	M5	P010202	NaOH (50%)	0.2	7.99	8.51	111.2	127.8	138.8	10.9	4.38	1100>	1834.3	1113.77
21	27.05.2025	M5	P010300	NaOH (50%)	0.16	8.03	8.5	112.3	128.4	137.7	9.3	3.72	1100>	1734.1	1102.75
21	27.05.2025	M5	P010301	NaOH (50%)	0.2	8.03	8.49	112.3	128.5	137.7	9.2	3.68	1100>	1740.3	1103.18
21	27.05.2025	M5	P010302	NaOH (50%)	0.24	7.99	8.38	113.9	129.0	136.1	7.0	2.81	1100>	1791.5	1108.28
21	27.05.2025	M5	P010303	NaOH (50%)	0.16	8.02	8.46	112.4	128.5	137.6	9.1	3.64	1100>	1753.6	1105.95
21	27.05.2025	M5	P020100	NaOH (50%)	0.16	8.03	8.41	111.3	127.4	138.7	11.3	4.51	1100>	1717.6	1101.30
21	27.05.2025	M5	P020101	NaOH (50%)	0.2	7.97	8.32	111.2	127.8	138.8	11.1	4.42	1100>	1737.1	1104.39
21	27.05.2025	M5	P020102	NaOH (50%)	0.24	8.02	8.37	111.8	128.2	138.2	10.0	3.99	1100>	1811.2	1104.56
21	27.05.2025	M5	P020200	NaOH (50%)	0.24	8.02	8.36	110.6	127.4	139.4	12.0	4.80	1100>	1691.3	1101.21
21	27.05.2025	M5	P020201	NaOH (50%)	0.16	7.98	8.49	110.7	127.5	139.3	11.8	4.74	1100>	1711.8	1104.20
21	27.05.2025	M5	P020202	NaOH (50%)	0.16	8.02	8.53	110.8	127.6	139.2	11.6	4.62	1100>	1784.9	1104.97
21	27.05.2025	M6	P010100	pH adjustment was not performed	-	8.02	-	113.4	129.0	136.6	7.6	3.04	1100>	1773.5	1117.22
21	27.05.2025	M6	P010101	pH adjustment was not performed	-	7.98	-	113.5	129.1	136.5	7.4	2.96	1100>	1791.9	1120.75
21	27.05.2025	M6	P010102	pH adjustment was not performed	-	8.03	-	113.7	129.2	136.3	7.1	2.85	1100>	1859.3	1118.85

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
21	27.05.2025	M6	P010200	pH adjustment was not performed	-	8.03	-	111.0	127.6	139.0	11.3	4.54	1100>	1750.1	1121.06
21	27.05.2025	M6	P010201	pH adjustment was not performed	-	7.97	-	111.2	127.7	138.8	11.2	4.46	1100>	1769.2	1124.37
21	27.05.2025	M6	P010202	pH adjustment was not performed	-	8.03	-	111.3	127.8	138.7	10.9	4.35	1100>	1859.3	1124.35
21	27.05.2025	M6	P010300	pH adjustment was not performed	-	7.98	-	112.4	128.4	137.6	9.2	3.70	1100>	1737.6	1113.23
21	27.05.2025	M6	P010301	pH adjustment was not performed	-	8.02	-	112.4	128.4	137.6	9.1	3.66	1100>	1743.7	1113.66
21	27.05.2025	M6	P010302	pH adjustment was not performed	-	8.03	-	114.0	129.0	136.0	7.0	2.79	1100>	1794.9	1118.81
21	27.05.2025	M6	P010303	pH adjustment was not performed	-	8.03	-	112.5	128.5	137.5	9.1	3.62	1100>	1757.0	1116.46
21	27.05.2025	M6	P020100	pH adjustment was not performed	-	7.97	-	111.4	127.3	138.6	11.2	4.49	1100>	1721.1	1111.77
21	27.05.2025	M6	P020101	pH adjustment was not performed	-	8.02	-	111.3	127.7	138.7	11.0	4.41	1100>	1740.5	1114.88
21	27.05.2025	M6	P020102	pH adjustment was not performed	-	7.97	-	111.9	128.1	138.1	9.9	3.97	1100>	1814.4	1115.05
21	27.05.2025	M6	P020200	pH adjustment was not performed	-	7.99	-	110.7	127.4	139.3	12.0	4.79	1100>	1694.7	1111.67
21	27.05.2025	M6	P020201	pH adjustment was not performed	-	7.99	-	110.8	127.4	139.2	11.8	4.71	1100>	1715.3	1114.69
21	27.05.2025	M6	P020202	pH adjustment was not performed	-	8.02	-	111.0	127.5	139.0	11.5	4.60	1100>	1787.8	1115.46
22	29.05.2025	M1	-	-	-	8	-	-	-	-	-	-	1100>	2629.2	1183.00
22	29.05.2025	M2	P040102	Lime (10%)	1.7	7.99	8.48	138.0	100.8	112.0	11.2	4.48	1091	2427.5	988.10
22	29.05.2025	M3	P040102	NaOH (50%)	0.18	8.03	8.4	140.5	99.5	109.5	10.0	4.00	1082	2477.3	995.90
22	29.05.2025	M4	P040100	NaOH (50%)	0.16	7.99	8.35	141.6	101.0	108.4	7.4	2.98	1065	2164.4	866.39
22	29.05.2025	M5	P010100	NaOH (50%)	0.24	8.02	8.54	142.5	101.5	107.5	6.0	2.41	1065	2120.1	883.73
22	29.05.2025	M5	P010101	NaOH (50%)	0.16	8.01	8.38	142.6	101.5	107.4	5.9	2.35	1066	2150.2	886.51
22	29.05.2025	M5	P010102	NaOH (50%)	0.17	7.99	8.34	142.8	101.6	107.2	5.6	2.26	1066	2288.1	885.01
22	29.05.2025	M5	P010200	NaOH (50%)	0.16	7.98	8.33	140.7	100.3	109.3	9.0	3.58	1045	2161.6	886.76
22	29.05.2025	M5	P010201	NaOH (50%)	0.2	8.03	8.47	140.8	100.4	109.2	8.8	3.53	1046	2185.3	889.38
22	29.05.2025	M5	P010202	NaOH (50%)	0.2	8.03	8.45	140.9	100.5	109.1	8.6	3.44	1053	2269.8	889.36
22	29.05.2025	M5	P010300	NaOH (50%)	0.15	8.02	8.38	141.7	101.0	108.3	7.3	2.92	1038	2145.9	880.56
22	29.05.2025	M5	P010301	NaOH (50%)	0.21	7.99	8.46	141.7	101.0	108.3	7.2	2.90	1036	2153.6	880.91
22	29.05.2025	M5	P010302	NaOH (50%)	0.24	8.03	8.55	143.0	101.4	107.0	5.5	2.22	1070	2216.9	884.98
22	29.05.2025	M5	P010303	NaOH (50%)	0.16	8.03	8.38	141.8	101.0	108.2	7.2	2.86	1039	2170.0	883.12
22	29.05.2025	M5	P020100	NaOH (50%)	0.16	8.01	8.38	141.0	100.1	109.0	8.9	3.55	1025	2125.5	879.41
22	29.05.2025	M5	P020101	NaOH (50%)	0.17	7.99	8.41	140.8	100.5	109.2	8.7	3.48	1027	2149.6	881.87
22	29.05.2025	M5	P020102	NaOH (50%)	0.25	7.98	8.52	141.3	100.8	108.7	7.9	3.15	1034	2241.2	882.00
22	29.05.2025	M5	P020200	NaOH (50%)	0.24	8.02	8.51	140.4	100.2	109.6	9.5	3.78	1010	2092.9	879.33
22	29.05.2025	M5	P020201	NaOH (50%)	0.16	8.01	8.37	140.5	100.2	109.5	9.3	3.72	1011	2118.3	881.72
22	29.05.2025	M5	P020202	NaOH (50%)	0.16	8.02	8.38	140.6	100.3	109.4	9.1	3.63	1015	2208.7	882.33
22	29.05.2025	M6	P010100	pH adjustment was not performed	-	8.03	-	142.6	101.4	107.4	6.0	2.39	1060	2194.7	889.47
22	29.05.2025	M6	P010101	pH adjustment was not performed	-	7.97	-	142.7	101.5	107.3	5.8	2.33	1061	2217.4	892.27
22	29.05.2025	M6	P010102	pH adjustment was not performed	-	8.02	-	142.9	101.6	107.1	5.6	2.24	1066	2300.8	890.76
22	29.05.2025	M6	P010200	pH adjustment was not performed	-	7.97	-	140.8	100.3	109.2	8.9	3.57	1045	2165.7	892.52
22	29.05.2025	M6	P010201	pH adjustment was not performed	-	8.03	-	140.9	100.4	109.1	8.8	3.51	1046	2189.3	895.16

Day	Date	Scenario	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (CEN + SLG) (mL)	Volume (SLG) (mL)	%SLG	Turbidity (Sup) (FAU)	COD (Sup) (mg/L)	TSS (Sup) (mg/L)
22	29.05.2025	M6	P010202	pH adjustment was not performed	-	8.01	-	141.0	100.4	109.0	8.6	3.42	1049	2300.8	895.14
22	29.05.2025	M6	P010300	pH adjustment was not performed	-	7.99	-	141.8	100.9	108.2	7.3	2.91	1038	2150.2	886.29
22	29.05.2025	M6	P010301	pH adjustment was not performed	-	8.03	-	141.9	101.0	108.1	7.2	2.88	1036	2157.8	886.63
22	29.05.2025	M6	P010302	pH adjustment was not performed	-	8.03	-	143.1	101.4	106.9	5.5	2.20	1070	2221.2	890.73
22	29.05.2025	M6	P010303	pH adjustment was not performed	-	7.98	-	141.9	101.0	108.1	7.1	2.85	1039	2174.3	888.86
22	29.05.2025	M6	P020100	pH adjustment was not performed	-	7.97	-	141.1	100.1	108.9	8.8	3.53	1022	2129.7	885.12
22	29.05.2025	M6	P020101	pH adjustment was not performed	-	8.02	-	140.9	100.4	109.1	8.7	3.46	1025	2153.8	887.60
22	29.05.2025	M6	P020102	pH adjustment was not performed	-	7.98	-	141.5	100.7	108.5	7.8	3.12	1034	2245.3	887.74
22	29.05.2025	M6	P020200	pH adjustment was not performed	-	8.01	-	140.5	100.1	109.5	9.4	3.76	1010	2097.1	885.04
22	29.05.2025	M6	P020201	pH adjustment was not performed	-	7.99	-	140.6	100.2	109.4	9.3	3.70	1011	2122.6	887.45
22	29.05.2025	M6	P020202	pH adjustment was not performed	-	8.02	-	140.7	100.3	109.3	9.0	3.62	1015	2212.4	888.06

Notes:

- ✓ The initial volume of the wastewater samples was 250 mL, and a uniform coagulant dose of 0.6 g/L was applied.
- ✓ Since Scenario M1 represents raw wastewater conditions, only turbidity, COD, and TSS measurements were conducted for this scenario.
- ✓ When the natural pH of the raw wastewater fell within the predefined target range, no pH-adjustment chemicals were introduced. Under such conditions, Scenarios M2 and M3, and likewise Scenarios M5 and M6, corresponded to identical operational settings. Therefore, repeating the same tests was considered unnecessary on days when this situation occurred. This overlap was documented on the 10th, 11th, 18th, and 20th test days.

APPENDIX B: PERFORMANCE-BASED RANKING OF HYBRID COAGULANT FORMULATIONS

Table B.1. Performance-based ranking of hybrid coagulant formulations.

Formulation	Average SLG (%)	Average Turbidity Removal (%)	Average COD Removal (%)	Average TSS Removal (%)	SLG_norm	Turb_norm	COD_norm	TSS_norm	Score	Rank
M6 - P010100	2.45	15.55	16.97	26.06	0.921	0.883	0.821	0.986	0.944	8
M6 - P010101	2.38	15.50	16.11	25.82	0.945	0.880	0.780	0.977	0.928	10
M6 - P010102	2.29	15.31	12.96	25.96	0.982	0.870	0.627	0.982	0.872	15
M6 - P010200	3.66	16.19	18.07	25.80	0.615	0.919	0.874	0.976	0.922	11
M6 - P010201	3.60	16.15	17.17	25.58	0.625	0.917	0.831	0.968	0.903	12
M6 - P010202	3.51	16.03	12.96	25.59	0.641	0.910	0.627	0.968	0.822	16
M6 - P010300	2.98	16.46	18.66	26.32	0.755	0.935	0.903	0.996	0.963	4
M6 - P010301	2.95	16.55	18.37	26.29	0.764	0.940	0.889	0.995	0.959	5
M6 - P010302	2.25	15.14	15.97	25.95	1.000	0.860	0.773	0.982	0.932	9
M6 - P010303	2.92	16.43	17.74	26.11	0.771	0.933	0.859	0.988	0.945	7
M6 - P020100	3.64	17.11	19.68	26.42	0.619	0.971	0.952	1.000	0.969	2
M6 - P020101	3.56	16.99	18.52	26.22	0.632	0.965	0.896	0.992	0.945	6
M6 - P020102	3.21	16.62	15.06	26.21	0.703	0.943	0.729	0.992	0.886	14
M6 - P020200	3.86	17.61	20.66	26.43	0.583	1.000	1.000	1.000	0.987	1
M6 - P020201	3.80	17.56	19.70	26.23	0.592	0.997	0.953	0.992	0.967	3
M6 - P020202	3.71	17.39	16.30	26.19	0.607	0.987	0.789	0.991	0.901	13

APPENDIX C: MASS BALANCE CALCULATIONS FOR COD

Table C.1. Mass balance calculations for COD.

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{COD, in}$ (mg/L)	$M_{COD, In Total}$ (mg)	$C_{COD, Coagulant}$ (mg/L)	$M_{COD, Coagulant}$ (mg)	$C_{COD, SUP}$ (mg/L)	$M_{COD, SUP}$ (mg)	$C_{COD, CEN}$ (mg/L)	$M_{COD, CEN}$ (mg)	$M_{COD, SLG}$ (mg)	COD Removal (%)	$C_{COD, SLG}$ (mg/L)
1	M2	P040102	Lime (10%)	3.68	7.39	8.46	250.0	168.3	58.3	23.4	1661.0	415.25	0	0.00	632.3	106.40	764.4	44.57	264.28	63.64	11281.8
1	M6	P010300	-	-	7.41	-	250.0	145.4	87.2	17.5	1661.0	415.25	5874	3.64	350.6	50.97	433.4	37.78	330.15	78.81	18899.5
1	M6	P010301	-	-	7.41	-	250.0	145.6	87.3	17.2	1661.0	415.25	7050	4.37	342.8	49.89	414.9	36.21	333.52	79.48	19427.8
1	M6	P020100	-	-	7.39	-	250.0	146.4	87.2	16.5	1661.0	415.25	6408	3.83	232.5	34.02	271.9	23.70	361.35	86.23	21947.3
1	M6	P020200	-	-	7.37	-	250.0	144.5	87.1	18.4	1661.0	415.25	6675	3.88	430.6	62.22	505.3	43.99	312.92	74.66	16982.0
1	M6	P020201	-	-	7.41	-	250.0	145.2	87.1	17.8	1661.0	415.25	9210	5.37	533.9	77.50	649.4	56.54	286.57	68.13	16126.9
2	M2	P040102	Lime (10%)	5.28	7.07	8.59	250.0	159.4	55.2	35.4	2540.6	635.15	0	0.00	868.4	138.39	1070.2	59.11	437.65	68.91	12362.0
2	M6	P010300	-	-	7.08	-	250.0	139.8	83.8	26.4	2540.6	635.15	5874	3.64	458.8	64.12	547.7	45.91	528.76	82.78	20028.2
2	M6	P010301	-	-	7.07	-	250.0	140.1	84.0	25.9	2540.6	635.15	7050	4.37	491.7	68.87	572.4	48.07	522.58	81.71	20141.5
2	M6	P020100	-	-	7.07	-	250.0	141.1	84.0	24.9	2540.6	635.15	6408	3.83	372.3	52.52	441.9	37.14	549.32	85.97	22075.9
2	M6	P020200	-	-	7.09	-	250.0	139.3	83.6	27.0	2540.6	635.15	6675	3.88	655.2	91.30	805.2	67.35	480.38	75.17	17786.8
2	M6	P020201	-	-	7.09	-	250.0	139.5	83.7	26.9	2540.6	635.15	9210	5.37	721.2	100.59	885.9	74.12	465.81	72.72	17344.9
3	M2	P040102	Lime (10%)	2.94	7.61	8.54	150.0	103.5	35.9	10.6	1905.2	285.78	0	0.00	634.2	65.66	766.2	27.49	192.63	67.40	18191.0
3	M6	P010300	-	-	7.62	-	150.0	88.8	53.3	7.9	1905.2	285.78	5874	2.18	330.3	29.34	385.9	20.56	238.06	82.67	30147.2
3	M6	P010301	-	-	7.59	-	150.0	88.9	53.3	7.8	1905.2	285.78	7050	2.62	371.0	32.99	436.0	23.24	232.17	80.50	29916.7
3	M6	P020100	-	-	7.61	-	150.0	89.3	53.2	7.4	1905.2	285.78	6408	2.30	291.5	26.05	355.2	18.90	243.13	84.40	32666.6
3	M6	P020200	-	-	7.60	-	150.0	88.5	53.2	8.3	1905.2	285.78	6675	2.33	499.5	44.20	616.8	32.83	211.07	73.26	25541.2
3	M6	P020201	-	-	7.62	-	150.0	88.7	53.2	8.0	1905.2	285.78	9210	3.22	523.2	46.43	628.0	33.43	209.14	72.37	26036.0
4	M2	P040102	Lime (10%)	5.12	7.03	8.51	250.0	159.3	55.2	35.5	2578.8	644.70	0	0.00	821.9	130.95	967.8	53.43	460.32	71.40	12978.5
4	M6	P010300	-	-	7.05	-	250.0	139.7	83.8	26.4	2578.8	644.70	5874	3.64	441.9	61.75	515.6	43.21	543.37	83.81	20544.3
4	M6	P010301	-	-	7.02	-	250.0	140.0	84.0	26.0	2578.8	644.70	7050	4.37	521.8	73.08	628.7	52.79	523.21	80.61	20128.8

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{COD, in}$ (mg/L)	$M_{COD, In\ Total}$ (mg)	$C_{COD, Coagulant}$ (mg/L)	$M_{COD, Coagulant}$ (mg)	$C_{COD, SUP}$ (mg/L)	$M_{COD, SUP}$ (mg)	$C_{COD, CEN}$ (mg/L)	$M_{COD, CEN}$ (mg)	$M_{COD, SLG}$ (mg)	COD Removal (%)	$C_{COD, SLG}$ (mg/L)
4	M6	P020100	-	-	7.01	-	250.0	141.1	84.0	24.9	2578.8	644.70	6408	3.83	406.8	57.38	502.7	42.23	548.92	84.64	22019.4
4	M6	P020200	-	-	7.06	-	250.0	139.2	83.6	27.2	2578.8	644.70	6675	3.88	662.8	92.25	804.8	67.30	489.03	75.40	17997.2
4	M6	P020201	-	-	7.05	-	250.0	139.4	83.6	26.9	2578.8	644.70	9210	5.37	678.5	94.62	795.2	66.52	488.93	75.21	18172.4
5	M2	P040102	Lime (10%)	2.72	7.62	8.41	250.0	165.3	57.3	27.4	1839.0	459.75	0	0.00	570.1	94.22	663.6	38.01	327.52	71.24	11933.0
5	M6	P010300	-	-	7.63	-	250.0	143.5	86.1	20.5	1839.0	459.75	5874	3.64	323.7	46.44	385.4	33.16	383.78	82.82	18751.0
5	M6	P010301	-	-	7.60	-	250.0	143.7	86.2	20.1	1839.0	459.75	7050	4.37	387.3	55.66	476.7	41.08	367.38	79.16	18264.4
5	M6	P020100	-	-	7.61	-	250.0	144.6	86.1	19.3	1839.0	459.75	6408	3.83	288.9	41.78	354.2	30.51	391.30	84.41	20283.7
5	M6	P020200	-	-	7.61	-	250.0	143.1	85.9	20.9	1839.0	459.75	6675	3.88	453.0	64.83	535.8	46.04	352.76	76.09	16847.8
5	M6	P020201	-	-	7.60	-	250.0	143.2	85.9	20.8	1839.0	459.75	9210	5.37	474.5	67.97	552.8	47.50	349.65	75.17	16793.5
6	M2	P040102	Lime (10%)	3.08	7.52	8.40	250.0	165.5	57.4	27.1	1819.5	454.88	0	0.00	570.1	94.37	671.4	38.52	321.99	70.79	11880.6
6	M6	P010300	-	-	7.51	-	250.0	143.6	86.1	20.2	1819.5	454.88	5874	3.64	334.5	48.05	408.6	35.20	375.27	81.84	18568.2
6	M6	P010301	-	-	7.53	-	250.0	143.9	86.3	19.9	1819.5	454.88	7050	4.37	388.0	55.82	478.7	41.29	362.13	78.85	18232.5
6	M6	P020100	-	-	7.54	-	250.0	144.7	86.2	19.0	1819.5	454.88	6408	3.83	275.9	39.93	330.1	28.46	390.32	85.09	20490.3
6	M6	P020200	-	-	7.53	-	250.0	143.3	86.0	20.7	1819.5	454.88	6675	3.88	433.4	62.10	504.7	43.41	353.24	77.00	17085.6
6	M6	P020201	-	-	7.51	-	250.0	143.4	86.0	20.6	1819.5	454.88	9210	5.37	478.9	68.68	567.2	48.80	342.76	74.47	16672.5
7	M2	P040102	Lime (10%)	2.44	7.68	8.38	250.0	169.8	58.8	21.3	1797.4	449.35	0	0.00	586.3	99.56	708.5	41.69	308.10	68.57	14432.8
7	M6	P010300	-	-	7.71	-	250.0	146.3	87.8	15.9	1797.4	449.35	5874	3.64	339.6	49.69	419.7	36.83	366.47	80.90	23020.9
7	M6	P010301	-	-	7.71	-	250.0	146.5	87.8	15.6	1797.4	449.35	7050	4.37	374.4	54.85	453.3	39.82	359.05	79.13	22950.4
7	M6	P020100	-	-	7.66	-	250.0	147.3	87.7	15.0	1797.4	449.35	6408	3.83	261.4	38.49	305.7	26.82	387.87	85.59	25850.8
7	M6	P020200	-	-	7.66	-	250.0	145.7	87.7	16.6	1797.4	449.35	6675	3.88	429.2	62.53	503.4	44.13	346.57	76.47	20838.1
7	M6	P020201	-	-	7.68	-	250.0	146.1	87.7	16.2	1797.4	449.35	9210	5.37	493.8	72.17	600.4	52.63	329.92	72.55	20373.6
8	M2	P040102	Lime (10%)	2.47	7.85	8.57	150.0	105.6	36.6	7.7	1050.4	157.56	0	0.00	396.3	41.87	479.1	17.54	98.15	62.29	12679.4
8	M6	P010300	-	-	7.86	-	150.0	89.8	54.1	6.1	1050.4	157.56	5874	2.18	219.2	19.69	271.0	14.65	125.40	78.50	20456.8
8	M6	P010301	-	-	7.84	-	150.0	90.2	54.1	5.7	1050.4	157.56	7050	2.62	212.3	19.16	257.0	13.90	127.13	79.36	22408.5
8	M6	P020100	-	-	7.83	-	150.0	90.6	54.0	5.4	1050.4	157.56	6408	2.30	143.5	13.00	167.8	9.05	137.80	86.20	25327.5
8	M6	P020200	-	-	7.85	-	150.0	90.0	54.1	5.9	1050.4	157.56	6675	2.33	268.3	24.16	314.8	17.02	118.72	74.25	20103.3

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{COD,in}$ (mg/L)	$M_{COD,In\ Total}$ (mg)	$C_{COD,Coagulant}$ (mg/L)	$M_{COD,Coagulant}$ (mg)	$C_{COD,SUP}$ (mg/L)	$M_{COD,SUP}$ (mg)	$C_{COD,CEN}$ (mg/L)	$M_{COD,CEN}$ (mg)	$M_{COD,SLG}$ (mg)	COD Removal (%)	$C_{COD,SLG}$ (mg/L)
8	M6	P020201	-	-	7.84	-	150.0	90.2	54.0	5.8	1050.4	157.56	9210	3.22	334.8	30.20	407.1	22.00	108.58	67.54	18852.1
9	M2	P040102	Lime (10%)	2.12	7.90	8.51	250.0	165.6	57.4	27.0	2007.6	501.90	0	0.00	686.1	113.63	845.4	48.52	339.75	67.69	12592.9
9	M6	P010300	-	-	7.90	-	250.0	143.7	86.2	20.1	2007.6	501.90	5874	3.64	362.2	52.05	432.2	37.25	416.24	82.34	20689.0
9	M6	P010301	-	-	7.92	-	250.0	143.9	86.3	19.8	2007.6	501.90	7050	4.37	388.4	55.91	452.2	39.02	411.34	81.25	20804.3
9	M6	P020100	-	-	7.88	-	250.0	144.8	86.2	19.0	2007.6	501.90	6408	3.83	294.4	42.62	349.6	30.15	432.95	85.61	22831.7
9	M6	P020200	-	-	7.88	-	250.0	143.0	86.1	20.9	2007.6	501.90	6675	3.88	518.1	74.09	636.9	54.81	376.89	74.52	17995.7
9	M6	P020201	-	-	7.92	-	250.0	143.5	86.1	20.5	2007.6	501.90	9210	5.37	569.7	81.73	699.6	60.21	365.33	72.02	17850.7
10	M2	P040102	Lime (10%)	0.80	8.31	8.53	250.0	158.5	54.9	36.6	2465.3	616.33	0	0.00	820.1	129.94	990.2	54.37	432.01	70.09	11793.0
10	M6	P010300	-	-	8.29	-	250.0	139.2	83.5	27.3	2465.3	616.33	5874	3.64	427.2	59.47	499.0	41.66	518.84	83.69	18992.8
10	M6	P010301	-	-	8.30	-	250.0	139.5	83.6	26.8	2465.3	616.33	7050	4.37	480.3	67.01	564.6	47.23	506.46	81.60	18864.8
10	M6	P020100	-	-	8.31	-	250.0	140.5	83.7	25.7	2465.3	616.33	6408	3.83	377.5	53.06	460.2	38.52	528.57	85.23	20528.9
10	M6	P020200	-	-	8.29	-	250.0	138.8	83.3	27.9	2465.3	616.33	6675	3.88	646.3	89.68	797.9	66.46	464.07	74.82	16606.0
10	M6	P020201	-	-	8.32	-	250.0	138.9	83.3	27.8	2465.3	616.33	9210	5.37	676.5	93.96	811.6	67.62	460.11	74.01	16557.4
11	M2	P040102	-	-	8.37	-	250.0	164.9	57.1	28.0	2853.7	713.43	0	0.00	1042.6	171.90	1260.4	72.01	469.51	65.81	16772.7
11	M6	P010300	-	-	8.36	-	150.0	85.9	51.5	12.5	2853.7	428.06	5874	2.18	540.4	46.44	667.9	34.42	349.38	81.21	27894.7
11	M6	P010301	-	-	8.39	-	150.0	86.1	51.6	12.3	2853.7	428.06	7050	2.62	680.5	58.58	823.6	42.51	329.59	76.53	26777.0
11	M6	P020100	-	-	8.40	-	150.0	86.6	51.6	11.8	2853.7	428.06	6408	2.30	563.0	48.76	658.4	33.97	347.63	80.78	29447.7
11	M6	P020200	-	-	8.38	-	150.0	85.7	51.5	12.8	2853.7	428.06	6675	2.33	897.3	76.92	1052.8	54.18	299.28	69.54	23358.5
11	M6	P020201	-	-	8.35	-	150.0	86.0	51.5	12.5	2853.7	428.06	9210	3.22	850.1	73.10	1033.8	53.21	304.97	70.71	24328.9
12	M2	P040102	Lime (10%)	2.00	8.02	8.59	250.0	158.9	55.1	36.0	3296.4	824.10	0	0.00	1229.0	195.32	1485.8	81.83	546.96	66.37	15189.4
12	M6	P010300	-	-	8.02	-	250.0	139.5	83.7	26.9	3296.4	824.10	5874	3.64	723.8	100.97	894.7	74.84	651.93	78.76	24278.0
12	M6	P010301	-	-	8.02	-	250.0	139.8	83.8	26.4	3296.4	824.10	7050	4.37	928.1	129.74	1123.3	94.15	604.58	72.97	22909.7
12	M6	P020100	-	-	8.00	-	250.0	140.8	83.9	25.3	3296.4	824.10	6408	3.83	695.6	97.95	813.5	68.23	661.75	79.93	26146.5
12	M6	P020200	-	-	8.01	-	250.0	139.1	83.5	27.5	3296.4	824.10	6675	3.88	1021.7	142.07	1198.8	100.07	585.84	70.76	21326.8
12	M6	P020201	-	-	7.99	-	250.0	139.2	83.5	27.3	3296.4	824.10	9210	5.37	1021.9	142.23	1242.8	103.77	583.47	70.34	21360.5
13	M2	P040102	Lime (10%)	3.84	7.46	8.56	250.0	159.3	55.2	35.4	2265.8	566.45	0	0.00	710.3	113.19	837.0	46.22	407.04	71.86	11487.4

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{COD,in}$ (mg/L)	$M_{COD,In\ Total}$ (mg)	$C_{COD,Coagulant}$ (mg/L)	$M_{COD,Coagulant}$ (mg)	$C_{COD,SUP}$ (mg/L)	$M_{COD,SUP}$ (mg)	$C_{COD,CEN}$ (mg/L)	$M_{COD,CEN}$ (mg)	$M_{COD,SLG}$ (mg)	COD Removal (%)	$C_{COD,SLG}$ (mg/L)
13	M6	P010300	-	-	7.48	-	250.0	139.8	83.8	26.4	2265.8	566.45	5874	3.64	416.9	58.26	509.3	42.69	469.13	82.29	17754.3
13	M6	P010301	-	-	7.47	-	250.0	140.1	84.0	26.0	2265.8	566.45	7050	4.37	483.1	67.66	595.9	50.04	453.12	79.38	17449.0
13	M6	P020100	-	-	7.43	-	250.0	141.1	84.0	24.9	2265.8	566.45	6408	3.83	343.2	48.42	410.5	34.50	487.36	85.46	19568.8
13	M6	P020200	-	-	7.46	-	250.0	139.3	83.6	27.0	2265.8	566.45	6675	3.88	539.5	75.17	628.2	52.54	442.62	77.61	16374.6
13	M6	P020201	-	-	7.47	-	250.0	140.8	83.7	25.5	2265.8	566.45	9210	5.37	596.8	84.03	707.2	59.16	428.63	74.96	16781.5
14	M2	P040102	Lime (10%)	3.47	7.36	8.37	150.0	101.0	35.0	14.0	2231.5	334.73	0	0.00	727.3	73.46	872.8	30.55	230.72	68.93	16480.1
14	M6	P010300	-	-	7.36	-	250.0	145.4	87.2	17.4	2231.5	557.88	5874	3.64	402.1	58.47	482.5	42.08	460.97	82.09	26492.4
14	M6	P010301	-	-	7.37	-	250.0	145.6	87.3	17.1	2231.5	557.88	7050	4.37	453.4	66.02	544.1	47.50	448.73	79.81	26241.3
14	M6	P020100	-	-	7.37	-	250.0	146.4	87.2	16.4	2231.5	557.88	6408	3.83	336.2	49.22	403.5	35.18	477.30	84.97	29103.4
14	M6	P020200	-	-	7.37	-	250.0	145.1	87.1	17.8	2231.5	557.88	6675	3.88	557.2	80.85	668.6	58.24	422.67	75.24	23745.5
14	M6	P020201	-	-	7.36	-	250.0	145.2	87.1	17.7	2231.5	557.88	9210	5.37	606.1	88.01	727.3	63.35	411.89	73.13	23270.6
15	M2	P040102	Lime (10%)	2.72	7.59	8.37	250.0	170.7	59.2	20.1	2360.0	590.00	0	0.00	800.1	136.58	986.4	58.35	395.07	66.96	19615.6
15	M6	P010300	-	-	7.58	-	250.0	146.9	88.1	15.0	2360.0	590.00	5874	3.64	442.0	64.93	540.6	47.62	481.09	81.04	32031.5
15	M6	P010301	-	-	7.58	-	250.0	147.1	88.2	14.8	2360.0	590.00	7050	4.37	470.4	69.18	554.8	48.92	476.28	80.13	32267.7
15	M6	P020100	-	-	7.58	-	250.0	147.8	88.0	14.2	2360.0	590.00	6408	3.83	337.9	49.95	394.1	34.69	509.19	85.75	35969.7
15	M6	P020200	-	-	7.60	-	250.0	146.6	88.0	15.4	2360.0	590.00	6675	3.88	584.9	85.76	703.3	61.90	446.22	75.14	29042.7
15	M6	P020201	-	-	7.60	-	250.0	147.0	88.0	15.0	2360.0	590.00	9210	5.37	670.3	98.53	828.0	72.87	423.97	71.21	28280.2
16	M2	P040102	Lime (10%)	1.68	7.92	8.40	250.0	163.2	56.6	30.2	2445.6	611.40	0	0.00	835.6	136.37	1029.4	58.22	416.81	68.17	13787.5
16	M6	P010300	-	-	7.93	-	250.0	142.2	85.3	22.5	2445.6	611.40	5874	3.64	440.9	62.69	525.8	44.83	507.52	82.52	22512.8
16	M6	P010301	-	-	7.94	-	250.0	142.4	85.4	22.2	2445.6	611.40	7050	4.37	473.1	67.38	550.7	47.03	501.36	81.42	22629.8
16	M6	P020100	-	-	7.90	-	250.0	143.4	85.4	21.2	2445.6	611.40	6408	3.83	358.9	51.45	426.4	36.41	527.37	85.72	24819.7
16	M6	P020200	-	-	7.91	-	250.0	141.8	85.1	23.1	2445.6	611.40	6675	3.88	631.5	89.55	776.5	66.10	459.63	74.70	19930.4
16	M6	P020201	-	-	7.91	-	250.0	142.1	85.1	22.8	2445.6	611.40	9210	5.37	693.7	98.58	851.6	72.51	445.69	72.26	19580.4
17	M2	P040102	Lime (10%)	2.20	7.72	8.39	250.0	168.9	58.5	22.5	1983.7	495.93	0	0.00	659.4	111.39	795.7	46.58	337.95	68.15	15005.9
17	M6	P010300	-	-	7.74	-	150.0	87.5	52.5	10.1	1983.7	297.56	5874	2.18	343.6	30.05	401.2	21.04	248.64	82.95	24675.4
17	M6	P010301	-	-	7.72	-	150.0	87.6	52.5	9.9	1983.7	297.56	7050	2.62	386.7	33.87	454.7	23.88	242.43	80.76	24480.9

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{COD,in}$ (mg/L)	$M_{COD,In\ Total}$ (mg)	$C_{COD,Coagulant}$ (mg/L)	$M_{COD,Coagulant}$ (mg)	$C_{COD,SUP}$ (mg/L)	$M_{COD,SUP}$ (mg)	$C_{COD,CEN}$ (mg/L)	$M_{COD,CEN}$ (mg)	$M_{COD,SLG}$ (mg)	COD Removal (%)	$C_{COD,SLG}$ (mg/L)
17	M6	P020100	-	-	7.75	-	150.0	88.1	52.4	9.5	1983.7	297.56	6408	2.30	304.0	26.77	370.7	19.44	253.64	84.59	26705.9
17	M6	P020200	-	-	7.69	-	150.0	87.3	52.4	10.3	1983.7	297.56	6675	2.33	520.0	45.39	641.9	33.64	220.86	73.65	21425.1
17	M6	P020201	-	-	7.70	-	150.0	87.4	52.4	10.3	1983.7	297.56	9210	3.22	543.9	47.51	652.2	34.17	219.09	72.84	21374.1
18	M2	P040102	-	-	8.47	-	250.0	175.0	60.7	14.3	2375.6	593.90	0	0.00	756.0	132.33	889.5	53.96	407.61	68.63	28523.3
18	M6	P010300	-	-	8.47	-	250.0	149.6	89.7	10.7	2375.6	593.90	5874	3.64	407.2	60.92	475.4	42.65	493.96	82.67	46352.6
18	M6	P010301	-	-	8.44	-	250.0	149.7	89.8	10.5	2375.6	593.90	7050	4.37	481.5	72.10	580.7	52.14	474.03	79.23	45262.8
18	M6	P020100	-	-	8.49	-	250.0	150.4	89.6	10.0	2375.6	593.90	6408	3.83	374.9	56.38	463.3	41.50	499.84	83.62	49764.6
18	M6	P020200	-	-	8.49	-	250.0	149.4	89.7	10.9	2375.6	593.90	6675	3.88	609.7	91.10	739.7	66.34	440.35	73.66	40392.9
18	M6	P020201	-	-	8.44	-	250.0	149.5	89.7	10.8	2375.6	593.90	9210	5.37	624.2	93.32	731.1	65.56	440.39	73.49	40625.3
19	M2	P040102	Lime (10%)	1.88	7.95	8.49	250.0	165.3	57.3	27.4	1767.9	441.98	0	0.00	580.7	95.99	702.1	40.21	305.77	69.18	11149.0
19	M6	P010300	-	-	7.93	-	250.0	143.5	86.1	20.5	1767.9	441.98	5874	3.64	330.4	47.40	408.3	35.14	363.07	81.48	17752.4
19	M6	P010301	-	-	7.93	-	250.0	143.7	86.2	20.1	1767.9	441.98	7050	4.37	395.1	56.78	478.2	41.21	348.35	78.05	17331.6
19	M6	P020100	-	-	7.96	-	250.0	144.6	86.1	19.3	1767.9	441.98	6408	3.83	294.2	42.54	344.1	29.63	373.64	83.81	19382.9
19	M6	P020200	-	-	7.98	-	250.0	143.1	85.9	20.9	1767.9	441.98	6675	3.88	460.8	65.96	540.7	46.46	333.43	74.78	15936.8
19	M6	P020201	-	-	7.95	-	250.0	143.3	85.9	20.8	1767.9	441.98	9210	5.37	483.6	69.27	588.1	50.54	327.53	73.22	15743.2
20	M2	P040102	-	-	8.41	-	150.0	105.9	36.7	7.4	1730.8	259.62	0	0.00	575.5	60.93	695.8	25.53	173.16	66.70	23280.5
20	M6	P010300	-	-	8.39	-	150.0	90.3	54.2	5.5	1730.8	259.62	5874	2.18	337.8	30.50	417.5	22.61	208.69	79.71	37624.1
20	M6	P010301	-	-	8.43	-	150.0	90.4	54.2	5.5	1730.8	259.62	7050	2.62	391.1	35.34	473.4	25.65	201.25	76.74	36919.0
20	M6	P020100	-	-	8.41	-	150.0	90.7	54.0	5.2	1730.8	259.62	6408	2.30	277.7	25.19	324.8	17.55	219.17	83.68	41923.2
20	M6	P020200	-	-	8.43	-	150.0	89.7	54.1	6.2	1730.8	259.62	6675	2.33	436.7	39.17	512.4	27.74	195.04	74.46	31650.4
20	M6	P020201	-	-	8.40	-	150.0	90.2	54.1	5.6	1730.8	259.62	9210	3.22	483.6	43.63	588.1	31.83	187.38	71.29	33208.8
21	M2	P040102	Lime (10%)	1.52	8.00	8.44	250.0	166.4	57.7	26.0	2132.7	533.18	0	0.00	696.9	115.93	842.9	48.59	368.65	69.14	14187.1
21	M6	P010300	-	-	8.00	-	250.0	144.2	86.5	19.4	2132.7	533.18	5874	3.64	403.1	58.11	498.2	43.07	435.63	81.15	22481.4
21	M6	P010301	-	-	7.99	-	250.0	144.4	86.6	19.0	2132.7	533.18	7050	4.37	443.6	64.04	536.6	46.46	427.05	79.44	22424.9
21	M6	P020100	-	-	7.98	-	250.0	145.2	86.5	18.3	2132.7	533.18	6408	3.83	309.7	44.98	362.1	31.33	460.70	85.79	25224.5
21	M6	P020200	-	-	8.02	-	250.0	143.8	86.3	19.8	2132.7	533.18	6675	3.88	509.7	73.31	598.2	51.65	412.10	76.73	20788.9

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{COD, in}$ (mg/L)	$M_{COD, In Total}$ (mg)	$C_{COD, Coagulant}$ (mg/L)	$M_{COD, Coagulant}$ (mg)	$C_{COD, SUP}$ (mg/L)	$M_{COD, SUP}$ (mg)	$C_{COD, CEN}$ (mg/L)	$M_{COD, CEN}$ (mg)	$M_{COD, SLG}$ (mg)	COD Removal (%)	$C_{COD, SLG}$ (mg/L)
21	M6	P020201	-	-	7.97	-	250.0	144.1	86.3	19.6	2132.7	533.18	9210	5.37	586.9	84.57	714.1	61.66	392.31	72.85	20062.6
22	M2	P040102	Lime (10%)	1.74	8.00	8.51	150.0	101.6	35.2	13.1	2629.2	394.38	0	0.00	891.8	90.64	1099.7	38.73	265.01	67.20	20170.7
22	M6	P010300	-	-	7.98	-	250.0	146.1	87.6	16.3	2629.2	657.30	5874	3.64	492.2	71.90	601.7	52.71	536.33	81.15	32845.3
22	M6	P010301	-	-	8.03	-	250.0	146.3	87.7	16.0	2629.2	657.30	7050	4.37	523.6	76.58	617.3	54.13	530.95	80.24	33086.4
22	M6	P020100	-	-	7.98	-	250.0	147.0	87.6	15.4	2629.2	657.30	6408	3.83	376.5	55.36	439.1	38.46	567.31	85.81	36860.8
22	M6	P020200	-	-	8.01	-	250.0	145.8	87.5	16.7	2629.2	657.30	6675	3.88	652.2	95.07	784.6	68.66	497.45	75.24	29779.7
22	M6	P020201	-	-	7.99	-	250.0	145.9	87.5	16.6	2629.2	657.30	9210	5.37	747.0	108.97	922.8	80.75	472.95	71.37	28473.0

Notes:

- ✓ In Scenario M2, the doses applied were 8 g/L for the conventional 40% aluminum sulfate coagulant and 4 g/L for PAM, whereas in Scenario M6, fixed doses of 2.8 g/L for the hybrid coagulants and 1.88 g/L for PAM were used for all formulations.
- ✓ The coagulant densities for the products P040102, P010300, P010301, P020100, P020200, and P020201 were 1.300, 1.130, 1.129, 1.172, 1.203, and 1.201 g/mL, respectively.

APPENDIX D: MASS BALANCE CALCULATIONS FOR TSS

Table D.1. Mass balance calculations for TSS.

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{TSS,in}$ *(mg/L)*	$M_{TSS,In\ Total}$ *(mg)*	$C_{TSS,SUP}$ *(mg/L)*	$M_{TSS,SUP}$ *(mg)*	$C_{TSS,CEN}$ *(mg/L)*	$M_{TSS,CEN}$ *(mg)*	$M_{TSS,SLG}$ *(mg)*	TSS Removal (%)	$C_{TSS,SLG}$ *(mg/L)*
1	M2	P040102	Lime (10%)	3.68	7.39	8.46	250.0	168.3	58.3	23.4	694	173.50	139.5	23.47	154.8	9.03	141.00	81.27	6019.4
1	M6	P010300	-	-	7.41	-	250.0	145.4	87.2	17.5	694	173.50	106.6	15.50	118.3	10.31	147.69	85.12	8454.7
1	M6	P010301	-	-	7.41	-	250.0	145.6	87.3	17.2	694	173.50	102.1	14.86	113.4	9.89	148.74	85.73	8664.3
1	M6	P020100	-	-	7.39	-	250.0	146.4	87.2	16.5	694	173.50	88.8	13.00	98.6	8.60	151.90	87.55	9226.1
1	M6	P020200	-	-	7.37	-	250.0	144.5	87.1	18.4	694	173.50	79.9	11.55	88.7	7.73	154.22	88.89	8369.7
1	M6	P020201	-	-	7.41	-	250.0	145.2	87.1	17.8	694	173.50	75.5	10.95	83.8	7.29	155.25	89.48	8736.8
2	M2	P040102	Lime (10%)	5.28	7.07	8.59	250.0	159.4	55.2	35.4	1130	282.50	177.4	28.28	196.9	10.88	243.35	86.14	6873.6
2	M6	P010300	-	-	7.08	-	250.0	139.8	83.8	26.4	1130	282.50	135.6	18.95	150.5	12.62	250.93	88.82	9504.7
2	M6	P010301	-	-	7.07	-	250.0	140.1	84.0	25.9	1130	282.50	129.9	18.20	144.2	12.11	252.20	89.27	9720.2
2	M6	P020100	-	-	7.07	-	250.0	141.1	84.0	24.9	1130	282.50	113.0	15.94	125.4	10.54	256.02	90.63	10288.7
2	M6	P020200	-	-	7.09	-	250.0	139.3	83.6	27.0	1130	282.50	101.7	14.17	112.9	9.44	258.89	91.64	9585.8
2	M6	P020201	-	-	7.09	-	250.0	139.5	83.7	26.9	1130	282.50	96.0	13.39	106.6	8.92	260.19	92.10	9688.6
3	M2	P040102	Lime (10%)	2.94	7.61	8.54	150.0	103.5	35.9	10.6	710	106.50	142.7	14.77	158.4	5.68	86.04	80.79	8125.6
3	M6	P010300	-	-	7.62	-	150.0	88.8	53.3	7.9	710	106.50	109.1	9.69	121.1	6.45	90.36	84.85	11443.4
3	M6	P010301	-	-	7.59	-	150.0	88.9	53.3	7.8	710	106.50	104.5	9.29	116.0	6.18	91.03	85.47	11729.7
3	M6	P020100	-	-	7.61	-	150.0	89.3	53.2	7.4	710	106.50	90.9	8.12	100.9	5.37	93.01	87.34	12497.0
3	M6	P020200	-	-	7.60	-	150.0	88.5	53.2	8.3	710	106.50	81.8	7.24	90.8	4.83	94.43	88.67	11426.6
3	M6	P020201	-	-	7.62	-	150.0	88.7	53.2	8.0	710	106.50	77.2	6.85	85.7	4.56	95.09	89.28	11837.4
4	M2	P040102	Lime (10%)	5.12	7.03	8.51	250.0	159.3	55.2	35.5	1178	294.50	185.0	29.47	205.3	11.33	253.70	86.15	7152.9
4	M6	P010300	-	-	7.05	-	250.0	139.7	83.8	26.4	1178	294.50	141.4	19.75	156.9	13.15	261.60	88.83	9890.6
4	M6	P010301	-	-	7.02	-	250.0	140.0	84.0	26.0	1178	294.50	135.4	18.96	150.3	12.62	262.92	89.28	10114.9
4	M6	P020100	-	-	7.01	-	250.0	141.1	84.0	24.9	1178	294.50	117.8	16.62	130.8	10.99	266.90	90.63	10706.4
4	M6	P020200	-	-	7.06	-	250.0	139.2	83.6	27.2	1178	294.50	106.0	14.76	117.7	9.84	269.90	91.65	9933.0

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{TSS,in}$ (mg/L)	$M_{TSS,In\ Total}$ (mg)	$C_{TSS,SUP}$ (mg/L)	$M_{TSS,SUP}$ (mg)	$C_{TSS,CEN}$ (mg/L)	$M_{TSS,CEN}$ (mg)	$M_{TSS,SLG}$ (mg)	TSS Removal (%)	$C_{TSS,SLG}$ (mg/L)
4	M6	P020201	-	-	7.05	-	250.0	139.4	83.6	26.9	1178	294.50	100.1	13.95	111.1	9.29	271.25	92.11	10081.9
5	M2	P040102	Lime (10%)	2.72	7.62	8.41	250.0	165.3	57.3	27.4	1325	331.25	245.5	40.57	272.5	15.61	275.07	83.04	10021.9
5	M6	P010300	-	-	7.63	-	250.0	143.5	86.1	20.5	1325	331.25	187.6	26.92	208.3	17.92	286.41	86.46	13993.4
5	M6	P010301	-	-	7.60	-	250.0	143.7	86.2	20.1	1325	331.25	179.7	25.83	199.5	17.19	288.23	87.01	14329.4
5	M6	P020100	-	-	7.61	-	250.0	144.6	86.1	19.3	1325	331.25	156.4	22.61	173.5	14.95	293.70	88.66	15224.5
5	M6	P020200	-	-	7.61	-	250.0	143.1	85.9	20.9	1325	331.25	140.7	20.14	156.2	13.42	297.69	89.87	14217.8
5	M6	P020201	-	-	7.60	-	250.0	143.2	85.9	20.8	1325	331.25	132.8	19.03	147.4	12.67	299.55	90.43	14387.6
6	M2	P040102	Lime (10%)	3.08	7.52	8.40	250.0	165.5	57.4	27.1	1186	296.50	186.2	30.82	206.7	11.86	253.82	85.60	9365.3
6	M6	P010300	-	-	7.51	-	250.0	143.6	86.1	20.2	1186	296.50	142.3	20.44	158.0	13.61	262.45	88.52	12985.8
6	M6	P010301	-	-	7.53	-	250.0	143.9	86.3	19.9	1186	296.50	136.3	19.61	151.3	13.05	263.83	88.98	13283.3
6	M6	P020100	-	-	7.54	-	250.0	144.7	86.2	19.0	1186	296.50	118.6	17.17	131.7	11.35	267.98	90.38	14068.3
6	M6	P020200	-	-	7.53	-	250.0	143.3	86.0	20.7	1186	296.50	106.7	15.29	118.5	10.19	271.01	91.40	13108.4
6	M6	P020201	-	-	7.51	-	250.0	143.4	86.0	20.6	1186	296.50	100.8	14.45	111.8	9.62	272.43	91.88	13251.3
7	M2	P040102	Lime (10%)	2.44	7.68	8.38	250.0	169.8	58.8	21.3	860	215.00	159.3	27.06	176.9	10.41	177.54	82.57	8316.5
7	M6	P010300	-	-	7.71	-	250.0	146.3	87.8	15.9	860	215.00	121.8	17.82	135.2	11.86	185.32	86.19	11641.3
7	M6	P010301	-	-	7.71	-	250.0	146.5	87.8	15.6	860	215.00	116.7	17.09	129.5	11.37	186.54	86.76	11923.3
7	M6	P020100	-	-	7.66	-	250.0	147.3	87.7	15.0	860	215.00	101.5	14.95	112.6	9.88	190.17	88.45	12674.8
7	M6	P020200	-	-	7.66	-	250.0	145.7	87.7	16.6	860	215.00	91.3	13.31	101.4	8.89	192.81	89.68	11592.8
7	M6	P020201	-	-	7.68	-	250.0	146.1	87.7	16.2	860	215.00	86.2	12.60	95.7	8.39	194.01	90.24	11980.8
8	M2	P040102	Lime (10%)	2.47	7.85	8.57	150.0	105.6	36.6	7.7	525	78.75	111.3	11.76	123.5	4.52	62.47	79.33	8070.1
8	M6	P010300	-	-	7.86	-	150.0	89.8	54.1	6.1	525	78.75	85.1	7.64	94.4	5.10	66.01	83.82	10767.6
8	M6	P010301	-	-	7.84	-	150.0	90.2	54.1	5.7	525	78.75	81.5	7.35	90.4	4.89	66.51	84.45	11723.2
8	M6	P020100	-	-	7.83	-	150.0	90.6	54.0	5.4	525	78.75	70.9	6.42	78.7	4.24	68.08	86.46	12513.5
8	M6	P020200	-	-	7.85	-	150.0	90.0	54.1	5.9	525	78.75	63.8	5.74	70.8	3.83	69.18	87.85	11714.9
8	M6	P020201	-	-	7.84	-	150.0	90.2	54.0	5.8	525	78.75	60.2	5.43	66.8	3.61	69.71	88.52	12102.3
9	M2	P040102	Lime (10%)	2.12	7.90	8.51	250.0	165.6	57.4	27.0	1435	358.75	288.4	47.77	320.1	18.37	292.61	81.56	10845.7
9	M6	P010300	-	-	7.90	-	250.0	143.7	86.2	20.1	1435	358.75	220.4	31.67	244.7	21.08	305.99	85.29	15209.1
9	M6	P010301	-	-	7.92	-	250.0	143.9	86.3	19.8	1435	358.75	211.2	30.39	234.4	20.23	308.13	85.89	15584.3
9	M6	P020100	-	-	7.88	-	250.0	144.8	86.2	19.0	1435	358.75	183.7	26.60	203.9	17.58	314.57	87.69	16588.9

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{TSS,in}$ *(mg/L)*	$M_{TSS,In\ Total}$ *(mg)*	$C_{TSS,SUP}$ *(mg/L)*	$M_{TSS,SUP}$ *(mg)*	$C_{TSS,CEN}$ *(mg/L)*	$M_{TSS,CEN}$ *(mg)*	$M_{TSS,SLG}$ *(mg)*	TSS Removal (%)	$C_{TSS,SLG}$ *(mg/L)*
9	M6	P020200	-	-	7.88	-	250.0	143.0	86.1	20.9	1435	358.75	165.3	23.64	183.5	15.79	319.32	89.01	15247.0
9	M6	P020201	-	-	7.92	-	250.0	143.5	86.1	20.5	1435	358.75	156.0	22.39	173.2	14.91	321.46	89.60	15706.9
10	M2	P040102	Lime (10%)	0.80	8.31	8.53	250.0	158.5	54.9	36.6	2640	660.00	766.8	121.51	851.2	46.74	491.75	74.51	13423.7
10	M6	P010300	-	-	8.29	-	250.0	139.2	83.5	27.3	2640	660.00	586.1	81.58	650.6	54.31	524.11	79.41	19185.7
10	M6	P010301	-	-	8.30	-	250.0	139.5	83.6	26.8	2640	660.00	561.4	78.32	623.2	52.13	529.55	80.23	19724.9
10	M6	P020100	-	-	8.31	-	250.0	140.5	83.7	25.7	2640	660.00	488.4	68.64	542.1	45.38	545.98	82.72	21204.9
10	M6	P020200	-	-	8.29	-	250.0	138.8	83.3	27.9	2640	660.00	439.5	60.99	487.9	40.64	558.38	84.60	19980.7
10	M6	P020201	-	-	8.32	-	250.0	138.9	83.3	27.8	2640	660.00	414.9	57.63	460.6	38.37	564.00	85.45	20295.9
11	M2	P040102	-	-	8.37	-	250.0	164.9	57.1	28.0	2020	505.00	539.2	88.89	598.5	34.19	381.91	75.63	13643.2
11	M6	P010300	-	-	8.36	-	150.0	85.9	51.5	12.5	2020	303.00	412.1	35.41	457.4	23.57	244.01	80.53	19482.5
11	M6	P010301	-	-	8.39	-	150.0	86.1	51.6	12.3	2020	303.00	394.8	33.98	438.2	22.62	246.40	81.32	20018.5
11	M6	P020100	-	-	8.40	-	150.0	86.6	51.6	11.8	2020	303.00	343.4	29.74	381.2	19.66	253.60	83.69	21482.1
11	M6	P020200	-	-	8.38	-	150.0	85.7	51.5	12.8	2020	303.00	309.0	26.49	343.0	17.65	258.86	85.43	20203.0
11	M6	P020201	-	-	8.35	-	150.0	86.0	51.5	12.5	2020	303.00	291.7	25.09	323.8	16.67	261.25	86.22	20841.0
12	M2	P040102	Lime (10%)	2.00	8.02	8.59	250.0	158.9	55.1	36.0	2053	513.25	467.4	74.28	518.8	28.57	410.40	79.96	11397.1
12	M6	P010300	-	-	8.02	-	250.0	139.5	83.7	26.9	2053	513.25	357.2	49.83	396.5	33.17	430.25	83.83	16022.7
12	M6	P010301	-	-	8.02	-	250.0	139.8	83.8	26.4	2053	513.25	342.2	47.84	379.8	31.84	433.58	84.48	16429.8
12	M6	P020100	-	-	8.00	-	250.0	140.8	83.9	25.3	2053	513.25	297.7	41.92	330.4	27.71	443.62	86.43	17527.8
12	M6	P020200	-	-	8.01	-	250.0	139.1	83.5	27.5	2053	513.25	267.9	37.25	297.4	24.82	451.18	87.91	16424.5
12	M6	P020201	-	-	7.99	-	250.0	139.2	83.5	27.3	2053	513.25	252.9	35.20	280.7	23.44	454.61	88.58	16643.0
13	M2	P040102	Lime (10%)	3.84	7.46	8.56	250.0	159.3	55.2	35.4	1630	407.50	345.5	55.06	383.5	21.18	331.27	81.29	9348.8
13	M6	P010300	-	-	7.48	-	250.0	139.8	83.8	26.4	1630	407.50	264.1	36.90	293.1	24.57	346.03	84.91	13095.4
13	M6	P010301	-	-	7.47	-	250.0	140.1	84.0	26.0	1630	407.50	253.0	35.43	280.8	23.58	348.49	85.52	13420.1
13	M6	P020100	-	-	7.43	-	250.0	141.1	84.0	24.9	1630	407.50	220.1	31.04	244.3	20.52	355.93	87.35	14291.6
13	M6	P020200	-	-	7.46	-	250.0	139.3	83.6	27.0	1630	407.50	198.0	27.59	219.8	18.38	361.53	88.72	13374.4
13	M6	P020201	-	-	7.47	-	250.0	140.8	83.7	25.5	1630	407.50	186.9	26.32	207.5	17.36	363.82	89.28	14244.2
14	M2	P040102	Lime (10%)	3.47	7.36	8.37	150.0	101.0	35.0	14.0	1070	160.50	168.0	16.97	186.5	6.53	137.01	85.36	9786.1
14	M6	P010300	-	-	7.36	-	250.0	145.4	87.2	17.4	1070	267.50	128.4	18.67	142.5	12.43	236.40	88.37	13586.4
14	M6	P010301	-	-	7.37	-	250.0	145.6	87.3	17.1	1070	267.50	123.0	17.91	136.5	11.92	237.67	88.85	13899.0

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{TSS,in}$ (mg/L)	$M_{TSS,In\ Total}$ (mg)	$C_{TSS,SUP}$ (mg/L)	$M_{TSS,SUP}$ (mg)	$C_{TSS,CEN}$ (mg/L)	$M_{TSS,CEN}$ (mg)	$M_{TSS,SLG}$ (mg)	TSS Removal (%)	$C_{TSS,SLG}$ (mg/L)
14	M6	P020100	-	-	7.37	-	250.0	146.4	87.2	16.4	1070	267.50	107.0	15.66	118.8	10.36	241.48	90.27	14724.3
14	M6	P020200	-	-	7.37	-	250.0	145.1	87.1	17.8	1070	267.50	96.3	13.97	106.9	9.31	244.22	91.30	13720.2
14	M6	P020201	-	-	7.36	-	250.0	145.2	87.1	17.7	1070	267.50	90.9	13.20	100.9	8.79	245.51	91.78	13870.8
15	M2	P040102	Lime (10%)	2.72	7.59	8.37	250.0	170.7	59.2	20.1	555	138.75	117.6	20.08	130.6	7.73	110.94	79.96	5508.4
15	M6	P010300	-	-	7.58	-	250.0	146.9	88.1	15.0	555	138.75	89.9	13.21	99.8	8.79	116.75	84.14	7773.5
15	M6	P010301	-	-	7.58	-	250.0	147.1	88.2	14.8	555	138.75	86.1	12.67	95.6	8.43	117.65	84.79	7970.9
15	M6	P020100	-	-	7.58	-	250.0	147.8	88.0	14.2	555	138.75	74.9	11.08	83.2	7.32	120.35	86.74	8502.0
15	M6	P020200	-	-	7.60	-	250.0	146.6	88.0	15.4	555	138.75	67.4	9.89	74.8	6.59	122.28	88.13	7958.5
15	M6	P020201	-	-	7.60	-	250.0	147.0	88.0	15.0	555	138.75	63.7	9.36	70.7	6.22	123.17	88.77	8216.1
16	M2	P040102	Lime (10%)	1.68	7.92	8.40	250.0	163.2	56.6	30.2	1785	446.25	392.4	64.04	435.5	24.63	357.58	80.13	11828.3
16	M6	P010300	-	-	7.93	-	250.0	142.2	85.3	22.5	1785	446.25	299.9	42.64	332.9	28.38	375.23	84.08	16644.6
16	M6	P010301	-	-	7.94	-	250.0	142.4	85.4	22.2	1785	446.25	287.3	40.92	318.9	27.23	378.10	84.73	17066.1
16	M6	P020100	-	-	7.90	-	250.0	143.4	85.4	21.2	1785	446.25	249.9	35.83	277.4	23.69	386.74	86.66	18201.1
16	M6	P020200	-	-	7.91	-	250.0	141.8	85.1	23.1	1785	446.25	224.9	31.89	249.6	21.25	393.11	88.09	17045.9
16	M6	P020201	-	-	7.91	-	250.0	142.1	85.1	22.8	1785	446.25	212.3	30.17	235.7	20.06	396.02	88.74	17398.4
17	M2	P040102	Lime (10%)	2.20	7.72	8.39	250.0	168.9	58.5	22.5	1006	251.50	158.0	26.68	175.3	10.26	214.55	85.31	9526.7
17	M6	P010300	-	-	7.74	-	150.0	87.5	52.5	10.1	1006	150.90	120.7	10.56	134.0	7.03	133.31	88.34	13229.8
17	M6	P010301	-	-	7.72	-	150.0	87.6	52.5	9.9	1006	150.90	115.6	10.13	128.4	6.74	134.03	88.82	13534.6
17	M6	P020100	-	-	7.75	-	150.0	88.1	52.4	9.5	1006	150.90	100.6	8.86	111.7	5.86	136.18	90.25	14339.0
17	M6	P020200	-	-	7.69	-	150.0	87.3	52.4	10.3	1006	150.90	90.5	7.90	100.5	5.27	137.73	91.27	13361.3
17	M6	P020201	-	-	7.70	-	150.0	87.4	52.4	10.3	1006	150.90	85.5	7.47	94.9	4.97	138.46	91.76	13508.3
18	M2	P040102	-	-	8.47	-	250.0	175.0	60.7	14.3	855	213.75	158.4	27.73	175.8	10.67	175.36	82.04	12270.9
18	M6	P010300	-	-	8.47	-	250.0	149.6	89.7	10.7	855	213.75	121.1	18.11	134.4	12.06	183.58	85.88	17226.7
18	M6	P010301	-	-	8.44	-	250.0	149.7	89.8	10.5	855	213.75	116.0	17.37	128.7	11.56	184.82	86.47	17647.9
18	M6	P020100	-	-	8.49	-	250.0	150.4	89.6	10.0	855	213.75	100.9	15.17	112.0	10.03	188.55	88.21	18771.9
18	M6	P020200	-	-	8.49	-	250.0	149.4	89.7	10.9	855	213.75	90.8	13.57	100.8	9.04	191.15	89.43	17533.8
18	M6	P020201	-	-	8.44	-	250.0	149.5	89.7	10.8	855	213.75	85.7	12.81	95.1	8.53	192.41	90.01	17749.0
19	M2	P040102	Lime (10%)	1.88	7.95	8.49	250.0	165.3	57.3	27.4	1596	399.00	338.3	55.92	375.5	21.51	321.57	80.59	11725.1
19	M6	P010300	-	-	7.93	-	250.0	143.5	86.1	20.5	1596	399.00	258.6	37.10	287.0	24.70	337.20	84.51	16487.5

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{TSS, in}$ *(mg/L)*	$M_{TSS, In Total}$ *(mg)*	$C_{TSS, SUP}$ *(mg/L)*	$M_{TSS, SUP}$ *(mg)*	$C_{TSS, CEN}$ *(mg/L)*	$M_{TSS, CEN}$ *(mg)*	$M_{TSS, SLG}$ *(mg)*	TSS Removal (%)	$C_{TSS, SLG}$ *(mg/L)*
19	M6	P010301	-	-	7.93	-	250.0	143.7	86.2	20.1	1596	399.00	247.7	35.60	274.9	23.69	339.71	85.14	16901.6
19	M6	P020100	-	-	7.96	-	250.0	144.6	86.1	19.3	1596	399.00	215.5	31.15	239.2	20.60	347.25	87.03	18013.9
19	M6	P020200	-	-	7.98	-	250.0	143.1	85.9	20.9	1596	399.00	193.9	27.76	215.2	18.49	352.75	88.41	16860.2
19	M6	P020201	-	-	7.95	-	250.0	143.3	85.9	20.8	1596	399.00	183.1	26.22	203.2	17.46	355.32	89.05	17078.8
20	M2	P040102	-	-	8.41	-	150.0	105.9	36.7	7.4	805	120.75	149.1	15.79	165.6	6.07	98.89	81.89	13294.6
20	M6	P010300	-	-	8.39	-	150.0	90.3	54.2	5.5	805	120.75	114.0	10.29	126.5	6.85	103.60	85.80	18678.6
20	M6	P010301	-	-	8.43	-	150.0	90.4	54.2	5.5	805	120.75	109.2	9.87	121.2	6.57	104.31	86.39	19136.6
20	M6	P020100	-	-	8.41	-	150.0	90.7	54.0	5.2	805	120.75	95.0	8.62	105.4	5.70	106.43	88.14	20358.8
20	M6	P020200	-	-	8.43	-	150.0	89.7	54.1	6.2	805	120.75	85.5	7.67	94.9	5.14	107.95	89.40	17517.2
20	M6	P020201	-	-	8.40	-	150.0	90.2	54.1	5.6	805	120.75	80.7	7.28	89.6	4.85	108.62	89.95	19251.0
21	M2	P040102	Lime (10%)	1.52	8.00	8.44	250.0	166.4	57.7	26.0	1505	376.25	319.0	53.07	354.1	20.41	302.76	80.47	11651.5
21	M6	P010300	-	-	8.00	-	250.0	144.2	86.5	19.4	1505	376.25	243.8	35.15	270.6	23.40	317.70	84.44	16395.5
21	M6	P010301	-	-	7.99	-	250.0	144.4	86.6	19.0	1505	376.25	233.6	33.72	259.3	22.44	320.09	85.07	16808.2
21	M6	P020100	-	-	7.98	-	250.0	145.2	86.5	18.3	1505	376.25	203.2	29.51	225.5	19.51	327.23	86.97	17917.0
21	M6	P020200	-	-	8.02	-	250.0	143.8	86.3	19.8	1505	376.25	182.8	26.30	203.0	17.52	332.43	88.35	16769.9
21	M6	P020201	-	-	7.97	-	250.0	144.1	86.3	19.6	1505	376.25	172.6	24.87	191.6	16.54	334.84	88.99	17123.4
22	M2	P040102	Lime (10%)	1.74	8.00	8.51	150.0	101.6	35.2	13.1	1183	177.45	185.7	18.88	206.2	7.26	151.31	85.27	11516.7
22	M6	P010300	-	-	7.98	-	250.0	146.1	87.6	16.3	1183	295.75	142.0	20.74	157.6	13.80	261.21	88.32	15996.7
22	M6	P010301	-	-	8.03	-	250.0	146.3	87.7	16.0	1183	295.75	136.0	19.89	151.0	13.24	262.62	88.80	16365.4
22	M6	P020100	-	-	7.98	-	250.0	147.0	87.6	15.4	1183	295.75	118.3	17.39	131.3	11.50	266.86	90.23	17339.0
22	M6	P020200	-	-	8.01	-	250.0	145.8	87.5	16.7	1183	295.75	106.5	15.52	118.2	10.34	269.89	91.26	16156.8
22	M6	P020201	-	-	7.99	-	250.0	145.9	87.5	16.6	1183	295.75	100.5	14.66	111.6	9.76	271.33	91.74	16334.7

Notes:

- ✓ In Scenario M2, the doses applied were 8 g/L for the conventional 40% aluminum sulfate coagulant and 4 g/L for PAM, whereas in Scenario M6, fixed doses of 2.8 g/L for the hybrid coagulants and 1.88 g/L for PAM were used for all formulations.

APPENDIX E: MASS BALANCE CALCULATIONS FOR SLUDGE TOTAL SOLIDS

Table E.1. Mass balance calculations for sludge total solids.

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SLG) (mL)	Empty Beaker Weight (g)	Beaker + Wet Sludge Weight (g)	M Wet (g) (*Wet Sludge Weight*)	Beaker + Dried Sludge Weight (g)	M Dry (g) (*Dry Sludge weight*)	Moisture Content (%)	Dry Solids Concentration (%)	Dry Solid Yield (g TS/L)	Total Dry Solids Concentration in Sludge (mg/L)
1	M2	P040102	Lime (10%)	3.68	7.39	8.46	250.0	23.4	30.49	33.10	2.61	30.97	0.48	81.68	18.32	1.91	20405.87
1	M6	P010300	-	-	7.41	-	250.0	17.5	28.77	30.23	1.46	29.14	0.37	74.58	25.42	1.48	21241.37
1	M6	P010301	-	-	7.41	-	250.0	17.2	29.47	30.87	1.40	29.83	0.36	74.00	26.00	1.45	21169.66
1	M6	P020100	-	-	7.39	-	250.0	16.5	29.33	30.89	1.56	29.75	0.43	72.49	27.51	1.72	26066.32
1	M6	P020200	-	-	7.37	-	250.0	18.4	30.76	32.79	2.03	31.27	0.50	75.16	24.84	2.01	27330.48
1	M6	P020201	-	-	7.41	-	250.0	17.8	30.59	32.43	1.84	31.07	0.48	74.08	25.92	1.90	26780.43
2	M2	P040102	Lime (10%)	5.28	7.07	8.59	250.0	35.4	31.20	35.46	4.26	32.06	0.86	79.79	20.21	3.45	24346.64
2	M6	P010300	-	-	7.08	-	250.0	26.4	28.94	31.22	2.28	29.58	0.64	72.07	27.93	2.54	24083.95
2	M6	P010301	-	-	7.07	-	250.0	25.9	29.88	32.07	2.19	30.51	0.62	71.44	28.56	2.50	24057.24
2	M6	P020100	-	-	7.07	-	250.0	24.9	28.78	31.15	2.36	29.50	0.71	69.82	30.18	2.85	28675.56
2	M6	P020200	-	-	7.09	-	250.0	27.0	29.31	32.38	3.06	30.17	0.86	71.91	28.09	3.44	31865.05
2	M6	P020201	-	-	7.09	-	250.0	26.9	30.12	32.67	2.55	30.84	0.73	71.57	28.43	2.90	27038.65
3	M2	P040102	Lime (10%)	2.94	7.61	8.54	150.0	10.6	28.77	29.91	1.13	29.05	0.28	75.65	24.35	1.84	26029.42
3	M6	P010300	-	-	7.62	-	150.0	7.9	29.26	29.97	0.72	29.50	0.25	65.78	34.22	1.63	31054.47
3	M6	P010301	-	-	7.59	-	150.0	7.8	30.52	31.19	0.67	30.75	0.24	64.94	35.06	1.57	30287.98
3	M6	P020100	-	-	7.61	-	150.0	7.4	30.23	30.96	0.73	30.50	0.27	62.74	37.26	1.82	36649.22
3	M6	P020200	-	-	7.60	-	150.0	8.3	29.32	30.20	0.89	29.62	0.30	65.98	34.02	2.01	36472.09
3	M6	P020201	-	-	7.62	-	150.0	8.0	30.35	31.15	0.80	30.63	0.28	64.71	35.29	1.88	35090.89
4	M2	P040102	Lime (10%)	5.12	7.03	8.51	250.0	35.5	30.97	34.94	3.98	31.82	0.85	78.55	21.45	3.41	24061.17
4	M6	P010300	-	-	7.05	-	250.0	26.4	28.72	31.09	2.38	29.42	0.70	70.37	29.63	2.82	26612.67

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH $_{Before}$	pH $_{After}$	Wastewater Volume (mL)	Volume $_{(SLG)}$ (mL)	Empty Beaker Weight (g)	Beaker + Wet Sludge Weight (g)	M $_{Wet}$ (g) *(Wet Sludge Weight)*	Beaker + Dried Sludge Weight (g)	M $_{Dry}$ (g) *(Dry Sludge weight)*	Moisture Content (%)	Dry Solids Concentration (%)	Dry Solid Yield (g TS/L)	Total Dry Solids Concentration in Sludge (mg/L)
4	M6	P010301	-	-	7.02	-	250.0	26.0	30.96	33.10	2.15	31.61	0.65	69.71	30.29	2.60	25007.53
4	M6	P020100	-	-	7.01	-	250.0	24.9	30.65	33.14	2.48	31.45	0.80	67.99	32.01	3.18	31904.05
4	M6	P020200	-	-	7.06	-	250.0	27.2	29.65	32.57	2.92	30.52	0.87	70.34	29.66	3.46	31868.61
4	M6	P020201	-	-	7.05	-	250.0	26.9	29.14	31.82	2.69	29.95	0.81	69.86	30.14	3.24	30126.35
5	M2	P040102	Lime (10%)	2.72	7.62	8.41	250.0	27.4	31.38	34.47	3.09	32.30	0.92	70.20	29.80	3.69	33603.23
5	M6	P010300	-	-	7.63	-	250.0	20.5	29.64	31.42	1.78	30.38	0.74	58.45	41.55	2.95	36066.71
5	M6	P010301	-	-	7.60	-	250.0	20.1	28.96	30.69	1.73	29.70	0.74	57.46	42.54	2.95	36609.96
5	M6	P020100	-	-	7.61	-	250.0	19.3	28.97	30.83	1.86	29.81	0.84	54.90	45.10	3.35	43427.99
5	M6	P020200	-	-	7.61	-	250.0	20.9	31.07	33.27	2.20	32.00	0.92	57.93	42.07	3.70	44174.19
5	M6	P020201	-	-	7.60	-	250.0	20.8	30.39	32.56	2.17	31.32	0.93	57.37	42.63	3.70	44447.77
6	M2	P040102	Lime (10%)	3.08	7.52	8.40	250.0	27.1	30.67	33.77	3.09	31.51	0.83	73.04	26.96	3.34	30776.50
6	M6	P010300	-	-	7.51	-	250.0	20.2	28.83	30.74	1.91	29.54	0.71	62.62	37.38	2.85	35291.85
6	M6	P010301	-	-	7.53	-	250.0	19.9	29.34	31.14	1.80	30.03	0.69	61.76	38.24	2.76	34718.40
6	M6	P020100	-	-	7.54	-	250.0	19.0	29.51	31.32	1.81	30.24	0.73	59.56	40.44	2.92	38351.99
6	M6	P020200	-	-	7.53	-	250.0	20.7	28.92	31.05	2.13	29.72	0.80	62.35	37.65	3.20	38710.57
6	M6	P020201	-	-	7.51	-	250.0	20.6	29.35	31.38	2.03	30.13	0.77	61.89	38.11	3.09	37609.82
7	M2	P040102	Lime (10%)	2.44	7.68	8.38	250.0	21.3	29.74	32.12	2.38	30.34	0.61	74.46	25.54	2.43	28463.25
7	M6	P010300	-	-	7.71	-	250.0	15.9	29.29	30.71	1.43	29.80	0.51	64.35	35.65	2.04	31989.88
7	M6	P010301	-	-	7.71	-	250.0	15.6	29.45	30.70	1.25	29.91	0.46	63.50	36.50	1.83	29269.14
7	M6	P020100	-	-	7.66	-	250.0	15.0	31.32	32.74	1.41	31.87	0.55	61.30	38.70	2.19	36462.99
7	M6	P020200	-	-	7.66	-	250.0	16.6	30.51	32.30	1.79	31.15	0.63	64.66	35.34	2.53	38023.91
7	M6	P020201	-	-	7.68	-	250.0	16.2	30.41	31.97	1.56	30.98	0.57	63.44	36.56	2.28	35257.80
8	M2	P040102	Lime (10%)	2.47	7.85	8.57	150.0	7.7	29.76	30.72	0.96	29.98	0.22	76.81	23.19	1.48	28680.87
8	M6	P010300	-	-	7.86	-	150.0	6.1	31.47	32.02	0.55	31.64	0.17	69.07	30.93	1.13	27584.36
8	M6	P010301	-	-	7.84	-	150.0	5.7	30.49	30.99	0.50	30.66	0.17	66.32	33.68	1.12	29576.10
8	M6	P020100	-	-	7.83	-	150.0	5.4	30.26	30.79	0.53	30.45	0.19	64.12	35.88	1.27	35100.78

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH $_{Before}$	pH $_{After}$	Wastewater Volume (mL)	Volume $_{(SLG)}$ (mL)	Empty Beaker Weight (g)	Beaker + Wet Sludge Weight (g)	M $_{Wet}$ (g) *(Wet Sludge Weight)*	Beaker + Dried Sludge Weight (g)	M $_{Dry}$ (g) *(Dry Sludge weight)*	Moisture Content (%)	Dry Solids Concentration (%)	Dry Solid Yield (g TS/L)	Total Dry Solids Concentration in Sludge (mg/L)
8	M6	P020200	-	-	7.85	-	150.0	5.9	30.62	31.28	0.66	30.84	0.22	66.45	33.55	1.48	37491.32
8	M6	P020201	-	-	7.84	-	150.0	5.8	31.06	31.65	0.59	31.26	0.20	65.27	34.73	1.36	35511.22
9	M2	P040102	Lime (10%)	2.12	7.90	8.51	250.0	27.0	30.87	33.90	3.02	31.84	0.97	67.93	32.07	3.88	35928.46
9	M6	P010300	-	-	7.90	-	250.0	20.1	29.34	31.20	1.85	30.17	0.83	55.09	44.91	3.33	41397.11
9	M6	P010301	-	-	7.92	-	250.0	19.8	28.79	30.39	1.60	29.53	0.74	53.99	46.01	2.94	37213.19
9	M6	P020100	-	-	7.88	-	250.0	19.0	29.58	31.37	1.78	30.45	0.87	51.14	48.86	3.49	45952.02
9	M6	P020200	-	-	7.88	-	250.0	20.9	29.45	31.56	2.11	30.40	0.95	55.15	44.85	3.78	45165.47
9	M6	P020201	-	-	7.92	-	250.0	20.5	29.29	31.24	1.95	30.19	0.90	53.72	46.28	3.61	44146.26
10	M2	P040102	Lime (10%)	0.80	8.31	8.53	250.0	36.6	31.15	35.19	4.03	32.78	1.63	59.61	40.39	6.52	44477.60
10	M6	P010300	-	-	8.29	-	250.0	27.3	29.58	31.95	2.37	30.95	1.37	42.43	57.57	5.47	50022.60
10	M6	P010301	-	-	8.30	-	250.0	26.8	30.54	32.79	2.26	31.87	1.33	40.83	59.17	5.34	49700.41
10	M6	P020100	-	-	8.31	-	250.0	25.7	29.81	32.36	2.55	31.42	1.62	36.64	63.36	6.46	62766.24
10	M6	P020200	-	-	8.29	-	250.0	27.9	31.26	34.34	3.08	33.10	1.84	40.42	59.58	7.35	65744.31
10	M6	P020201	-	-	8.32	-	250.0	27.8	29.98	32.78	2.79	31.68	1.69	39.36	60.64	6.77	60946.28
11	M2	P040102	-	-	8.37	-	250.0	28.0	29.39	32.52	3.13	30.68	1.29	58.71	41.29	5.17	46162.54
11	M6	P010300	-	-	8.36	-	150.0	12.5	30.27	31.39	1.12	30.93	0.66	41.22	58.78	4.39	52534.09
11	M6	P010301	-	-	8.39	-	150.0	12.3	29.44	30.42	0.99	30.03	0.60	39.63	60.37	3.98	48453.38
11	M6	P020100	-	-	8.40	-	150.0	11.8	30.34	31.48	1.14	31.07	0.74	35.45	64.55	4.91	62399.02
11	M6	P020200	-	-	8.38	-	150.0	12.8	31.21	32.59	1.37	32.05	0.83	39.42	60.58	5.54	64912.00
11	M6	P020201	-	-	8.35	-	150.0	12.5	29.82	31.04	1.22	30.58	0.76	37.40	62.60	5.10	60990.67
12	M2	P040102	Lime (10%)	2.00	8.02	8.59	250.0	36.0	29.31	33.67	4.36	30.75	1.44	67.01	32.99	5.75	39900.75
12	M6	P010300	-	-	8.02	-	250.0	26.9	31.49	33.90	2.40	32.62	1.12	53.27	46.73	4.49	41836.62
12	M6	P010301	-	-	8.02	-	250.0	26.4	30.13	32.43	2.30	31.23	1.11	52.02	47.98	4.42	41903.38
12	M6	P020100	-	-	8.00	-	250.0	25.3	28.95	31.30	2.34	30.16	1.20	48.76	51.24	4.80	47439.63
12	M6	P020200	-	-	8.01	-	250.0	27.5	28.83	31.69	2.86	30.21	1.38	51.92	48.08	5.50	50082.40
12	M6	P020201	-	-	7.99	-	250.0	27.3	29.01	31.82	2.81	30.38	1.37	51.12	48.88	5.50	50297.74

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SLG) (mL)	Empty Beaker Weight (g)	Beaker + Wet Sludge Weight (g)	M Wet (g) *(Wet Sludge Weight)*	Beaker + Dried Sludge Weight (g)	M Dry (g) *(Dry Sludge weight)*	Moisture Content (%)	Dry Solids Concentration (%)	Dry Solid Yield (g TS/L)	Total Dry Solids Concentration in Sludge (mg/L)
13	M2	P040102	Lime (10%)	3.84	7.46	8.56	250.0	35.4	30.92	35.16	4.24	32.10	1.18	72.15	27.85	4.73	33362.36
13	M6	P010300	-	-	7.48	-	250.0	26.4	29.88	32.14	2.26	30.76	0.88	61.05	38.95	3.53	33353.90
13	M6	P010301	-	-	7.47	-	250.0	26.0	28.88	31.02	2.14	29.73	0.85	60.09	39.91	3.41	32870.34
13	M6	P020100	-	-	7.43	-	250.0	24.9	29.77	32.11	2.34	30.76	0.99	57.60	42.40	3.96	39791.72
13	M6	P020200	-	-	7.46	-	250.0	27.0	31.49	34.31	2.83	32.61	1.12	60.38	39.62	4.48	41411.73
13	M6	P020201	-	-	7.47	-	250.0	25.5	30.18	32.78	2.60	31.28	1.10	57.74	42.26	4.40	43053.10
14	M2	P040102	Lime (10%)	3.47	7.36	8.37	150.0	14.0	31.25	32.82	1.57	31.72	0.47	70.41	29.60	3.10	33247.71
14	M6	P010300	-	-	7.36	-	250.0	17.4	28.73	30.31	1.58	29.37	0.65	58.99	41.01	2.59	37260.17
14	M6	P010301	-	-	7.37	-	250.0	17.1	29.71	31.08	1.37	30.29	0.57	58.05	41.95	2.29	33529.91
14	M6	P020100	-	-	7.37	-	250.0	16.4	29.40	30.94	1.53	30.08	0.68	55.65	44.35	2.72	41484.85
14	M6	P020200	-	-	7.37	-	250.0	17.8	28.76	30.65	1.89	29.54	0.78	58.73	41.27	3.12	43801.37
14	M6	P020201	-	-	7.36	-	250.0	17.7	29.68	31.50	1.82	30.44	0.76	58.23	41.77	3.04	43004.56
15	M2	P040102	Lime (10%)	2.72	7.59	8.37	250.0	20.1	31.11	33.48	2.37	31.49	0.38	84.00	16.00	1.52	18836.14
15	M6	P010300	-	-	7.58	-	250.0	15.0	28.73	30.12	1.39	29.05	0.31	77.43	22.57	1.25	20839.94
15	M6	P010301	-	-	7.58	-	250.0	14.8	30.72	31.96	1.24	31.01	0.29	76.86	23.14	1.15	19480.09
15	M6	P020100	-	-	7.58	-	250.0	14.2	30.61	31.98	1.37	30.95	0.34	75.37	24.63	1.35	23915.34
15	M6	P020200	-	-	7.60	-	250.0	15.4	30.20	31.79	1.58	30.57	0.36	76.97	23.03	1.46	23722.12
15	M6	P020201	-	-	7.60	-	250.0	15.0	29.45	30.97	1.53	29.81	0.36	76.19	23.81	1.45	24244.18
16	M2	P040102	Lime (10%)	1.68	7.92	8.40	250.0	30.2	29.01	32.69	3.68	30.27	1.26	65.83	34.17	5.02	41534.31
16	M6	P010300	-	-	7.93	-	250.0	22.5	29.92	31.91	1.99	30.88	0.97	51.54	48.46	3.86	42839.85
16	M6	P010301	-	-	7.94	-	250.0	22.2	29.97	31.82	1.85	30.89	0.92	50.24	49.76	3.68	41581.00
16	M6	P020100	-	-	7.90	-	250.0	21.2	31.37	33.44	2.07	32.47	1.10	46.86	53.14	4.39	51641.49
16	M6	P020200	-	-	7.91	-	250.0	23.1	31.15	33.54	2.38	32.34	1.19	50.16	49.84	4.75	51523.35
16	M6	P020201	-	-	7.91	-	250.0	22.8	29.44	31.72	2.28	30.60	1.17	48.97	51.03	4.66	51209.15
17	M2	P040102	Lime (10%)	2.20	7.72	8.39	250.0	22.5	29.20	31.68	2.48	29.91	0.71	71.28	28.72	2.85	31659.71
17	M6	P010300	-	-	7.74	-	150.0	10.1	31.26	32.14	0.89	31.61	0.35	60.19	39.81	2.36	35082.95

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH $_{Before}$	pH $_{After}$	Wastewater Volume (mL)	Volume $_{(SLG)}$ (mL)	Empty Beaker Weight (g)	Beaker + Wet Sludge Weight (g)	M $_{Wet}$ (g) *(Wet Sludge Weight)*	Beaker + Dried Sludge Weight (g)	M $_{Dry}$ (g) *(Dry Sludge weight)*	Moisture Content (%)	Dry Solids Concentration (%)	Dry Solid Yield (g TS/L)	Total Dry Solids Concentration in Sludge (mg/L)
17	M6	P010301	-	-	7.72	-	150.0	9.9	31.14	32.00	0.86	31.49	0.35	59.28	40.72	2.35	35522.28
17	M6	P020100	-	-	7.75	-	150.0	9.5	29.54	30.45	0.92	29.93	0.39	56.95	43.05	2.63	41507.52
17	M6	P020200	-	-	7.69	-	150.0	10.3	30.49	31.63	1.14	30.95	0.46	59.93	40.07	3.05	44351.87
17	M6	P020201	-	-	7.70	-	150.0	10.3	30.41	31.43	1.02	30.82	0.41	59.45	40.55	2.76	40405.77
18	M2	P040102	-	-	8.47	-	250.0	14.3	30.19	31.84	1.65	30.78	0.60	63.77	36.23	2.40	41941.06
18	M6	P010300	-	-	8.47	-	250.0	10.7	28.70	29.65	0.95	29.18	0.48	49.21	50.79	1.93	45292.46
18	M6	P010301	-	-	8.44	-	250.0	10.5	29.61	30.46	0.85	30.05	0.44	47.98	52.02	1.78	42392.01
18	M6	P020100	-	-	8.49	-	250.0	10.0	28.75	29.73	0.98	29.29	0.54	44.78	55.22	2.15	53599.95
18	M6	P020200	-	-	8.49	-	250.0	10.9	31.30	32.47	1.17	31.91	0.60	48.48	51.52	2.42	55413.97
18	M6	P020201	-	-	8.44	-	250.0	10.8	31.16	32.24	1.08	31.73	0.57	47.78	52.22	2.26	52207.42
19	M2	P040102	Lime (10%)	1.88	7.95	8.49	250.0	27.4	29.56	32.74	3.18	30.67	1.11	65.05	34.95	4.45	40550.02
19	M6	P010300	-	-	7.93	-	250.0	20.5	28.86	30.76	1.89	29.79	0.93	50.94	49.06	3.71	45410.34
19	M6	P010301	-	-	7.93	-	250.0	20.1	31.16	32.88	1.73	32.03	0.87	49.72	50.28	3.47	43161.41
19	M6	P020100	-	-	7.96	-	250.0	19.3	31.35	33.20	1.84	32.34	0.99	46.55	53.45	3.94	51128.81
19	M6	P020200	-	-	7.98	-	250.0	20.9	28.94	31.04	2.10	29.99	1.05	50.04	49.96	4.19	50112.13
19	M6	P020201	-	-	7.95	-	250.0	20.8	30.06	32.14	2.08	31.11	1.05	49.32	50.68	4.22	50650.59
20	M2	P040102	-	-	8.41	-	150.0	7.4	28.89	29.70	0.81	29.22	0.32	59.82	40.18	2.16	43540.75
20	M6	P010300	-	-	8.39	-	150.0	5.5	30.83	31.30	0.47	31.09	0.26	43.68	56.32	1.75	47304.63
20	M6	P010301	-	-	8.43	-	150.0	5.5	30.84	31.28	0.44	31.10	0.25	42.31	57.69	1.69	46431.39
20	M6	P020100	-	-	8.41	-	150.0	5.2	29.06	29.57	0.51	29.37	0.31	38.79	61.21	2.08	59602.81
20	M6	P020200	-	-	8.43	-	150.0	6.2	30.03	30.64	0.61	30.35	0.32	47.41	52.59	2.14	52180.66
20	M6	P020201	-	-	8.40	-	150.0	5.6	30.24	30.80	0.56	30.56	0.32	42.13	57.87	2.15	57046.18
21	M2	P040102	Lime (10%)	1.52	8.00	8.44	250.0	26.0	29.44	32.21	2.77	30.42	0.98	64.61	35.39	3.92	37692.71
21	M6	P010300	-	-	8.00	-	250.0	19.4	31.14	32.77	1.63	31.95	0.81	50.33	49.67	3.24	41748.57
21	M6	P010301	-	-	7.99	-	250.0	19.0	29.88	31.47	1.59	30.69	0.81	49.10	50.90	3.23	42461.79
21	M6	P020100	-	-	7.98	-	250.0	18.3	29.29	31.09	1.79	30.26	0.97	45.90	54.10	3.88	53152.99

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH_{Before}	pH_{After}	Wastewater Volume (mL)	Volume (SLG) (mL)	Empty Beaker Weight (g)	Beaker + Wet Sludge Weight (g)	M_{Wet} (g) *(Wet Sludge Weight)*	Beaker + Dried Sludge Weight (g)	M_{Dry} (g) *(Dry Sludge weight)*	Moisture Content (%)	Dry Solids Concentration (%)	Dry Solid Yield (g TS/L)	Total Dry Solids Concentration in Sludge (mg/L)
21	M6	P020200	-	-	8.02	-	250.0	19.8	30.21	32.32	2.11	31.27	1.06	49.45	50.55	4.26	53698.43
21	M6	P020201	-	-	7.97	-	250.0	19.6	30.74	32.68	1.94	31.75	1.00	48.31	51.69	4.01	51206.11
22	M2	P040102	Lime (10%)	1.74	8.00	8.51	150.0	13.1	29.65	31.05	1.41	30.13	0.48	65.60	34.40	3.23	36827.49
22	M6	P010300	-	-	7.98	-	250.0	16.3	30.35	31.79	1.44	31.03	0.69	52.29	47.71	2.75	42065.75
22	M6	P010301	-	-	8.03	-	250.0	16.0	29.34	30.71	1.36	30.01	0.67	51.20	48.80	2.66	41491.31
22	M6	P020100	-	-	7.98	-	250.0	15.4	29.32	30.79	1.48	30.08	0.76	48.39	51.61	3.05	49479.16
22	M6	P020200	-	-	8.01	-	250.0	16.7	28.90	30.67	1.77	29.75	0.85	51.96	48.04	3.41	51016.56
22	M6	P020201	-	-	7.99	-	250.0	16.6	30.47	32.16	1.70	31.29	0.82	51.38	48.62	3.30	49666.90

Notes:

- ✓ In Scenario M2, the doses applied were 8 g/L for the conventional 40% aluminum sulfate coagulant and 4 g/L for PAM, whereas in Scenario M6, fixed doses of 2.8 g/L for the hybrid coagulants and 1.88 g/L for PAM were used for all formulations.

APPENDIX F: MASS BALANCE CALCULATIONS FOR TOC

Table F.1. Mass balance calculations for TOC.

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH_{Before}	pH_{After}	Wastewater Volume (mL)	$Volume_{(SUP)}$ (mL)	$Volume_{(CEN)}$ (mL)	$Volume_{(SLG)}$ (mL)	$C_{TOC,\ in}$ (mg/L)	$M_{TOC,\ In\ Total}$ (mg)	$C_{TOC,\ Coagulant}$ (mg/L)	$M_{TOC,\ Coagulant}$ (mg)	$C_{TOC,\ SUP}$ (mg/L)	$M_{TOC,\ SUP}$ (mg)	$C_{TOC,\ CEN}$ (mg/L)	$M_{TOC,\ CEN}$ (mg)	$M_{TOC,\ SLG}$ (mg)	TOC Removal (%)	$C_{TOC,\ SLG}$ (mg/L)	$\Delta M_{TOC,\ SUP}$ (mg)	$\Delta M_{TOC,\ CEN}$ (mg)	$\Delta M_{TOC,\ SLG}$ (mg)
1	M2	P040102	Lime (10%)	3.68	7.39	8.46	250.0	168.3	58.3	23.4	534.4	133.6	0.0	0.00	212.1	35.69	254.9	14.86	83.04	62.16	3544.9	-	-	-
1	M6	P010300	-	-	7.41	-	250.0	145.4	87.2	17.5	534.4	133.6	2510.3	1.55	117.5	17.08	140.8	12.27	105.79	79.19	6056.0	-	-	-
1	M6	P010301	-	-	7.41	-	250.0	145.6	87.3	17.2	534.4	133.6	3164.1	1.96	132.5	19.28	159.0	13.88	102.39	76.65	5964.5	-	-	-
1	M6	P020100	-	-	7.39	-	250.0	146.4	87.2	16.5	534.4	133.6	2822.0	1.69	98.2	14.37	117.9	10.28	110.63	82.81	6719.0	-2.25	-1.70	5.63
1	M6	P020200	-	-	7.37	-	250.0	144.5	87.1	18.4	534.4	133.6	2966.7	1.73	162.9	23.54	195.3	17.01	94.77	70.94	5143.1	-5.04	-3.42	10.18
1	M6	P020201	-	-	7.41	-	250.0	145.2	87.1	17.8	534.4	133.6	4349.1	2.54	177.0	25.70	212.2	18.48	91.95	68.83	5174.6	-2.88	-1.95	7.36
1	M6	P020102	-	-	7.38	-	250.0	147.2	88.3	14.5	534.4	133.6	0.0	0.00	112.9	16.62	135.6	11.98	104.99	78.59	7262.4	-	-	-
1	M6	P020202	-	-	7.37	-	250.0	146.2	87.2	16.7	534.4	133.6	0.0	0.00	195.5	28.58	234.3	20.42	84.59	63.32	5075.7	-	-	-
2	M2	P040102	Lime (10%)	5.28	7.07	8.59	250.0	159.4	55.2	35.4	827.2	206.8	0.0	0.00	293.1	46.72	352.2	19.45	140.62	68.00	3971.8	-	-	-
2	M6	P010300	-	-	7.08	-	250.0	139.8	83.8	26.4	827.2	206.8	2510.3	1.55	162.4	22.70	194.6	16.31	169.33	81.89	6413.8	-	-	-
2	M6	P010301	-	-	7.07	-	250.0	140.1	84.0	25.9	827.2	206.8	3164.1	1.96	183.1	25.64	219.8	18.46	164.65	79.62	6346.0	-	-	-
2	M6	P020100	-	-	7.07	-	250.0	141.1	84.0	24.9	827.2	206.8	2822.0	1.69	135.7	19.15	162.9	13.69	175.63	84.93	7058.3	-3.10	-2.35	7.13
2	M6	P020200	-	-	7.09	-	250.0	139.3	83.6	27.0	827.2	206.8	2966.7	1.73	225.2	31.37	270.0	22.58	154.56	74.74	5722.7	-6.68	-4.62	13.02
2	M6	P020201	-	-	7.09	-	250.0	139.5	83.7	26.9	827.2	206.8	4349.1	2.54	244.7	34.13	293.3	24.54	150.66	72.86	5609.9	-3.93	-2.66	9.12
2	M6	P020102	-	-	7.07	-	250.0	142.6	85.6	21.8	827.2	206.8	0.0	0.00	156.0	22.25	187.5	16.04	168.50	81.49	7712.1	-	-	-
2	M6	P020202	-	-	7.09	-	250.0	140.8	84.0	25.2	827.2	206.8	0.0	0.00	270.2	38.05	323.8	27.20	141.53	68.44	5619.4	-	-	-
3	M2	P040102	Lime (10%)	2.94	7.61	8.54	150.0	103.5	35.9	10.6	617.3	92.6	0.0	0.00	218.8	22.65	262.9	9.43	60.51	65.35	5714.3	-	-	-
3	M6	P010300	-	-	7.62	-	150.0	88.8	53.3	7.9	617.3	92.6	2510.3	0.93	121.2	10.77	145.2	7.74	75.02	81.02	9500.5	-	-	-
3	M6	P010301	-	-	7.59	-	150.0	88.9	53.3	7.8	617.3	92.6	3164.1	1.18	136.6	12.15	164.0	8.74	72.87	78.71	9390.6	-	-	-

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{TOC,in}$ (mg/L)	$M_{TOC,In\ Total}$ (mg)	$C_{TOC,Coagulant}$ (mg/L)	$M_{TOC,Coagulant}$ (mg)	$C_{TOC,SUP}$ (mg/L)	$M_{TOC,SUP}$ (mg)	$C_{TOC,CEN}$ (mg/L)	$M_{TOC,CEN}$ (mg)	$M_{TOC,SLG}$ (mg)	TOC Removal (%)	$C_{TOC,SLG}$ (mg/L)	$\Delta M_{TOC,SUP}$ (mg)	$\Delta M_{TOC,CEN}$ (mg)	$\Delta M_{TOC,SLG}$ (mg)
3	M6	P020100	-	-	7.61	-	150.0	89.3	53.2	7.4	617.3	92.6	2822.0	1.01	101.3	9.05	121.6	6.47	78.08	84.33	10491.1	-1.39	-1.06	3.46
3	M6	P020200	-	-	7.60	-	150.0	88.5	53.2	8.3	617.3	92.6	2966.7	1.04	168.0	14.87	201.5	10.73	68.03	73.47	8232.1	-3.13	-2.14	6.30
3	M6	P020201	-	-	7.62	-	150.0	88.7	53.2	8.0	617.3	92.6	4349.1	1.52	182.6	16.20	218.9	11.65	66.26	71.56	8248.7	-1.79	-1.21	4.53
3	M6	P020102	-	-	7.63	-	150.0	89.7	53.8	6.5	617.3	92.6	0.0	0.00	116.4	10.44	139.9	7.53	74.62	80.60	11419.0	-	-	-
3	M6	P020202	-	-	7.62	-	150.0	89.2	53.2	7.5	617.3	92.6	0.0	0.00	201.7	18.00	241.7	12.86	61.73	66.67	8194.3	-	-	-
4	M2	P040102	Lime (10%)	5.12	7.03	8.51	250.0	159.3	55.2	35.5	836.4	209.1	0.0	0.00	296.4	47.22	356.2	19.66	142.20	68.01	4009.2	-	-	-
4	M6	P010300	-	-	7.05	-	250.0	139.7	83.8	26.4	836.4	209.1	2510.3	1.55	164.2	22.95	196.8	16.49	171.20	81.88	6473.0	-	-	-
4	M6	P010301	-	-	7.02	-	250.0	140.0	84.0	26.0	836.4	209.1	3164.1	1.96	185.1	25.92	222.2	18.66	166.47	79.62	6404.3	-	-	-
4	M6	P020100	-	-	7.01	-	250.0	141.1	84.0	24.9	836.4	209.1	2822.0	1.69	137.3	19.36	164.7	13.84	177.57	84.93	7123.2	-3.13	-2.37	7.19
4	M6	P020200	-	-	7.06	-	250.0	139.2	83.6	27.2	836.4	209.1	2966.7	1.73	227.7	31.69	273.0	22.83	156.29	74.75	5752.0	-6.78	-4.67	13.17
4	M6	P020201	-	-	7.05	-	250.0	139.4	83.6	26.9	836.4	209.1	4349.1	2.54	247.4	34.50	296.5	24.80	152.32	72.85	5661.3	-3.97	-2.69	9.19
4	M6	P020102	-	-	7.06	-	250.0	142.6	85.5	21.9	836.4	209.1	0.0	0.00	157.8	22.49	189.5	16.21	170.38	81.49	7783.9	-	-	-
4	M6	P020202	-	-	7.04	-	250.0	140.8	84.0	25.2	836.4	209.1	0.0	0.00	273.2	38.47	327.4	27.50	143.12	68.45	5672.1	-	-	-
5	M2	P040102	Lime (10%)	2.72	7.62	8.41	250.0	165.3	57.3	27.4	590.5	147.6	0.0	0.00	209.3	34.59	251.5	14.40	98.64	66.81	3593.8	-	-	-
5	M6	P010300	-	-	7.63	-	250.0	143.5	86.1	20.5	590.5	147.6	2510.3	1.55	116.0	16.64	138.9	11.95	120.59	81.69	5892.0	-	-	-
5	M6	P010301	-	-	7.60	-	250.0	143.7	86.2	20.1	590.5	147.6	3164.1	1.96	130.7	18.78	156.9	13.52	117.29	79.45	5831.0	-	-	-
5	M6	P020100	-	-	7.61	-	250.0	144.6	86.1	19.3	590.5	147.6	2822.0	1.69	96.9	14.01	116.3	10.02	125.29	84.87	6494.6	-2.21	-1.68	5.58
5	M6	P020200	-	-	7.61	-	250.0	143.1	85.9	20.9	590.5	147.6	2966.7	1.73	160.7	23.01	192.7	16.56	109.79	74.37	5243.4	-4.84	-3.35	9.91
5	M6	P020201	-	-	7.60	-	250.0	143.2	85.9	20.8	590.5	147.6	4349.1	2.54	174.7	25.02	209.4	17.99	107.15	72.58	5146.5	-2.83	-1.92	7.28
5	M6	P020102	-	-	7.63	-	250.0	145.7	87.4	16.9	590.5	147.6	0.0	0.00	111.4	16.23	133.8	11.70	119.71	81.09	7067.2	-	-	-
5	M6	P020202	-	-	7.62	-	250.0	144.4	86.1	19.5	590.5	147.6	0.0	0.00	192.9	27.85	231.2	19.91	99.87	67.65	5114.7	-	-	-
6	M2	P040102	Lime (10%)	3.08	7.52	8.40	250.0	165.5	57.4	27.1	584.9	146.2	0.0	0.00	207.3	34.32	249.1	14.29	97.63	66.76	3602.3	-	-	-
6	M6	P010300	-	-	7.51	-	250.0	143.6	86.1	20.2	584.9	146.2	2510.3	1.55	114.9	16.50	137.6	11.85	119.44	81.67	5909.7	-	-	-
6	M6	P010301	-	-	7.53	-	250.0	143.9	86.3	19.9	584.9	146.2	3164.1	1.96	129.5	18.63	155.4	13.41	116.16	79.44	5848.5	-	-	-

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	C TOC, in (mg/L)	M TOC, In Total (mg)	C TOC, Coagulant (mg/L)	M TOC, Coagulant (mg)	C TOC, SUP (mg/L)	M TOC, SUP (mg)	C TOC, CEN (mg/L)	M TOC, CEN (mg)	M TOC, SLG (mg)	TOC Removal (%)	C TOC, SLG (mg/L)	ΔM TOC, SUP (mg)	ΔM TOC, CEN (mg)	ΔM TOC, SLG (mg)
6	M6	P020100	-	-	7.54	-	250.0	144.7	86.2	19.0	584.9	146.2	2822.0	1.69	96.0	13.89	115.2	9.93	124.09	84.86	6514.5	-2.19	-1.66	5.54
6	M6	P020200	-	-	7.53	-	250.0	143.3	86.0	20.7	584.9	146.2	2966.7	1.73	159.2	22.82	190.9	16.42	108.72	74.35	5258.6	-4.80	-3.32	9.84
6	M6	P020201	-	-	7.51	-	250.0	143.4	86.0	20.6	584.9	146.2	4349.1	2.54	173.0	24.82	207.4	17.84	106.11	72.56	5161.5	-2.80	-1.90	7.23
6	M6	P020102	-	-	7.54	-	250.0	145.8	87.5	16.7	584.9	146.2	0.0	0.00	110.3	16.09	132.6	11.60	118.55	81.07	7087.9	-	-	-
6	M6	P020202	-	-	7.51	-	250.0	144.5	86.2	19.3	584.9	146.2	0.0	0.00	191.1	27.62	229.0	19.74	98.88	67.62	5128.2	-	-	-
7	M2	P040102	Lime (10%)	2.44	7.68	8.38	250.0	169.8	58.8	21.3	575.4	143.9	0.0	0.00	203.9	34.63	245.1	14.42	94.81	65.90	4441.3	-	-	-
7	M6	P010300	-	-	7.71	-	250.0	146.3	87.8	15.9	575.4	143.9	2510.3	1.55	113.0	16.53	135.4	11.88	117.00	81.33	7349.8	-	-	-
7	M6	P010301	-	-	7.71	-	250.0	146.5	87.8	15.6	575.4	143.9	3164.1	1.96	127.4	18.66	152.9	13.43	113.73	79.06	7269.7	-	-	-
7	M6	P020100	-	-	7.66	-	250.0	147.3	87.7	15.0	575.4	143.9	2822.0	1.69	94.4	13.91	113.3	9.94	121.70	84.59	8110.8	-2.16	-1.64	5.48
7	M6	P020200	-	-	7.66	-	250.0	145.7	87.7	16.6	575.4	143.9	2966.7	1.73	156.6	22.82	187.8	16.47	106.30	73.89	6391.3	-4.83	-3.30	9.85
7	M6	P020201	-	-	7.68	-	250.0	146.1	87.7	16.2	575.4	143.9	4349.1	2.54	170.2	24.88	204.0	17.89	103.63	72.04	6399.6	-2.77	-1.88	7.19
7	M6	P020102	-	-	7.66	-	250.0	148.0	88.8	13.2	575.4	143.9	0.0	0.00	108.5	16.07	130.4	11.58	116.21	80.78	8821.1	-	-	-
7	M6	P020202	-	-	7.68	-	250.0	147.1	87.7	15.2	575.4	143.9	0.0	0.00	188.0	27.65	225.3	19.76	96.45	67.04	6350.5	-	-	-
8	M2	P040102	Lime (10%)	2.47	7.85	8.57	150.0	105.6	36.6	7.7	341.6	51.2	0.0	0.00	141.6	14.96	170.2	6.23	30.04	58.63	3880.8	-	-	-
8	M6	P010300	-	-	7.86	-	150.0	89.8	54.1	6.1	341.6	51.2	2510.3	0.93	78.5	7.05	94.0	5.08	40.04	78.15	6531.4	-	-	-
8	M6	P010301	-	-	7.84	-	150.0	90.2	54.1	5.7	341.6	51.2	3164.1	1.18	88.5	7.98	106.2	5.74	38.69	75.51	6819.5	-	-	-
8	M6	P020100	-	-	7.83	-	150.0	90.6	54.0	5.4	341.6	51.2	2822.0	1.01	65.6	5.94	78.7	4.25	42.06	82.09	7730.0	-0.90	-0.68	2.60
8	M6	P020200	-	-	7.85	-	150.0	90.0	54.1	5.9	341.6	51.2	2966.7	1.04	108.8	9.80	130.4	7.05	35.43	69.14	5998.9	-2.02	-1.40	4.45
8	M6	P020201	-	-	7.84	-	150.0	90.2	54.0	5.8	341.6	51.2	4349.1	1.52	118.2	10.66	141.7	7.66	34.44	67.21	5978.6	-1.15	-0.79	3.46
8	M6	P020102	-	-	7.83	-	150.0	90.8	54.5	4.8	341.6	51.2	0.0	0.00	75.4	6.84	90.6	4.93	39.46	77.02	8260.1	-	-	-
8	M6	P020202	-	-	7.83	-	150.0	90.5	54.0	5.5	341.6	51.2	0.0	0.00	130.6	11.82	156.5	8.45	30.97	60.45	5624.0	-	-	-
9	M2	P040102	Lime (10%)	2.12	7.90	8.51	250.0	165.6	57.4	27.0	648.6	162.1	0.0	0.00	229.9	38.07	276.2	15.85	108.22	66.74	4011.4	-	-	-
9	M6	P010300	-	-	7.90	-	250.0	143.7	86.2	20.1	648.6	162.1	2510.3	1.55	127.4	18.30	152.6	13.15	132.25	81.56	6573.5	-	-	-
9	M6	P010301	-	-	7.92	-	250.0	143.9	86.3	19.8	648.6	162.1	3164.1	1.96	143.6	20.66	172.3	14.87	128.58	79.30	6503.0	-	-	-

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH_{Before}	pH_{After}	Wastewater Volume (mL)	$Volume_{(SUP)}$ (mL)	$Volume_{(CEN)}$ (mL)	$Volume_{(SLG)}$ (mL)	$C_{TOC,\,in}$ *(mg/L)*	$M_{TOC,\,In\ Total}$ *(mg)*	$C_{TOC,\,Coagulant}$ *(mg/L)*	$M_{TOC,\,Coagulant}$ *(mg)*	$C_{TOC,\,SUP}$ *(mg/L)*	$M_{TOC,\,SUP}$ *(mg)*	$C_{TOC,\,CEN}$ *(mg/L)*	$M_{TOC,\,CEN}$ *(mg)*	$M_{TOC,\,SLG}$ *(mg)*	TOC Removal (%)	$C_{TOC,\,SLG}$ *(mg/L)*	$\Delta M_{TOC,\,SUP}$ *(mg)*	$\Delta M_{TOC,\,CEN}$ *(mg)*	$\Delta M_{TOC,\,SLG}$ *(mg)*
9	M6	P020100	-	-	7.88	-	250.0	144.8	86.2	19.0	648.6	162.1	2822.0	1.69	106.4	15.41	127.7	11.02	137.40	84.74	7246.0	-2.43	-1.84	5.96
9	M6	P020200	-	-	7.88	-	250.0	143.0	86.1	20.9	648.6	162.1	2966.7	1.73	176.5	25.25	211.7	18.22	120.41	74.26	5749.3	-5.39	-3.68	10.79
9	M6	P020201	-	-	7.92	-	250.0	143.5	86.1	20.5	648.6	162.1	4349.1	2.54	191.9	27.53	230.0	19.79	117.37	72.38	5734.7	-3.11	-2.10	7.75
9	M6	P020102	-	-	7.90	-	250.0	145.8	87.5	16.7	648.6	162.1	0.0	0.00	122.3	17.84	147.0	12.86	131.44	81.06	7894.4	-	-	-
9	M6	P020202	-	-	7.92	-	250.0	144.6	86.2	19.2	648.6	162.1	0.0	0.00	211.9	30.63	253.9	21.90	109.62	67.60	5711.0	-	-	-
10	M2	P040102	Lime (10%)	0.80	8.31	8.53	250.0	158.5	54.9	36.6	802.6	200.6	0.0	0.00	284.4	45.07	341.8	18.77	136.80	68.18	3734.4	-	-	-
10	M6	P010300	-	-	8.29	-	250.0	139.2	83.5	27.3	802.6	200.6	2510.3	1.55	157.6	21.94	188.8	15.76	164.50	81.99	6021.6	-	-	-
10	M6	P010301	-	-	8.30	-	250.0	139.5	83.6	26.8	802.6	200.6	3164.1	1.96	177.6	24.78	213.2	17.84	159.99	79.74	5959.2	-	-	-
10	M6	P020100	-	-	8.31	-	250.0	140.5	83.7	25.7	802.6	200.6	2822.0	1.69	131.7	18.51	158.1	13.23	170.58	85.02	6625.2	-3.01	-2.28	6.97
10	M6	P020200	-	-	8.29	-	250.0	138.8	83.3	27.9	802.6	200.6	2966.7	1.73	218.5	30.31	261.9	21.82	150.23	74.88	5375.9	-6.47	-4.47	12.66
10	M6	P020201	-	-	8.32	-	250.0	138.9	83.3	27.8	802.6	200.6	4349.1	2.54	237.4	32.98	284.5	23.71	146.49	73.01	5271.7	-3.80	-2.58	8.92
10	M6	P020102	-	-	8.29	-	250.0	142.1	85.3	22.6	802.6	200.6	0.0	0.00	151.4	21.52	181.9	15.51	163.61	81.55	7237.1	-	-	-
10	M6	P020202	-	-	8.30	-	250.0	140.3	83.7	26.1	802.6	200.6	0.0	0.00	262.2	36.78	314.2	26.29	137.57	68.57	5278.8	-	-	-
11	M2	P040102	-	-	8.37	-	250.0	164.9	57.1	28.0	925.6	231.4	0.0	0.00	367.4	60.57	441.5	25.22	145.60	62.92	5201.4	-	-	-
11	M6	P010300	-	-	8.36	-	150.0	85.9	51.5	12.5	925.6	138.8	2510.3	0.93	203.5	17.49	243.9	12.57	109.71	79.02	8759.5	-	-	-
11	M6	P010301	-	-	8.39	-	150.0	86.1	51.6	12.3	925.6	138.8	3164.1	1.18	229.4	19.75	275.4	14.22	106.05	76.38	8615.8	-	-	-
11	M6	P020100	-	-	8.40	-	150.0	86.6	51.6	11.8	925.6	138.8	2822.0	1.01	170.1	14.73	204.2	10.53	114.58	82.53	9706.4	-2.33	-1.77	5.11
11	M6	P020200	-	-	8.38	-	150.0	85.7	51.5	12.8	925.6	138.8	2966.7	1.04	282.2	24.19	338.4	17.41	98.27	70.78	7669.9	-5.10	-3.52	9.65
11	M6	P020201	-	-	8.35	-	150.0	86.0	51.5	12.5	925.6	138.8	4349.1	1.52	306.6	26.37	367.5	18.92	95.07	68.48	7584.4	-2.91	-2.02	6.45
11	M6	P020102	-	-	8.37	-	150.0	87.3	52.4	10.4	925.6	138.8	0.0	0.00	195.5	17.07	234.9	12.30	109.47	78.85	10561.2	-	-	-
11	M6	P020202	-	-	8.35	-	150.0	86.5	51.6	11.9	925.6	138.8	0.0	0.00	338.7	29.29	405.8	20.93	88.62	63.83	7416.6	-	-	-
12	M2	P040102	Lime (10%)	2.00	8.02	8.59	250.0	158.9	55.1	36.0	1063.2	265.8	0.0	0.00	440.9	70.06	529.8	29.17	166.57	62.67	4625.8	-	-	-
12	M6	P010300	-	-	8.02	-	250.0	139.5	83.7	26.9	1063.2	265.8	2510.3	1.55	244.3	34.07	292.7	24.48	208.81	78.56	7776.2	-	-	-
12	M6	P010301	-	-	8.02	-	250.0	139.8	83.8	26.4	1063.2	265.8	3164.1	1.96	275.3	38.49	330.5	27.70	201.58	75.84	7638.6	-	-	-
12	M6	P020100	-	-	8.00	-	250.0	140.8	83.9	25.3	1063.2	265.8	2822.0	1.69	204.1	28.75	245.0	20.55	218.20	82.09	8621.3	-4.66	-3.53	9.88

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH_{Before}	pH_{After}	Wastewater Volume (mL)	$Volume_{(SUP)}$ (mL)	$Volume_{(CEN)}$ (mL)	$Volume_{(SLG)}$ (mL)	$C_{TOC,\,in}$ (mg/L)	$M_{TOC,\,In\ Total}$ (mg)	$C_{TOC,\,Coagulant}$ (mg/L)	$M_{TOC,\,Coagulant}$ (mg)	$C_{TOC,\,SUP}$ (mg/L)	$M_{TOC,\,SUP}$ (mg)	$C_{TOC,\,CEN}$ (mg/L)	$M_{TOC,\,CEN}$ (mg)	$M_{TOC,\,SLG}$ (mg)	TOC Removal (%)	$C_{TOC,\,SLG}$ (mg/L)	$\Delta M_{TOC,\,SUP}$ (mg)	$\Delta M_{TOC,\,CEN}$ (mg)	$\Delta M_{TOC,\,SLG}$ (mg)
12	M6	P020200	-	-	8.01	-	250.0	139.1	83.5	27.5	1063.2	265.8	2966.7	1.73	338.6	47.09	406.0	33.89	186.56	70.18	6791.4	-10.04	-6.93	18.70
12	M6	P020201	-	-	7.99	-	250.0	139.2	83.5	27.3	1063.2	265.8	4349.1	2.54	368.0	51.22	441.1	36.83	180.30	67.83	6600.6	-5.90	-4.00	12.44
12	M6	P020102	-	-	8.03	-	250.0	142.4	85.4	22.2	1063.2	265.8	0.0	0.00	234.7	33.41	281.9	24.08	208.32	78.37	9374.3	-	-	-
12	M6	P020202	-	-	8.05	-	250.0	140.6	83.8	25.6	1063.2	265.8	0.0	0.00	406.4	57.12	487.0	40.83	167.86	63.15	6552.5	-	-	-
13	M2	P040102	Lime (10%)	3.84	7.46	8.56	250.0	159.3	55.2	35.4	737.7	184.4	0.0	0.00	261.4	41.66	314.1	17.35	125.41	68.00	3539.3	-	-	-
13	M6	P010300	-	-	7.48	-	250.0	139.8	83.8	26.4	737.7	184.4	2510.3	1.55	144.8	20.24	173.5	14.55	151.18	81.98	5721.4	-	-	-
13	M6	P010301	-	-	7.47	-	250.0	140.1	84.0	26.0	737.7	184.4	3164.1	1.96	163.3	22.87	196.0	16.46	147.05	79.74	5662.8	-	-	-
13	M6	P020100	-	-	7.43	-	250.0	141.1	84.0	24.9	737.7	184.4	2822.0	1.69	121.1	17.08	145.3	12.21	156.82	85.03	6296.5	-2.76	-2.09	6.54
13	M6	P020200	-	-	7.46	-	250.0	139.3	83.6	27.0	737.7	184.4	2966.7	1.73	200.8	27.98	240.8	20.14	138.03	74.85	5106.2	-5.96	-4.12	11.80
13	M6	P020201	-	-	7.47	-	250.0	140.8	83.7	25.5	737.7	184.4	4349.1	2.54	218.2	30.72	261.5	21.88	134.35	72.85	5259.9	-3.21	-2.37	8.12
13	M6	P020102	-	-	7.44	-	250.0	142.6	85.5	21.9	737.7	184.4	0.0	0.00	139.1	19.84	167.2	14.30	150.27	81.49	6871.9	-	-	-
13	M6	P020202	-	-	7.48	-	250.0	140.8	84.0	25.2	737.7	184.4	0.0	0.00	241.0	33.93	288.8	24.25	126.23	68.45	5007.3	-	-	-
14	M2	P040102	Lime (10%)	3.47	7.36	8.37	150.0	101.0	35.0	14.0	720.0	108.0	0.0	0.00	255.2	25.77	306.6	10.73	71.50	66.20	5106.9	-	-	-
14	M6	P010300	-	-	7.36	-	250.0	145.4	87.2	17.4	720.0	180.0	2510.3	1.55	141.4	20.56	169.4	14.77	146.23	81.24	8404.0	-	-	-
14	M6	P010301	-	-	7.37	-	250.0	145.6	87.3	17.1	720.0	180.0	3164.1	1.96	159.4	23.20	191.3	16.70	142.06	78.92	8307.6	-	-	-
14	M6	P020100	-	-	7.37	-	250.0	146.4	87.2	16.4	720.0	180.0	2822.0	1.69	118.2	17.30	141.8	12.37	152.02	84.46	9269.6	-2.73	-2.08	6.50
14	M6	P020200	-	-	7.37	-	250.0	145.1	87.1	17.8	720.0	180.0	2966.7	1.73	196.0	28.44	235.0	20.47	132.82	73.79	7461.8	-5.95	-4.11	11.79
14	M6	P020201	-	-	7.36	-	250.0	145.2	87.1	17.7	720.0	180.0	4349.1	2.54	213.0	30.93	255.3	22.23	129.38	71.88	7309.3	-3.46	-2.34	8.34
14	M6	P020102	-	-	7.36	-	250.0	147.5	88.5	14.0	720.0	180.0	0.0	0.00	135.8	20.03	163.2	14.44	145.53	80.85	10394.8	-	-	-
14	M6	P020202	-	-	7.36	-	250.0	146.2	87.2	16.6	720.0	180.0	0.0	0.00	235.2	34.39	281.9	24.58	121.03	67.24	7291.0	-	-	-
15	M2	P040102	Lime (10%)	2.72	7.59	8.37	250.0	170.7	59.2	20.1	759.1	189.8	0.0	0.00	269.0	45.92	323.3	19.12	124.73	65.72	6192.8	-	-	-
15	M6	P010300	-	-	7.58	-	250.0	146.9	88.1	15.0	759.1	189.8	2510.3	1.55	149.0	21.89	178.6	15.73	153.70	80.99	10233.7	-	-	-
15	M6	P010301	-	-	7.58	-	250.0	147.1	88.2	14.8	759.1	189.8	3164.1	1.96	168.0	24.71	201.7	17.78	149.24	78.64	10111.1	-	-	-
15	M6	P020100	-	-	7.58	-	250.0	147.8	88.0	14.2	759.1	189.8	2822.0	1.69	124.6	18.41	149.5	13.16	159.88	84.25	11294.4	-2.85	-2.16	6.70

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{TOC,\,in}$ (mg/L)	$M_{TOC,\,In\ Total}$ (mg)	$C_{TOC,\,Coagulant}$ (mg/L)	$M_{TOC,\,Coagulant}$ (mg)	$C_{TOC,\,SUP}$ (mg/L)	$M_{TOC,\,SUP}$ (mg)	$C_{TOC,\,CEN}$ (mg/L)	$M_{TOC,\,CEN}$ (mg)	$M_{TOC,\,SLG}$ (mg)	TOC Removal (%)	$C_{TOC,\,SLG}$ (mg/L)	$\Delta M_{TOC,\,SUP}$ (mg)	$\Delta M_{TOC,\,CEN}$ (mg)	$\Delta M_{TOC,\,SLG}$ (mg)
15	M6	P020200	-	-	7.60	-	250.0	146.6	88.0	15.4	759.1	189.8	2966.7	1.73	206.6	30.30	247.8	21.81	139.40	73.45	9072.7	-6.31	-4.36	12.40
15	M6	P020201	-	-	7.60	-	250.0	147.0	88.0	15.0	759.1	189.8	4349.1	2.54	224.6	33.01	269.1	23.69	135.61	71.46	9045.7	-3.60	-2.48	8.62
15	M6	P020102	-	-	7.60	-	250.0	148.5	89.1	12.4	759.1	189.8	0.0	0.00	143.2	21.26	172.0	15.33	153.19	80.72	12324.3	-	-	-
15	M6	P020202	-	-	7.61	-	250.0	147.6	88.0	14.3	759.1	189.8	0.0	0.00	248.0	36.61	297.2	26.17	127.00	66.92	8863.1	-	-	-
16	M2	P040102	Lime (10%)	1.68	7.92	8.40	250.0	163.2	56.6	30.2	788.2	197.1	0.0	0.00	279.3	45.59	335.7	18.98	132.48	67.23	4382.2	-	-	-
16	M6	P010300	-	-	7.93	-	250.0	142.2	85.3	22.5	788.2	197.1	2510.3	1.55	154.8	22.01	185.4	15.81	160.79	81.60	7132.5	-	-	-
16	M6	P010301	-	-	7.94	-	250.0	142.4	85.4	22.2	788.2	197.1	3164.1	1.96	174.5	24.85	209.4	17.89	156.28	79.31	7054.0	-	-	-
16	M6	P020100	-	-	7.90	-	250.0	143.4	85.4	21.2	788.2	197.1	2822.0	1.69	129.4	18.54	155.2	13.26	166.94	84.72	7856.8	-2.95	-2.24	6.88
16	M6	P020200	-	-	7.91	-	250.0	141.8	85.1	23.1	788.2	197.1	2966.7	1.73	214.6	30.43	257.3	21.90	146.45	74.32	6350.5	-6.43	-4.44	12.60
16	M6	P020201	-	-	7.91	-	250.0	142.1	85.1	22.8	788.2	197.1	4349.1	2.54	233.2	33.13	279.5	23.79	142.67	72.40	6267.7	-3.72	-2.55	8.81
16	M6	P020102	-	-	7.94	-	250.0	144.6	86.8	18.7	788.2	197.1	0.0	0.00	148.7	21.50	178.6	15.50	160.06	81.23	8579.2	-	-	-
16	M6	P020202	-	-	7.92	-	250.0	143.1	85.4	21.5	788.2	197.1	0.0	0.00	257.5	36.86	308.6	26.34	133.86	67.93	6223.8	-	-	-
17	M2	P040102	Lime (10%)	2.20	7.72	8.39	250.0	168.9	58.5	22.5	643.4	160.8	0.0	0.00	228.0	38.52	274.0	16.04	106.29	66.08	4719.3	-	-	-
17	M6	P010300	-	-	7.74	-	150.0	87.5	52.5	10.1	643.4	96.5	2510.3	0.93	126.3	11.05	151.4	7.94	78.45	81.29	7785.4	-	-	-
17	M6	P010301	-	-	7.72	-	150.0	87.6	52.5	9.9	643.4	96.5	3164.1	1.18	142.4	12.47	170.9	8.98	76.24	79.00	7698.4	-	-	-
17	M6	P020100	-	-	7.75	-	150.0	88.1	52.4	9.5	643.4	96.5	2822.0	1.01	105.6	9.30	126.7	6.65	81.58	84.53	8589.2	-1.45	-1.10	3.56
17	M6	P020200	-	-	7.69	-	150.0	87.3	52.4	10.3	643.4	96.5	2966.7	1.04	175.1	15.29	210.0	11.00	71.25	73.83	6912.0	-3.20	-2.21	6.44
17	M6	P020201	-	-	7.70	-	150.0	87.4	52.4	10.3	643.4	96.5	4349.1	1.52	190.3	16.63	228.1	11.95	69.45	71.96	6775.4	-1.86	-1.26	4.64
17	M6	P020102	-	-	7.69	-	150.0	88.5	53.1	8.3	643.4	96.5	0.0	0.00	121.4	10.75	145.8	7.75	78.02	80.84	9355.3	-	-	-
17	M6	P020202	-	-	7.70	-	150.0	87.9	52.4	9.6	643.4	96.5	0.0	0.00	210.2	18.48	251.9	13.21	64.81	67.16	6741.9	-	-	-
18	M2	P040102	-	-	8.47	-	250.0	175.0	60.7	14.3	765.0	191.3	0.0	0.00	271.1	47.46	325.8	19.76	124.03	64.85	8679.2	-	-	-
18	M6	P010300	-	-	8.47	-	250.0	149.6	89.7	10.7	765.0	191.3	2510.3	1.55	150.2	22.47	180.0	16.15	154.18	80.62	14468.3	-	-	-
18	M6	P010301	-	-	8.44	-	250.0	149.7	89.8	10.5	765.0	191.3	3164.1	1.96	169.3	25.35	203.3	18.25	149.61	78.23	14285.3	-	-	-
18	M6	P020100	-	-	8.49	-	250.0	150.4	89.6	10.0	765.0	191.3	2822.0	1.69	125.5	18.88	150.7	13.50	160.56	83.95	15985.6	-2.87	-2.18	6.74
18	M6	P020200	-	-	8.49	-	250.0	149.4	89.7	10.9	765.0	191.3	2966.7	1.73	208.2	31.11	249.7	22.39	139.47	72.92	12793.5	-6.43	-4.44	12.60

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{TOC,\,in}$ (mg/L)	$M_{TOC,\,In\ Total}$ (mg)	$C_{TOC,\,Coagulant}$ (mg/L)	$M_{TOC,\,Coagulant}$ (mg)	$C_{TOC,\,SUP}$ (mg/L)	$M_{TOC,\,SUP}$ (mg)	$C_{TOC,\,CEN}$ (mg/L)	$M_{TOC,\,CEN}$ (mg)	$M_{TOC,\,SLG}$ (mg)	TOC Removal (%)	$C_{TOC,\,SLG}$ (mg/L)	$\Delta M_{TOC,\,SUP}$ (mg)	$\Delta M_{TOC,\,CEN}$ (mg)	$\Delta M_{TOC,\,SLG}$ (mg)
18	M6	P020201	-	-	8.44	-	250.0	149.5	89.7	10.8	765.0	191.3	4349.1	2.54	226.3	33.83	271.2	24.32	135.63	70.92	12512.1	-3.72	-2.51	8.77
18	M6	P020102	-	-	8.47	-	250.0	150.7	90.4	8.8	765.0	191.3	0.0	0.00	144.3	21.75	173.4	15.68	153.82	80.43	17441.1	-	-	-
18	M6	P020202	-	-	8.47	-	250.0	150.2	89.6	10.2	765.0	191.3	0.0	0.00	249.9	37.55	299.5	26.84	126.87	66.34	12478.9	-	-	-
19	M2	P040102	Lime (10%)	1.88	7.95	8.49	250.0	165.3	57.3	27.4	566.9	141.7	0.0	0.00	213.0	35.20	255.9	14.66	91.87	64.82	3349.6	-	-	-
19	M6	P010300	-	-	7.93	-	250.0	143.5	86.1	20.5	566.9	141.7	2510.3	1.55	118.0	16.93	141.4	12.17	114.18	80.57	5583.0	-	-	-
19	M6	P010301	-	-	7.93	-	250.0	143.7	86.2	20.1	566.9	141.7	3164.1	1.96	133.0	19.12	159.7	13.76	110.81	78.19	5513.3	-	-	-
19	M6	P020100	-	-	7.96	-	250.0	144.6	86.1	19.3	566.9	141.7	2822.0	1.69	98.6	14.26	118.4	10.19	118.96	83.94	6171.1	-2.25	-1.71	5.65
19	M6	P020200	-	-	7.98	-	250.0	143.1	85.9	20.9	566.9	141.7	2966.7	1.73	163.6	23.41	196.1	16.85	103.18	72.80	4931.7	-4.93	-3.40	10.06
19	M6	P020201	-	-	7.95	-	250.0	143.3	85.9	20.8	566.9	141.7	4349.1	2.54	177.8	25.47	213.1	18.31	100.49	70.90	4830.0	-2.88	-1.95	7.36
19	M6	P020102	-	-	7.98	-	250.0	145.7	87.4	16.9	566.9	141.7	0.0	0.00	113.4	16.51	136.2	11.90	113.31	79.95	6694.5	-	-	-
19	M6	P020202	-	-	7.96	-	250.0	144.4	86.1	19.5	566.9	141.7	0.0	0.00	196.3	28.34	235.3	20.26	93.12	65.71	4772.8	-	-	-
20	M2	P040102	-	-	8.41	-	150.0	105.9	36.7	7.4	563.7	84.6	0.0	0.00	211.8	22.42	254.5	9.34	52.80	62.44	7098.6	-	-	-
20	M6	P010300	-	-	8.39	-	150.0	90.3	54.2	5.5	563.7	84.6	2510.3	0.93	117.3	10.59	140.6	7.61	67.28	79.57	12130.1	-	-	-
20	M6	P010301	-	-	8.43	-	150.0	90.4	54.2	5.5	563.7	84.6	3164.1	1.18	132.2	11.95	158.7	8.60	65.18	77.09	11957.5	-	-	-
20	M6	P020100	-	-	8.41	-	150.0	90.7	54.0	5.2	563.7	84.6	2822.0	1.01	98.1	8.90	117.7	6.36	70.31	83.15	13449.2	-1.35	-1.02	3.38
20	M6	P020200	-	-	8.43	-	150.0	89.7	54.1	6.2	563.7	84.6	2966.7	1.04	162.6	14.59	195.0	10.56	60.44	71.48	9808.6	-3.11	-2.09	6.23
20	M6	P020201	-	-	8.40	-	150.0	90.2	54.1	5.6	563.7	84.6	4349.1	1.52	176.8	15.95	211.9	11.47	58.66	69.38	10396.8	-1.75	-1.18	4.45
20	M6	P020102	-	-	8.41	-	150.0	90.9	54.5	4.6	563.7	84.6	0.0	0.00	112.7	10.24	135.4	7.38	66.93	79.15	14580.5	-	-	-
20	M6	P020202	-	-	8.41	-	150.0	90.6	54.1	5.3	563.7	84.6	0.0	0.00	195.2	17.70	233.9	12.65	54.21	64.12	10245.1	-	-	-
21	M2	P040102	Lime (10%)	1.52	8.00	8.44	250.0	166.4	57.7	26.0	683.9	171.0	0.0	0.00	242.4	40.32	291.2	16.79	113.87	66.60	4382.0	-	-	-
21	M6	P010300	-	-	8.00	-	250.0	144.2	86.5	19.4	683.9	171.0	2510.3	1.55	134.3	19.36	160.9	13.91	139.26	81.45	7186.9	-	-	-
21	M6	P010301	-	-	7.99	-	250.0	144.4	86.6	19.0	683.9	171.0	3164.1	1.96	151.4	21.86	181.7	15.73	135.36	79.16	7107.7	-	-	-
21	M6	P020100	-	-	7.98	-	250.0	145.2	86.5	18.3	683.9	171.0	2822.0	1.69	112.2	16.30	134.7	11.65	144.71	84.64	7923.5	-2.56	-1.95	6.20
21	M6	P020200	-	-	8.02	-	250.0	143.8	86.3	19.8	683.9	171.0	2966.7	1.73	186.2	26.78	223.2	19.27	126.66	74.08	6389.3	-5.63	-3.88	11.24
21	M6	P020201	-	-	7.97	-	250.0	144.1	86.3	19.6	683.9	171.0	4349.1	2.54	202.3	29.15	242.5	20.94	123.42	72.19	6311.9	-3.25	-2.22	8.01

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH_{Before}	pH_{After}	Wastewater Volume (mL)	$Volume_{(SUP)}$ (mL)	$Volume_{(CEN)}$ (mL)	$Volume_{(SLG)}$ (mL)	$C_{TOC,\ in}$ (mg/L)	$M_{TOC,\ In\ Total}$ (mg)	$C_{TOC,\ Coagulant}$ (mg/L)	$M_{TOC,\ Coagulant}$ (mg)	$C_{TOC,\ SUP}$ (mg/L)	$M_{TOC,\ SUP}$ (mg)	$C_{TOC,\ CEN}$ (mg/L)	$M_{TOC,\ CEN}$ (mg)	$M_{TOC,\ SLG}$ (mg)	TOC Removal (%)	$C_{TOC,\ SLG}$ (mg/L)	$\Delta M_{TOC,\ SUP}$ (mg)	$\Delta M_{TOC,\ CEN}$ (mg)	$\Delta M_{TOC,\ SLG}$ (mg)
21	M6	P020102	-	-	8.00	-	250.0	146.2	87.7	16.0	683.9	171.0	0.0	0.00	129.0	18.87	155.0	13.60	138.52	81.01	8637.5	-	-	-
21	M6	P020202	-	-	8.02	-	250.0	145.0	86.5	18.5	683.9	171.0	0.0	0.00	223.4	32.40	267.7	23.16	115.42	67.50	6243.4	-	-	-
22	M2	P040102	Lime (10%)	1.74	8.00	8.51	150.0	101.6	35.2	13.1	844.9	126.7	0.0	0.00	299.4	30.43	359.8	12.67	83.63	65.99	6365.1	-	-	-
22	M6	P010300	-	-	7.98	-	250.0	146.1	87.6	16.3	844.9	211.2	2510.3	1.55	165.9	24.23	198.8	17.41	171.13	81.02	10480.3	-	-	-
22	M6	P010301	-	-	8.03	-	250.0	146.3	87.7	16.0	844.9	211.2	3164.1	1.96	187.0	27.35	224.5	19.69	166.15	78.66	10353.6	-	-	-
22	M6	P020100	-	-	7.98	-	250.0	147.0	87.6	15.4	844.9	211.2	2822.0	1.69	138.6	20.39	166.4	14.57	177.95	84.25	11562.2	-3.17	-2.41	7.26
22	M6	P020200	-	-	8.01	-	250.0	145.8	87.5	16.7	844.9	211.2	2966.7	1.73	230.0	33.53	275.8	24.13	155.29	73.52	9296.2	-7.00	-4.84	13.57
22	M6	P020201	-	-	7.99	-	250.0	145.9	87.5	16.6	844.9	211.2	4349.1	2.54	249.9	36.46	299.6	26.21	151.09	71.53	9095.7	-4.07	-2.76	9.36
22	M6	P020102	-	-	8.00	-	250.0	147.8	88.7	13.5	844.9	211.2	0.0	0.00	159.4	23.56	191.5	16.98	170.69	80.81	12630.7	-	-	-
22	M6	P020202	-	-	8.03	-	250.0	146.8	87.6	15.6	844.9	211.2	0.0	0.00	276.0	40.53	330.8	28.97	141.72	67.10	9097.4	-	-	-

Notes:

- ✓ In Scenario M2, the doses applied were 8 g/L for the conventional 40% aluminum sulfate coagulant and 4 g/L for PAM, whereas in Scenario M6, fixed doses of 2.8 g/L for the hybrid coagulants and 1.88 g/L for PAM were used for all formulations.

APPENDIX G: MASS BALANCE CALCULATIONS FOR ALUMINUM (Al)

Table G.1. Mass balance calculations for Aluminum (Al).

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{Al,in}$ (mg/L)	$M_{Al,In\ Total}$ (mg)	$M_{Al,Coagulant}$ (mg)	$C_{Al,SUP}$ (mg/L)	$M_{Al,SUP}$ (mg)	$C_{Al,CEN}$ (mg/L)	$M_{Al,CEN}$ (mg)	$C_{Al,SLG}$ (mg/L)	M_{Dry} (g) (Dry Sludge Weight)	$M_{Al,SLG}$ (mg)	$\Delta M_{Al,Loss}$	%SUP	%CEN	%SLG
1	M2	P040102	Lime (10%)	3.68	7.39	8.46	250.0	168.3	58.3	23.4	0.00	0.00	64.80	18.89	3.18	218.04	12.71	398.96	0.48	47.68	1.90	4.91	19.62	73.58
1	M6	P010300	-	-	7.41	-	250.0	145.4	87.2	17.5	0.00	0.00	23.32	4.59	0.67	51.01	4.45	184.54	0.37	17.12	4.66	2.86	19.07	73.41
1	M6	P010301	-	-	7.41	-	250.0	145.6	87.3	17.2	0.00	0.00	23.32	4.60	0.67	51.88	4.53	190.18	0.36	17.28	3.61	2.87	19.42	74.10
1	M6	P020100	-	-	7.39	-	250.0	146.4	87.2	16.5	0.00	0.00	31.49	8.51	1.24	70.93	6.18	215.53	0.43	23.12	2.97	3.95	19.64	73.44
1	M6	P020200	-	-	7.37	-	250.0	144.5	87.1	18.4	0.00	0.00	35.90	4.83	0.70	72.19	6.29	227.24	0.50	28.61	0.85	1.94	17.51	79.70
1	M6	P020201	-	-	7.41	-	250.0	145.2	87.1	17.8	0.00	0.00	35.90	4.78	0.69	72.15	6.28	240.54	0.48	28.62	0.85	1.93	17.50	79.72
2	M2	P040102	Lime (10%)	5.28	7.07	8.59	250.0	159.4	55.2	35.4	0.80	0.20	64.80	19.79	3.15	215.00	11.87	223.08	0.86	48.07	2.93	4.85	18.27	73.96
2	M6	P010300	-	-	7.08	-	250.0	139.8	83.8	26.4	0.80	0.20	23.32	4.87	0.68	53.49	4.48	107.16	0.64	17.03	5.62	2.89	19.06	72.42
2	M6	P010301	-	-	7.07	-	250.0	140.1	84.0	25.9	0.80	0.20	23.32	4.99	0.70	52.76	4.43	115.13	0.62	17.97	1.80	2.97	18.84	76.39
2	M6	P020100	-	-	7.07	-	250.0	141.1	84.0	24.9	0.80	0.20	31.49	8.72	1.23	72.22	6.07	132.56	0.71	23.65	2.35	3.88	19.15	74.62
2	M6	P020200	-	-	7.09	-	250.0	139.3	83.6	27.0	0.80	0.20	35.90	4.87	0.68	74.11	6.20	129.11	0.86	27.78	3.99	1.88	17.17	76.95
2	M6	P020201	-	-	7.09	-	250.0	139.5	83.7	26.9	0.80	0.20	35.90	4.99	0.70	73.51	6.15	158.70	0.73	28.81	1.22	1.93	17.04	79.81
3	M2	P040102	Lime (10%)	2.94	7.61	8.54	150.0	103.5	35.9	10.6	0.40	0.06	38.88	18.51	1.92	213.68	7.67	417.21	0.28	28.75	1.56	4.92	19.69	73.83
3	M6	P010300	-	-	7.62	-	150.0	88.8	53.3	7.9	0.40	0.06	13.99	4.62	0.41	51.38	2.74	171.87	0.25	10.54	2.62	2.92	19.48	74.98
3	M6	P010301	-	-	7.59	-	150.0	88.9	53.3	7.8	0.40	0.06	13.99	4.61	0.41	51.94	2.77	179.84	0.24	10.57	2.17	2.92	19.71	75.20
3	M6	P020100	-	-	7.61	-	150.0	89.3	53.2	7.4	0.40	0.06	18.89	8.51	0.76	71.01	3.78	207.21	0.27	14.13	1.50	4.01	19.94	74.55
3	M6	P020200	-	-	7.60	-	150.0	88.5	53.2	8.3	0.40	0.06	21.54	4.64	0.41	69.47	3.70	223.40	0.30	16.83	3.04	1.90	17.12	77.94
3	M6	P020201	-	-	7.62	-	150.0	88.7	53.2	8.0	0.40	0.06	21.54	4.71	0.42	71.07	3.78	244.53	0.28	17.23	0.77	1.93	17.52	79.78
4	M2	P040102	Lime (10%)	5.12	7.03	8.51	250.0	159.3	55.2	35.5	0.90	0.23	64.80	19.94	3.18	230.16	12.71	223.35	0.85	47.65	2.29	4.89	19.54	73.28
4	M6	P010300	-	-	7.05	-	250.0	139.7	83.8	26.4	0.90	0.23	23.32	4.86	0.68	54.02	4.53	99.04	0.70	17.43	3.87	2.88	19.23	74.02
4	M6	P010301	-	-	7.02	-	250.0	140.0	84.0	26.0	0.90	0.23	23.32	4.96	0.69	55.89	4.69	110.20	0.65	17.91	1.06	2.95	19.93	76.06
4	M6	P020100	-	-	7.01	-	250.0	141.1	84.0	24.9	0.90	0.23	31.49	8.93	1.26	74.44	6.25	117.62	0.80	23.39	2.57	3.97	19.72	73.74
4	M6	P020200	-	-	7.06	-	250.0	139.2	83.6	27.2	0.90	0.23	35.90	4.94	0.69	74.04	6.19	130.17	0.87	28.18	2.94	1.90	17.14	78.01
4	M6	P020201	-	-	7.05	-	250.0	139.4	83.6	26.9	0.90	0.23	35.90	5.03	0.70	75.98	6.36	142.86	0.81	28.95	0.32	1.94	17.59	80.14
5	M2	P040102	Lime (10%)	2.72	7.62	8.41	250.0	165.3	57.3	27.4	0.30	0.08	64.80	19.55	3.23	225.60	12.92	210.15	0.92	48.46	0.41	4.98	19.92	74.69
5	M6	P010300	-	-	7.63	-	250.0	143.5	86.1	20.5	0.30	0.08	23.32	4.66	0.67	51.85	4.46	93.07	0.74	17.18	4.65	2.86	19.07	73.42
5	M6	P010301	-	-	7.60	-	250.0	143.7	86.2	20.1	0.30	0.08	23.32	4.62	0.66	52.10	4.49	93.07	0.74	17.13	4.74	2.84	19.19	73.24
5	M6	P020100	-	-	7.61	-	250.0	144.6	86.1	19.3	0.30	0.08	31.49	8.54	1.23	71.23	6.13	109.52	0.84	22.94	3.98	3.91	19.43	72.67
5	M6	P020200	-	-	7.61	-	250.0	143.1	85.9	20.9	0.30	0.08	35.90	4.85	0.69	72.78	6.25	123.10	0.92	28.46	1.56	1.93	17.38	79.12
5	M6	P020201	-	-	7.60	-	250.0	143.2	85.9	20.8	0.30	0.08	35.90	4.87	0.70	73.47	6.31	124.30	0.93	28.76	0.57	1.94	17.55	79.94

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{Al,in}$ (mg/L)	$M_{Al,In\ Total}$ (mg)	$M_{Al,Coagulant}$ (mg)	$C_{Al,SUP}$ (mg/L)	$M_{Al,SUP}$ (mg)	$C_{Al,CEN}$ (mg/L)	$M_{Al,CEN}$ (mg)	$C_{Al,SLG}$ (mg/L)	M_{Dry} (g) (Dry Sludge Weight)	$M_{Al,SLG}$ (mg)	$\Delta M_{Al,Loss}$	%SUP	%CEN	%SLG
6	M2	P040102	Lime (10%)	3.08	7.52	8.40	250.0	165.5	57.4	27.1	0.30	0.08	64.80	19.46	3.22	224.64	12.89	231.73	0.83	48.32	0.69	4.97	19.86	74.49
6	M6	P010300	-	-	7.51	-	250.0	143.6	86.1	20.2	0.30	0.08	23.32	4.76	0.68	52.97	4.56	98.52	0.71	17.57	2.48	2.92	19.51	75.09
6	M6	P010301	-	-	7.53	-	250.0	143.9	86.3	19.9	0.30	0.08	23.32	4.83	0.70	54.49	4.70	104.05	0.69	17.94	0.27	2.97	20.09	76.67
6	M6	P020100	-	-	7.54	-	250.0	144.7	86.2	19.0	0.30	0.08	31.49	8.49	1.23	70.79	6.10	124.96	0.73	22.82	4.46	3.89	19.34	72.31
6	M6	P020200	-	-	7.53	-	250.0	143.3	86.0	20.7	0.30	0.08	35.90	4.86	0.70	72.86	6.27	142.57	0.80	28.53	1.34	1.93	17.42	79.30
6	M6	P020201	-	-	7.51	-	250.0	143.4	86.0	20.6	0.30	0.08	35.90	4.73	0.68	71.39	6.14	144.71	0.77	27.97	3.28	1.89	17.07	77.76
7	M2	P040102	Lime (10%)	2.44	7.68	8.38	250.0	169.8	58.8	21.3	0.20	0.05	64.80	18.58	3.15	214.40	12.62	311.46	0.61	47.31	2.72	4.86	19.45	72.96
7	M6	P010300	-	-	7.71	-	250.0	146.3	87.8	15.9	0.20	0.05	23.32	4.74	0.69	52.74	4.63	139.95	0.51	17.82	0.99	2.97	19.80	76.24
7	M6	P010301	-	-	7.71	-	250.0	146.5	87.8	15.6	0.20	0.05	23.32	4.53	0.66	51.04	4.48	149.48	0.46	17.11	4.75	2.84	19.19	73.22
7	M6	P020100	-	-	7.66	-	250.0	147.3	87.7	15.0	0.20	0.05	31.49	8.39	1.24	69.99	6.14	167.86	0.55	22.96	3.82	3.92	19.47	72.79
7	M6	P020200	-	-	7.66	-	250.0	145.7	87.7	16.6	0.20	0.05	35.90	4.62	0.67	69.08	6.06	174.34	0.63	27.56	4.61	1.87	16.85	76.67
7	M6	P020201	-	-	7.68	-	250.0	146.1	87.7	16.2	0.20	0.05	35.90	4.58	0.67	69.20	6.07	193.59	0.57	27.63	4.40	1.86	16.88	76.87
8	M2	P040102	Lime (10%)	2.47	7.85	8.57	150.0	105.6	36.6	7.7	0.00	0.00	38.88	18.31	1.93	211.28	7.74	522.60	0.22	29.01	0.52	4.97	19.89	74.61
8	M6	P010300	-	-	7.86	-	150.0	89.8	54.1	6.1	0.00	0.00	13.99	4.62	0.42	51.22	2.77	252.20	0.17	10.66	1.04	2.97	19.79	76.20
8	M6	P010301	-	-	7.84	-	150.0	90.2	54.1	5.7	0.00	0.00	13.99	4.61	0.42	51.94	2.81	255.62	0.17	10.72	0.32	2.97	20.08	76.63
8	M6	P020100	-	-	7.83	-	150.0	90.6	54.0	5.4	0.00	0.00	18.89	8.36	0.76	69.69	3.76	294.53	0.19	14.06	1.66	4.01	19.90	74.43
8	M6	P020200	-	-	7.85	-	150.0	90.0	54.1	5.9	0.00	0.00	21.54	4.60	0.41	68.99	3.73	306.64	0.22	16.97	1.97	1.92	17.31	78.80
8	M6	P020201	-	-	7.84	-	150.0	90.2	54.0	5.8	0.00	0.00	21.54	4.59	0.41	69.36	3.75	333.91	0.20	17.07	1.40	1.92	17.40	79.27
9	M2	P040102	Lime (10%)	2.12	7.90	8.51	250.0	165.6	57.4	27.0	0.50	0.13	64.80	19.32	3.20	222.96	12.80	198.03	0.97	47.99	1.45	4.93	19.71	73.91
9	M6	P010300	-	-	7.90	-	250.0	143.7	86.2	20.1	0.50	0.13	23.32	4.76	0.68	52.94	4.56	84.36	0.83	17.56	2.70	2.92	19.46	74.92
9	M6	P010301	-	-	7.92	-	250.0	143.9	86.3	19.8	0.50	0.13	23.32	4.82	0.69	54.30	4.69	97.22	0.74	17.88	0.78	2.96	19.99	76.28
9	M6	P020100	-	-	7.88	-	250.0	144.8	86.2	19.0	0.50	0.13	31.49	8.54	1.24	71.26	6.15	105.50	0.87	22.98	3.95	3.91	19.44	72.70
9	M6	P020200	-	-	7.88	-	250.0	143.0	86.1	20.9	0.50	0.13	35.90	4.92	0.70	73.58	6.33	121.88	0.95	28.82	0.46	1.95	17.58	80.01
9	M6	P020201	-	-	7.92	-	250.0	143.5	86.1	20.5	0.50	0.13	35.90	4.66	0.67	70.31	6.05	122.02	0.90	27.56	4.84	1.86	16.80	76.51
10	M2	P040102	Lime (10%)	0.80	8.31	8.53	250.0	158.5	54.9	36.6	0.90	0.23	64.80	20.49	3.25	236.54	12.99	119.57	1.63	48.71	0.13	4.99	19.97	74.90
10	M6	P010300	-	-	8.29	-	250.0	139.2	83.5	27.3	0.90	0.23	23.32	4.87	0.68	54.15	4.52	50.94	1.37	17.40	4.01	2.88	19.20	73.91
10	M6	P010301	-	-	8.30	-	250.0	139.5	83.6	26.8	0.90	0.23	23.32	4.85	0.68	54.72	4.58	52.37	1.33	17.47	3.49	2.88	19.44	74.19
10	M6	P020100	-	-	8.31	-	250.0	140.5	83.7	25.7	0.90	0.23	31.49	8.86	1.25	73.92	6.19	57.27	1.62	23.14	3.60	3.93	19.51	72.96
10	M6	P020200	-	-	8.29	-	250.0	138.8	83.3	27.9	0.90	0.23	35.90	4.91	0.68	73.67	6.14	60.81	1.84	27.93	3.80	1.89	16.99	77.32
10	M6	P020201	-	-	8.32	-	250.0	138.9	83.3	27.8	0.90	0.23	35.90	5.05	0.70	76.18	6.35	68.28	1.69	28.91	0.46	1.94	17.57	80.03
11	M2	P040102	-	-	8.37	-	250.0	164.9	57.1	28.0	0.90	0.23	64.80	18.89	3.11	217.96	12.45	144.56	1.29	46.70	4.24	4.79	19.15	71.82
11	M6	P010300	-	-	8.36	-	150.0	85.9	51.5	12.5	0.90	0.14	13.99	4.78	0.41	53.13	2.74	64.08	0.66	10.54	3.09	2.91	19.38	74.62
11	M6	P010301	-	-	8.39	-	150.0	86.1	51.6	12.3	0.90	0.14	13.99	4.81	0.41	54.21	2.80	71.61	0.60	10.68	1.69	2.93	19.80	75.58
11	M6	P020100	-	-	8.40	-	150.0	86.6	51.6	11.8	0.90	0.14	18.89	8.92	0.77	74.35	3.84	77.89	0.74	14.34	0.41	4.06	20.16	75.38
11	M6	P020200	-	-	8.38	-	150.0	85.7	51.5	12.8	0.90	0.14	21.54	4.88	0.42	73.19	3.77	82.45	0.83	17.14	1.59	1.93	17.38	79.10
11	M6	P020201	-	-	8.35	-	150.0	86.0	51.5	12.5	0.90	0.14	21.54	4.83	0.42	73.10	3.76	89.66	0.76	17.14	1.66	1.92	17.36	79.06
12	M2	P040102	Lime (10%)	2.00	8.02	8.59	250.0	158.9	55.1	36.0	1.00	0.25	64.80	19.58	3.11	225.94	12.44	129.90	1.44	46.66	4.36	4.78	19.13	71.73

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH	pH_{Before}	pH_{After}	Wastewater Volume (mL)	$Volume_{(SUP)}$ (mL)	$Volume_{(CEN)}$ (mL)	$Volume_{(SLG)}$ (mL)	$C_{Al,in}$ *(mg/L)*	$M_{Al,In\ Total}$ *(mg)*	$M_{Al,Coagulant}$ *(mg)*	$C_{Al,SUP}$ *(mg/L)*	$M_{Al,SUP}$ *(mg)*	$C_{Al,CEN}$ *(mg/L)*	$M_{Al,CEN}$ *(mg)*	$C_{Al,SLG}$ *(mg/L)*	M_{Dry} (g) *(Dry Sludge Weight)*	$M_{Al,SLG}$ *(mg)*	$\Delta M_{Al,Loss}$	%SUP	%CEN	%SLG
12	M6	P010300	-	-	8.02	-	250.0	139.5	83.7	26.9	1.00	0.25	23.32	4.95	0.69	55.02	4.60	63.09	1.12	17.72	2.37	2.93	19.53	75.18
12	M6	P010301	-	-	8.02	-	250.0	139.8	83.8	26.4	1.00	0.25	23.32	4.99	0.70	56.27	4.72	65.10	1.11	18.00	0.67	2.96	20.01	76.36
12	M6	P020100	-	-	8.00	-	250.0	140.8	83.9	25.3	1.00	0.25	31.49	8.86	1.25	73.89	6.20	77.21	1.20	23.18	3.52	3.93	19.53	73.02
12	M6	P020200	-	-	8.01	-	250.0	139.1	83.5	27.5	1.00	0.25	35.90	4.91	0.68	73.61	6.14	81.31	1.38	27.97	3.75	1.89	17.00	77.36
12	M6	P020201	-	-	7.99	-	250.0	139.2	83.5	27.3	1.00	0.25	35.90	4.92	0.68	74.28	6.20	82.25	1.37	28.25	2.79	1.89	17.16	78.15
13	M2	P040102	Lime (10%)	3.84	7.46	8.56	250.0	159.3	55.2	35.4	0.80	0.20	64.80	19.87	3.17	229.28	12.66	160.65	1.18	47.48	2.61	4.87	19.48	73.04
13	M6	P010300	-	-	7.48	-	250.0	139.8	83.8	26.4	0.80	0.20	23.32	4.94	0.69	54.92	4.60	80.43	0.88	17.72	2.15	2.93	19.57	75.34
13	M6	P010301	-	-	7.47	-	250.0	140.1	84.0	26.0	0.80	0.20	23.32	4.99	0.70	56.30	4.73	84.54	0.85	18.04	0.22	2.97	20.10	76.70
13	M6	P020100	-	-	7.43	-	250.0	141.1	84.0	24.9	0.80	0.20	31.49	9.10	1.28	75.86	6.37	96.21	0.99	23.84	0.62	4.05	20.11	75.22
13	M6	P020200	-	-	7.46	-	250.0	139.3	83.6	27.0	0.80	0.20	35.90	5.07	0.71	76.03	6.36	103.42	1.12	28.94	0.25	1.96	17.62	80.18
13	M6	P020201	-	-	7.47	-	250.0	140.8	83.7	25.5	0.80	0.20	35.90	4.84	0.68	73.76	6.17	102.24	1.10	28.11	3.15	1.89	17.09	77.86
14	M2	P040102	Lime (10%)	3.47	7.36	8.37	150.0	101.0	35.0	14.0	0.80	0.12	38.88	19.25	1.94	222.17	7.78	250.59	0.47	29.16	0.31	4.99	19.94	74.77
14	M6	P010300	-	-	7.36	-	250.0	145.4	87.2	17.4	0.80	0.20	23.32	4.81	0.70	53.49	4.66	110.79	0.65	17.96	0.85	2.97	19.83	76.35
14	M6	P010301	-	-	7.37	-	250.0	145.6	87.3	17.1	0.80	0.20	23.32	4.68	0.68	52.76	4.61	122.62	0.57	17.58	2.79	2.90	19.58	74.73
14	M6	P020100	-	-	7.37	-	250.0	146.4	87.2	16.4	0.80	0.20	31.49	8.66	1.27	72.22	6.30	138.46	0.68	23.55	1.81	4.00	19.87	74.32
14	M6	P020200	-	-	7.37	-	250.0	145.1	87.1	17.8	0.80	0.20	35.90	4.94	0.72	74.11	6.45	150.73	0.78	29.38	-1.26	1.99	17.88	81.39
14	M6	P020201	-	-	7.36	-	250.0	145.2	87.1	17.7	0.80	0.20	35.90	4.87	0.71	73.51	6.40	153.26	0.76	29.16	-0.49	1.96	17.74	80.79
15	M2	P040102	Lime (10%)	2.72	7.59	8.37	250.0	170.7	59.2	20.1	0.80	0.20	64.80	18.19	3.11	209.97	12.42	491.10	0.38	46.58	4.46	4.78	19.11	71.66
15	M6	P010300	-	-	7.58	-	250.0	146.9	88.1	15.0	0.80	0.20	23.32	4.74	0.70	52.71	4.64	228.44	0.31	17.88	1.30	2.96	19.74	76.00
15	M6	P010301	-	-	7.58	-	250.0	147.1	88.2	14.8	0.80	0.20	23.32	4.67	0.69	52.62	4.64	246.33	0.29	17.71	2.07	2.92	19.73	75.28
15	M6	P020100	-	-	7.58	-	250.0	147.8	88.0	14.2	0.80	0.20	31.49	8.41	1.24	70.14	6.17	272.82	0.34	23.09	3.73	3.92	19.48	72.87
15	M6	P020200	-	-	7.60	-	250.0	146.6	88.0	15.4	0.80	0.20	35.90	4.77	0.70	71.56	6.30	314.62	0.36	28.67	1.20	1.94	17.45	79.42
15	M6	P020201	-	-	7.60	-	250.0	147.0	88.0	15.0	0.80	0.20	35.90	4.76	0.70	72.06	6.34	317.90	0.36	28.89	0.47	1.94	17.57	80.02
16	M2	P040102	Lime (10%)	1.68	7.92	8.40	250.0	163.2	56.6	30.2	0.90	0.23	64.80	19.01	3.10	219.45	12.41	148.27	1.26	46.54	4.56	4.77	19.09	71.58
16	M6	P010300	-	-	7.93	-	250.0	142.2	85.3	22.5	0.90	0.23	23.32	4.77	0.68	53.03	4.52	72.10	0.97	17.41	3.98	2.88	19.21	73.94
16	M6	P010301	-	-	7.94	-	250.0	142.4	85.4	22.2	0.90	0.23	23.32	4.77	0.68	53.79	4.59	76.12	0.92	17.53	3.14	2.89	19.51	74.46
16	M6	P020100	-	-	7.90	-	250.0	143.4	85.4	21.2	0.90	0.23	31.49	8.63	1.24	71.95	6.14	83.75	1.10	22.98	4.28	3.90	19.37	72.44
16	M6	P020200	-	-	7.91	-	250.0	141.8	85.1	23.1	0.90	0.23	35.90	4.80	0.68	71.97	6.13	93.88	1.19	27.89	3.96	1.88	16.96	77.20
16	M6	P020201	-	-	7.91	-	250.0	142.1	85.1	22.8	0.90	0.23	35.90	4.91	0.70	74.15	6.31	98.67	1.17	28.75	1.00	1.93	17.48	79.60
17	M2	P040102	Lime (10%)	2.20	7.72	8.39	250.0	168.9	58.5	22.5	0.50	0.13	64.80	18.45	3.12	212.98	12.47	262.31	0.71	46.76	3.98	4.80	19.20	72.02
17	M6	P010300	-	-	7.74	-	150.0	87.5	52.5	10.1	0.50	0.08	13.99	4.61	0.40	51.28	2.69	117.16	0.35	10.35	4.40	2.87	19.12	73.61
17	M6	P010301	-	-	7.72	-	150.0	87.6	52.5	9.9	0.50	0.08	13.99	4.71	0.41	53.08	2.79	120.97	0.35	10.64	1.63	2.93	19.82	75.62
17	M6	P020100	-	-	7.75	-	150.0	88.1	52.4	9.5	0.50	0.08	18.89	8.72	0.77	72.74	3.81	144.76	0.39	14.27	0.63	4.05	20.11	75.21
17	M6	P020200	-	-	7.69	-	150.0	87.3	52.4	10.3	0.50	0.08	21.54	4.80	0.42	71.97	3.77	150.18	0.46	17.17	1.19	1.94	17.45	79.42
17	M6	P020201	-	-	7.70	-	150.0	87.4	52.4	10.3	0.50	0.08	21.54	4.72	0.41	71.24	3.73	164.22	0.41	17.00	2.15	1.91	17.27	78.67
18	M2	P040102	-	-	8.47	-	250.0	175.0	60.7	14.3	0.70	0.18	64.80	18.54	3.24	213.94	12.98	324.79	0.60	48.67	0.13	4.99	19.97	74.90
18	M6	P010300	-	-	8.47	-	250.0	149.6	89.7	10.7	0.70	0.18	23.32	4.59	0.69	51.04	4.58	146.10	0.48	17.63	2.55	2.92	19.49	75.03

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH	pH_{Before}	pH_{After}	Wastewater Volume (mL)	$Volume_{(SUP)}$ (mL)	$Volume_{(CEN)}$ (mL)	$Volume_{(SLG)}$ (mL)	$C_{Al,in}$ (mg/L)	$M_{Al,In\ Total}$ (mg)	$M_{Al,Coagulant}$ (mg)	$C_{Al,SUP}$ (mg/L)	$M_{Al,SUP}$ (mg)	$C_{Al,CEN}$ (mg/L)	$M_{Al,CEN}$ (mg)	$C_{Al,SLG}$ (mg/L)	M_{Dry} (g) (Dry Sludge Weight)	$M_{Al,SLG}$ (mg)	$\Delta M_{Al,Loss}$	%SUP	%CEN	%SLG
18	M6	P010301	-	-	8.44	-	250.0	149.7	89.8	10.5	0.70	0.18	23.32	4.58	0.69	51.61	4.63	159.31	0.44	17.68	2.10	2.92	19.72	75.26
18	M6	P020100	-	-	8.49	-	250.0	150.4	89.6	10.0	0.70	0.18	31.49	8.48	1.28	70.71	6.33	175.99	0.54	23.69	1.17	4.03	20.00	74.80
18	M6	P020200	-	-	8.49	-	250.0	149.4	89.7	10.9	0.70	0.18	35.90	4.70	0.70	70.55	6.33	190.69	0.60	28.80	0.68	1.95	17.54	79.84
18	M6	P020201	-	-	8.44	-	250.0	149.5	89.7	10.8	0.70	0.18	35.90	4.62	0.69	69.78	6.26	201.46	0.57	28.50	1.72	1.92	17.35	79.02
19	M2	P040102	Lime (10%)	1.88	7.95	8.49	250.0	165.3	57.3	27.4	0.30	0.08	64.80	19.12	3.16	220.65	12.64	170.47	1.11	47.40	2.59	4.87	19.48	73.06
19	M6	P010300	-	-	7.93	-	250.0	143.5	86.1	20.5	0.30	0.08	23.32	4.72	0.68	52.49	4.52	74.89	0.93	17.39	3.47	2.89	19.31	74.32
19	M6	P010301	-	-	7.93	-	250.0	143.7	86.2	20.1	0.30	0.08	23.32	4.76	0.68	53.68	4.63	81.40	0.87	17.65	1.85	2.93	19.77	75.46
19	M6	P020100	-	-	7.96	-	250.0	144.6	86.1	19.3	0.30	0.08	31.49	8.47	1.22	70.64	6.08	92.34	0.99	22.75	4.76	3.88	19.27	72.08
19	M6	P020200	-	-	7.98	-	250.0	143.1	85.9	20.9	0.30	0.08	35.90	4.70	0.67	70.44	6.05	105.11	1.05	27.55	4.72	1.87	16.83	76.59
19	M6	P020201	-	-	7.95	-	250.0	143.3	85.9	20.8	0.30	0.08	35.90	4.83	0.69	72.92	6.27	108.35	1.05	28.54	1.31	1.92	17.42	79.35
20	M2	P040102	-	-	8.41	-	150.0	105.9	36.7	7.4	0.20	0.03	38.88	18.11	1.92	208.99	7.67	355.14	0.32	28.75	1.47	4.93	19.71	73.90
20	M6	P010300	-	-	8.39	-	150.0	90.3	54.2	5.5	0.20	0.03	13.99	4.64	0.42	51.65	2.80	164.14	0.26	10.77	0.28	2.99	19.95	76.79
20	M6	P010301	-	-	8.43	-	150.0	90.4	54.2	5.5	0.20	0.03	13.99	4.48	0.41	50.56	2.74	165.20	0.25	10.45	3.03	2.89	19.54	74.55
20	M6	P020100	-	-	8.41	-	150.0	90.7	54.0	5.2	0.20	0.03	18.89	8.28	0.75	69.09	3.73	179.24	0.31	13.96	2.51	3.97	19.73	73.78
20	M6	P020200	-	-	8.43	-	150.0	89.7	54.1	6.2	0.20	0.03	21.54	4.70	0.42	70.11	3.80	214.92	0.32	17.28	0.35	1.95	17.60	80.10
20	M6	P020201	-	-	8.40	-	150.0	90.2	54.1	5.6	0.20	0.03	21.54	4.59	0.41	69.33	3.75	212.41	0.32	17.09	1.44	1.92	17.40	79.24
21	M2	P040102	Lime (10%)	1.52	8.00	8.44	250.0	166.4	57.7	26.0	0.60	0.15	64.80	19.37	3.22	223.53	12.89	197.35	0.98	48.32	0.80	4.96	19.84	74.40
21	M6	P010300	-	-	8.00	-	250.0	144.2	86.5	19.4	0.60	0.15	23.32	4.76	0.69	52.97	4.58	87.17	0.81	17.63	2.45	2.93	19.51	75.11
21	M6	P010301	-	-	7.99	-	250.0	144.4	86.6	19.0	0.60	0.15	23.32	4.61	0.67	51.97	4.50	84.94	0.81	17.17	4.83	2.84	19.17	73.16
21	M6	P020100	-	-	7.98	-	250.0	145.2	86.5	18.3	0.60	0.15	31.49	8.76	1.27	73.09	6.32	97.43	0.97	23.64	1.26	4.02	19.98	74.73
21	M6	P020200	-	-	8.02	-	250.0	143.8	86.3	19.8	0.60	0.15	35.90	4.75	0.68	71.28	6.15	105.26	1.06	28.01	3.33	1.90	17.07	77.71
21	M6	P020201	-	-	7.97	-	250.0	144.1	86.3	19.6	0.60	0.15	35.90	4.69	0.68	70.92	6.12	111.43	1.00	27.89	3.76	1.88	16.99	77.38
22	M2	P040102	Lime (10%)	1.74	8.00	8.51	150.0	101.6	35.2	13.1	0.90	0.14	38.88	18.84	1.91	217.40	7.66	237.39	0.48	28.72	1.87	4.91	19.63	73.60
22	M6	P010300	-	-	7.98	-	250.0	146.1	87.6	16.3	0.90	0.23	23.32	4.68	0.68	52.07	4.56	102.27	0.69	17.56	3.14	2.90	19.37	74.59
22	M6	P010301	-	-	8.03	-	250.0	146.3	87.7	16.0	0.90	0.23	23.32	4.65	0.68	52.39	4.59	105.32	0.67	17.53	3.14	2.89	19.51	74.46
22	M6	P020100	-	-	7.98	-	250.0	147.0	87.6	15.4	0.90	0.23	31.49	8.55	1.26	71.33	6.25	122.72	0.76	23.36	2.67	3.97	19.70	73.66
22	M6	P020200	-	-	8.01	-	250.0	145.8	87.5	16.7	0.90	0.23	35.90	4.83	0.70	72.51	6.35	135.56	0.85	28.88	0.53	1.95	17.57	79.95
22	M6	P020201	-	-	7.99	-	250.0	145.9	87.5	16.6	0.90	0.23	35.90	4.63	0.68	69.87	6.11	135.03	0.82	27.85	4.11	1.87	16.93	77.10

Notes:

- ✓ In Scenario M2, the doses applied were 8 g/L for the conventional 40% aluminum sulfate coagulant and 4 g/L for PAM, whereas in Scenario M6, fixed doses of 2.8 g/L for the hybrid coagulants and 1.88 g/L for PAM were used for all formulations.
- ✓ The theoretical aluminum content in 100 g of solution for the products P040102, P010300, P010301, P020100, P020200, and P020201 was calculated 3240.00, 3331.44, 3331.44, 4498.50, 5128.29, and 5128.29 mg, respectively.
- ✓ For sludge samples, ICP-OES results represent the concentration in the digested solution (prepared from 0.1 g dry sludge in 25 mL acid). Therefore, ppm values converted to mg/g based on the original dry mass before use in mass balance calculations.

APPENDIX H: MASS BALANCE CALCULATIONS FOR IRON (Fe)

Table H.1. Mass balance calculations for Iron (Fe).

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH_{Before}	pH_{After}	Wastewater Volume (mL)	$Volume_{(SUP)}$ (mL)	$Volume_{(CEN)}$ (mL)	$Volume_{(SLG)}$ (mL)	$C_{Fe,in}$ (mg/L)	$M_{Fe,In\ Total}$ (mg)	$M_{Fe,Coagulant}$ (mg)	$C_{Fe,SUP}$ (mg/L)	$M_{Fe,SUP}$ (mg)	$C_{Fe,CEN}$ (mg/L)	$M_{Fe,CEN}$ (mg)	$C_{Fe,SLG}$ (mg/L)	M_{DRY} (g) (Dry Sludge Weight)	$M_{Fe,SLG}$ (mg)	$\Delta M_{Fe,Loss}$	%SUP	%CEN	%SLG
1	M2	P040102	Lime (10%)	3.68	7.39	8.46	250.0	168.3	58.3	23.4	5.70	1.43	0.00	1.81	0.30	4.76	0.28	6.73	0.48	0.80	2.72	21.38	19.47	56.43
1	M6	P010300	-	-	7.41	-	250.0	145.4	87.2	17.5	5.70	1.43	0.00	0.47	0.07	3.15	0.27	11.09	0.37	1.03	3.70	4.81	19.26	72.22
1	M6	P010301	-	-	7.41	-	250.0	145.6	87.3	17.2	5.70	1.43	0.00	0.46	0.07	3.07	0.27	11.06	0.36	1.01	5.99	4.68	18.81	70.53
1	M6	P020100	-	-	7.39	-	250.0	146.4	87.2	16.5	5.70	1.43	0.00	0.68	0.10	3.26	0.28	9.65	0.43	1.04	0.44	6.98	19.92	72.67
1	M6	P020200	-	-	7.37	-	250.0	144.5	87.1	18.4	5.70	1.43	0.79	0.29	0.04	4.37	0.38	13.43	0.50	1.69	4.66	1.90	17.17	76.27
1	M6	P020201	-	-	7.41	-	250.0	145.2	87.1	17.8	5.70	1.43	0.79	0.30	0.04	4.50	0.39	14.63	0.48	1.74	1.88	1.95	17.66	78.51
2	M2	P040102	Lime (10%)	5.28	7.07	8.59	250.0	159.4	55.2	35.4	14.50	3.63	0.00	4.89	0.78	12.84	0.71	9.54	0.86	2.06	2.25	21.48	19.56	56.70
2	M6	P010300	-	-	7.08	-	250.0	139.8	83.8	26.4	14.50	3.63	0.00	1.27	0.18	8.44	0.71	16.70	0.64	2.65	2.37	4.88	19.52	73.22
2	M6	P010301	-	-	7.07	-	250.0	140.1	84.0	25.9	14.50	3.63	0.00	1.25	0.17	8.37	0.70	16.89	0.62	2.64	3.07	4.82	19.39	72.72
2	M6	P020100	-	-	7.07	-	250.0	141.1	84.0	24.9	14.50	3.63	0.00	1.75	0.25	8.37	0.70	14.38	0.71	2.56	3.06	6.79	19.40	70.75
2	M6	P020200	-	-	7.09	-	250.0	139.3	83.6	27.0	14.50	3.63	0.79	0.62	0.09	9.33	0.78	16.11	0.86	3.47	1.90	1.96	17.67	78.48
2	M6	P020201	-	-	7.09	-	250.0	139.5	83.7	26.9	14.50	3.63	0.79	0.62	0.09	9.42	0.79	19.29	0.73	3.50	0.88	1.97	17.84	79.30
3	M2	P040102	Lime (10%)	2.94	7.61	8.54	150.0	103.5	35.9	10.6	7.40	1.11	0.00	2.28	0.24	6.00	0.22	9.06	0.28	0.62	3.04	21.31	19.40	56.25
3	M6	P010300	-	-	7.62	-	150.0	88.8	53.3	7.9	7.40	1.11	0.00	0.60	0.05	4.00	0.21	13.05	0.25	0.80	3.89	4.80	19.22	72.08
3	M6	P010301	-	-	7.59	-	150.0	88.9	53.3	7.8	7.40	1.11	0.00	0.60	0.05	4.04	0.22	13.73	0.24	0.81	3.10	4.82	19.39	72.69
3	M6	P020100	-	-	7.61	-	150.0	89.3	53.2	7.4	7.40	1.11	0.00	0.86	0.08	4.11	0.22	11.69	0.27	0.80	1.63	6.89	19.68	71.79
3	M6	P020200	-	-	7.60	-	150.0	88.5	53.2	8.3	7.40	1.11	0.47	0.33	0.03	4.99	0.27	15.66	0.30	1.18	6.93	1.86	16.76	74.46
3	M6	P020201	-	-	7.62	-	150.0	88.7	53.2	8.0	7.40	1.11	0.47	0.34	0.03	5.09	0.27	17.09	0.28	1.20	5.02	1.89	17.10	75.99
4	M2	P040102	Lime (10%)	5.12	7.03	8.51	250.0	159.3	55.2	35.5	15.00	3.75	0.00	4.93	0.79	12.96	0.72	9.72	0.85	2.07	4.68	20.95	19.07	55.29
4	M6	P010300	-	-	7.05	-	250.0	139.7	83.8	26.4	15.00	3.75	0.00	1.26	0.18	8.38	0.70	14.96	0.70	2.63	6.39	4.68	18.72	70.21

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH_{Before}	pH_{After}	Wastewater Volume (mL)	$Volume_{(SUP)}$ (mL)	$Volume_{(CEN)}$ (mL)	$Volume_{(SLG)}$ (mL)	$C_{Fe,In}$ (mg/L)	$M_{Fe,In\ Total}$ (mg)	$M_{Fe,Coagulant}$ (mg)	$C_{Fe,SUP}$ (mg/L)	$M_{Fe,SUP}$ (mg)	$C_{Fe,CEN}$ (mg/L)	$M_{Fe,CEN}$ (mg)	$C_{Fe,SLG}$ (mg/L)	M_{Dry} (g) (Dry Sludge Weight)	$M_{Fe,SLG}$ (mg)	$\Delta M_{Fe,Loss}$	%SUP	%CEN	%SLG
4	M6	P010301	-	-	7.02	-	250.0	140.0	84.0	26.0	15.00	3.75	0.00	1.31	0.18	8.81	0.74	17.06	0.65	2.77	1.44	4.90	19.72	73.94
4	M6	P020100	-	-	7.01	-	250.0	141.1	84.0	24.9	15.00	3.75	0.00	1.80	0.25	8.62	0.72	13.29	0.80	2.64	3.46	6.76	19.31	70.46
4	M6	P020200	-	-	7.06	-	250.0	139.2	83.6	27.2	15.00	3.75	0.79	0.62	0.09	9.32	0.78	15.99	0.87	3.46	4.71	1.90	17.16	76.23
4	M6	P020201	-	-	7.05	-	250.0	139.4	83.6	26.9	15.00	3.75	0.79	0.64	0.09	9.59	0.80	17.59	0.81	3.57	1.89	1.95	17.66	78.50
5	M2	P040102	Lime (10%)	2.72	7.62	8.41	250.0	165.3	57.3	27.4	6.90	1.73	0.00	2.19	0.36	5.76	0.33	4.15	0.92	0.96	4.40	21.01	19.13	55.46
5	M6	P010300	-	-	7.63	-	250.0	143.5	86.1	20.5	6.90	1.73	0.00	0.59	0.08	3.95	0.34	6.90	0.74	1.27	1.51	4.92	19.70	73.87
5	M6	P010301	-	-	7.60	-	250.0	143.7	86.2	20.1	6.90	1.73	0.00	0.56	0.08	3.74	0.32	6.56	0.74	1.21	6.74	4.64	18.66	69.97
5	M6	P020100	-	-	7.61	-	250.0	144.6	86.1	19.3	6.90	1.73	0.00	0.80	0.12	3.84	0.33	5.76	0.84	1.21	4.22	6.71	19.16	69.91
5	M6	P020200	-	-	7.61	-	250.0	143.1	85.9	20.9	6.90	1.73	0.79	0.33	0.05	5.00	0.43	8.25	0.92	1.91	5.24	1.89	17.07	75.81
5	M6	P020201	-	-	7.60	-	250.0	143.2	85.9	20.8	6.90	1.73	0.79	0.33	0.05	5.05	0.43	8.34	0.93	1.93	4.21	1.90	17.25	76.64
6	M2	P040102	Lime (10%)	3.08	7.52	8.40	250.0	165.5	57.4	27.1	6.80	1.70	0.00	2.12	0.35	5.56	0.32	4.44	0.83	0.93	6.17	20.62	18.78	54.43
6	M6	P010300	-	-	7.51	-	250.0	143.6	86.1	20.2	6.80	1.70	0.00	0.59	0.08	3.91	0.34	7.09	0.71	1.26	0.85	4.96	19.83	74.36
6	M6	P010301	-	-	7.53	-	250.0	143.9	86.3	19.9	6.80	1.70	0.00	0.58	0.08	3.88	0.33	7.28	0.69	1.25	1.65	4.89	19.68	73.78
6	M6	P020100	-	-	7.54	-	250.0	144.7	86.2	19.0	6.80	1.70	0.00	0.78	0.11	3.73	0.32	6.41	0.73	1.17	5.57	6.62	18.89	68.92
6	M6	P020200	-	-	7.53	-	250.0	143.3	86.0	20.7	6.80	1.70	0.79	0.34	0.05	5.13	0.44	9.79	0.80	1.96	1.74	1.96	17.70	78.61
6	M6	P020201	-	-	7.51	-	250.0	143.4	86.0	20.6	6.80	1.70	0.79	0.34	0.05	5.19	0.45	10.27	0.77	1.98	0.45	1.98	17.92	79.65
7	M2	P040102	Lime (10%)	2.44	7.68	8.38	250.0	169.8	58.8	21.3	6.70	1.68	0.00	2.11	0.36	5.54	0.33	6.22	0.61	0.95	2.74	21.38	19.46	56.42
7	M6	P010300	-	-	7.71	-	250.0	146.3	87.8	15.9	6.70	1.68	0.00	0.55	0.08	3.69	0.32	9.53	0.51	1.21	3.44	4.83	19.31	72.42
7	M6	P010301	-	-	7.71	-	250.0	146.5	87.8	15.6	6.70	1.68	0.00	0.53	0.08	3.55	0.31	10.21	0.46	1.17	6.99	4.63	18.61	69.78
7	M6	P020100	-	-	7.66	-	250.0	147.3	87.7	15.0	6.70	1.68	0.00	0.76	0.11	3.62	0.32	8.48	0.55	1.16	5.11	6.65	18.98	69.25
7	M6	P020200	-	-	7.66	-	250.0	145.7	87.7	16.6	6.70	1.68	0.79	0.34	0.05	5.04	0.44	12.42	0.63	1.96	0.50	1.98	17.92	79.59
7	M6	P020201	-	-	7.68	-	250.0	146.1	87.7	16.2	6.70	1.68	0.79	0.33	0.05	5.05	0.44	13.78	0.57	1.97	0.32	1.98	17.94	79.75
8	M2	P040102	Lime (10%)	2.47	7.85	8.57	150.0	105.6	36.6	7.7	5.00	0.75	0.00	1.51	0.16	3.96	0.15	7.57	0.22	0.42	3.38	21.24	19.34	56.05
8	M6	P010300	-	-	7.86	-	150.0	89.8	54.1	6.1	5.00	0.75	0.00	0.42	0.04	2.77	0.15	13.26	0.17	0.56	0.32	4.98	19.94	74.76
8	M6	P010301	-	-	7.84	-	150.0	90.2	54.1	5.7	5.00	0.75	0.00	0.41	0.04	2.72	0.15	13.17	0.17	0.55	1.78	4.88	19.65	73.68
8	M6	P020100	-	-	7.83	-	150.0	90.6	54.0	5.4	5.00	0.75	0.00	0.55	0.05	2.65	0.14	10.93	0.19	0.52	4.65	6.68	19.08	69.59

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH_{Before}	pH_{After}	Wastewater Volume (mL)	$Volume_{(SUP)}$ (mL)	$Volume_{(CEN)}$ (mL)	$Volume_{(SLG)}$ (mL)	$C_{Fe,in}$ (mg/L)	$M_{Fe,In\ Total}$ (mg)	$M_{Fe,Coagulant}$ (mg)	$C_{Fe,SUP}$ (mg/L)	$M_{Fe,SUP}$ (mg)	$C_{Fe,CEN}$ (mg/L)	$M_{Fe,CEN}$ (mg)	$C_{Fe,SLG}$ (mg/L)	M_{Dry} (g) (Dry Sludge Weight)	$M_{Fe,SLG}$ (mg)	$\Delta M_{Fe,Loss}$	%SUP	%CEN	%SLG
8	M6	P020200	-	-	7.85	-	150.0	90.0	54.1	5.9	5.00	0.75	0.47	0.25	0.02	3.82	0.21	16.55	0.22	0.92	6.49	1.86	16.84	74.80
8	M6	P020201	-	-	7.84	-	150.0	90.2	54.0	5.8	5.00	0.75	0.47	0.26	0.02	3.97	0.21	18.64	0.20	0.95	2.74	1.93	17.51	77.82
9	M2	P040102	Lime (10%)	2.12	7.90	8.51	250.0	165.6	57.4	27.0	8.20	2.05	0.00	2.61	0.43	6.85	0.39	4.70	0.97	1.14	4.16	21.07	19.18	55.60
9	M6	P010300	-	-	7.90	-	250.0	143.7	86.2	20.1	8.20	2.05	0.00	0.69	0.10	4.62	0.40	7.17	0.83	1.49	2.91	4.85	19.42	72.82
9	M6	P010301	-	-	7.92	-	250.0	143.9	86.3	19.8	8.20	2.05	0.00	0.68	0.10	4.59	0.40	8.07	0.74	1.48	3.49	4.80	19.31	72.40
9	M6	P020100	-	-	7.88	-	250.0	144.8	86.2	19.0	8.20	2.05	0.00	0.96	0.14	4.62	0.40	6.67	0.87	1.45	2.85	6.81	19.44	70.90
9	M6	P020200	-	-	7.88	-	250.0	143.0	86.1	20.9	8.20	2.05	0.79	0.37	0.05	5.60	0.48	9.06	0.95	2.14	5.75	1.88	16.97	75.39
9	M6	P020201	-	-	7.92	-	250.0	143.5	86.1	20.5	8.20	2.05	0.79	0.38	0.05	5.70	0.49	9.66	0.90	2.18	4.04	1.91	17.27	76.77
10	M2	P040102	Lime (10%)	0.80	8.31	8.53	250.0	158.5	54.9	36.6	13.40	3.35	0.00	4.55	0.72	11.94	0.66	4.67	1.63	1.90	2.18	21.50	19.57	56.74
10	M6	P010300	-	-	8.29	-	250.0	139.2	83.5	27.3	13.40	3.35	0.00	1.20	0.17	7.97	0.67	7.31	1.37	2.50	0.66	4.97	19.87	74.50
10	M6	P010301	-	-	8.30	-	250.0	139.5	83.6	26.8	13.40	3.35	0.00	1.19	0.17	7.96	0.67	7.48	1.33	2.50	0.67	4.94	19.87	74.52
10	M6	P020100	-	-	8.31	-	250.0	140.5	83.7	25.7	13.40	3.35	0.00	1.67	0.23	7.99	0.67	6.04	1.62	2.44	0.19	6.99	19.97	72.85
10	M6	P020200	-	-	8.29	-	250.0	138.8	83.3	27.9	13.40	3.35	0.79	0.59	0.08	8.84	0.74	7.12	1.84	3.27	1.30	1.97	17.78	78.96
10	M6	P020201	-	-	8.32	-	250.0	138.9	83.3	27.8	13.40	3.35	0.79	0.57	0.08	8.65	0.72	7.57	1.69	3.20	3.33	1.92	17.40	77.35
11	M2	P040102	-	-	8.37	-	250.0	164.9	57.1	28.0	19.30	4.83	0.00	6.28	1.04	16.51	0.94	8.46	1.29	2.73	2.30	21.47	19.55	56.68
11	M6	P010300	-	-	8.36	-	150.0	85.9	51.5	12.5	19.30	2.90	0.00	1.59	0.14	10.62	0.55	12.48	0.66	2.05	5.45	4.73	18.91	70.92
11	M6	P010301	-	-	8.39	-	150.0	86.1	51.6	12.3	19.30	2.90	0.00	1.61	0.14	10.79	0.56	14.01	0.60	2.09	3.83	4.78	19.24	72.15
11	M6	P020100	-	-	8.40	-	150.0	86.6	51.6	11.8	19.30	2.90	0.00	2.24	0.19	10.73	0.55	10.97	0.74	2.02	4.43	6.70	19.12	69.75
11	M6	P020200	-	-	8.38	-	150.0	85.7	51.5	12.8	19.30	2.90	0.47	0.74	0.06	11.08	0.57	12.18	0.83	2.53	6.06	1.87	16.92	75.15
11	M6	P020201	-	-	8.35	-	150.0	86.0	51.5	12.5	19.30	2.90	0.47	0.75	0.06	11.41	0.59	13.66	0.76	2.61	3.18	1.93	17.43	77.46
12	M2	P040102	Lime (10%)	2.00	8.02	8.59	250.0	158.9	55.1	36.0	20.00	5.00	0.00	6.66	1.06	17.49	0.96	7.77	1.44	2.79	3.72	21.16	19.27	55.85
12	M6	P010300	-	-	8.02	-	250.0	139.5	83.7	26.9	20.00	5.00	0.00	1.70	0.24	11.33	0.95	12.65	1.12	3.55	5.22	4.74	18.96	71.08
12	M6	P010301	-	-	8.02	-	250.0	139.8	83.8	26.4	20.00	5.00	0.00	1.74	0.24	11.69	0.98	13.30	1.11	3.68	2.01	4.87	19.60	73.51
12	M6	P020100	-	-	8.00	-	250.0	140.8	83.9	25.3	20.00	5.00	0.00	2.48	0.35	11.90	1.00	12.13	1.20	3.64	0.21	6.99	19.96	72.83
12	M6	P020200	-	-	8.01	-	250.0	139.1	83.5	27.5	20.00	5.00	0.79	0.81	0.11	12.22	1.02	13.17	1.38	4.53	2.22	1.95	17.61	78.22
12	M6	P020201	-	-	7.99	-	250.0	139.2	83.5	27.3	20.00	5.00	0.79	0.82	0.11	12.42	1.04	13.41	1.37	4.61	0.57	1.98	17.90	79.55

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH_{Before}	pH_{After}	Wastewater Volume (mL)	$Volume_{(SUP)}$ (mL)	$Volume_{(CEN)}$ (mL)	$Volume_{(SLG)}$ (mL)	$C_{Fe,in}$ (mg/L)	$M_{Fe,In\ Total}$ (mg)	$M_{Fe,Coagulant}$ (mg)	$C_{Fe,SUP}$ (mg/L)	$M_{Fe,SUP}$ (mg)	$C_{Fe,CEN}$ (mg/L)	$M_{Fe,CEN}$ (mg)	$C_{Fe,SLG}$ (mg/L)	M_{Dry} (g) (Dry Sludge Weight)	$M_{Fe,SLG}$ (mg)	$\Delta M_{Fe,Loss}$	%SUP	%CEN	%SLG
13	M2	P040102	Lime (10%)	3.84	7.46	8.56	250.0	159.3	55.2	35.4	10.32	2.58	0.00	3.40	0.54	8.93	0.49	4.84	1.18	1.43	4.45	21.00	19.12	55.43
13	M6	P010300	-	-	7.48	-	250.0	139.8	83.8	26.4	10.32	2.58	0.00	0.91	0.13	6.07	0.51	8.66	0.88	1.91	1.40	4.93	19.72	73.95
13	M6	P010301	-	-	7.47	-	250.0	140.1	84.0	26.0	10.32	2.58	0.00	0.89	0.12	5.95	0.50	8.79	0.85	1.88	3.12	4.82	19.38	72.68
13	M6	P020100	-	-	7.43	-	250.0	141.1	84.0	24.9	10.32	2.58	0.00	1.25	0.18	5.99	0.50	7.41	0.99	1.84	2.52	6.83	19.50	71.15
13	M6	P020200	-	-	7.46	-	250.0	139.3	83.6	27.0	10.32	2.58	0.79	0.48	0.07	7.24	0.61	9.62	1.12	2.69	0.23	1.99	17.97	79.81
13	M6	P020201	-	-	7.47	-	250.0	140.8	83.7	25.5	10.32	2.58	0.79	0.46	0.06	6.98	0.58	9.44	1.10	2.60	3.76	1.91	17.33	77.00
14	M2	P040102	Lime (10%)	3.47	7.36	8.37	150.0	101.0	35.0	14.0	9.80	1.47	0.00	3.14	0.32	8.25	0.29	7.19	0.47	0.84	1.84	21.57	19.64	56.94
14	M6	P010300	-	-	7.36	-	250.0	145.4	87.2	17.4	9.80	2.45	0.00	0.88	0.13	5.87	0.51	11.84	0.65	1.92	-4.46	5.22	20.89	78.35
14	M6	P010301	-	-	7.37	-	250.0	145.6	87.3	17.1	9.80	2.45	0.00	0.86	0.13	5.77	0.50	13.18	0.57	1.89	-2.77	5.11	20.56	77.10
14	M6	P020100	-	-	7.37	-	250.0	146.4	87.2	16.4	9.80	2.45	0.00	1.21	0.18	5.80	0.51	10.85	0.68	1.85	-3.18	7.23	20.64	75.31
14	M6	P020200	-	-	7.37	-	250.0	145.1	87.1	17.8	9.80	2.45	0.79	0.46	0.07	6.92	0.60	13.74	0.78	2.68	-3.25	2.06	18.59	82.59
14	M6	P020201	-	-	7.36	-	250.0	145.2	87.1	17.7	9.80	2.45	0.79	0.43	0.06	6.49	0.57	13.20	0.76	2.51	3.13	1.93	17.44	77.50
15	M2	P040102	Lime (10%)	2.72	7.59	8.37	250.0	170.7	59.2	20.1	11.70	2.93	0.00	3.69	0.63	9.69	0.57	17.51	0.38	1.66	2.11	21.51	19.59	56.78
15	M6	P010300	-	-	7.58	-	250.0	146.9	88.1	15.0	11.70	2.93	0.00	0.95	0.14	6.33	0.56	26.74	0.31	2.09	4.61	4.77	19.08	71.54
15	M6	P010301	-	-	7.58	-	250.0	147.1	88.2	14.8	11.70	2.93	0.00	0.94	0.14	6.29	0.56	28.96	0.29	2.08	5.15	4.72	18.98	71.16
15	M6	P020100	-	-	7.58	-	250.0	147.8	88.0	14.2	11.70	2.93	0.00	1.29	0.19	6.19	0.54	23.47	0.34	1.99	6.94	6.52	18.62	67.92
15	M6	P020200	-	-	7.60	-	250.0	146.6	88.0	15.4	11.70	2.93	0.79	0.48	0.07	7.22	0.64	30.99	0.36	2.82	5.02	1.89	17.10	75.98
15	M6	P020201	-	-	7.60	-	250.0	147.0	88.0	15.0	11.70	2.93	0.79	0.50	0.07	7.56	0.67	32.53	0.36	2.96	0.59	1.98	17.90	79.53
16	M2	P040102	Lime (10%)	1.68	7.92	8.40	250.0	163.2	56.6	30.2	13.00	3.25	0.00	4.12	0.67	10.84	0.61	5.66	1.26	1.78	5.75	20.71	18.86	54.67
16	M6	P010300	-	-	7.93	-	250.0	142.2	85.3	22.5	13.00	3.25	0.00	1.14	0.16	7.59	0.65	10.05	0.97	2.43	0.48	4.98	19.90	74.64
16	M6	P010301	-	-	7.94	-	250.0	142.4	85.4	22.2	13.00	3.25	0.00	1.11	0.16	7.46	0.64	10.38	0.92	2.39	1.96	4.88	19.61	73.55
16	M6	P020100	-	-	7.90	-	250.0	143.4	85.4	21.2	13.00	3.25	0.00	1.56	0.22	7.49	0.64	8.50	1.10	2.33	1.68	6.89	19.67	71.76
16	M6	P020200	-	-	7.91	-	250.0	141.8	85.1	23.1	13.00	3.25	0.79	0.55	0.08	8.31	0.71	10.58	1.19	3.14	2.76	1.94	17.51	77.79
16	M6	P020201	-	-	7.91	-	250.0	142.1	85.1	22.8	13.00	3.25	0.79	0.53	0.08	8.01	0.68	10.40	1.17	3.03	6.26	1.86	16.88	75.00
17	M2	P040102	Lime (10%)	2.20	7.72	8.39	250.0	168.9	58.5	22.5	8.00	2.00	0.00	2.50	0.42	6.56	0.38	6.24	0.71	1.11	4.07	21.08	19.20	55.65
17	M6	P010300	-	-	7.74	-	150.0	87.5	52.5	10.1	8.00	1.20	0.00	0.68	0.06	4.57	0.24	10.17	0.35	0.90	0.17	4.99	19.97	74.87

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH_{Before}	pH_{After}	Wastewater Volume (mL)	$Volume_{(SUP)}$ (mL)	$Volume_{(CEN)}$ (mL)	$Volume_{(SLG)}$ (mL)	$C_{Fe,in}$ (mg/L)	$M_{Fe,In\ Total}$ (mg)	$M_{Fe,Coagulant}$ (mg)	$C_{Fe,SUP}$ (mg/L)	$M_{Fe,SUP}$ (mg)	$C_{Fe,CEN}$ (mg/L)	$M_{Fe,CEN}$ (mg)	$C_{Fe,SLG}$ (mg/L)	M_{Dry} (g) (Dry Sludge Weight)	$M_{Fe,SLG}$ (mg)	$\Delta M_{Fe,Loss}$	%SUP	%CEN	%SLG
17	M6	P010301	-	-	7.72	-	150.0	87.6	52.5	9.9	8.00	1.20	0.00	0.65	0.06	4.36	0.23	9.76	0.35	0.86	4.62	4.74	19.08	71.56
17	M6	P020100	-	-	7.75	-	150.0	88.1	52.4	9.5	8.00	1.20	0.00	0.94	0.08	4.48	0.24	8.70	0.39	0.86	2.08	6.86	19.59	71.47
17	M6	P020200	-	-	7.69	-	150.0	87.3	52.4	10.3	8.00	1.20	0.47	0.38	0.03	5.70	0.30	11.60	0.46	1.33	1.04	1.97	17.82	79.16
17	M6	P020201	-	-	7.70	-	150.0	87.4	52.4	10.3	8.00	1.20	0.47	0.37	0.03	5.54	0.29	12.46	0.41	1.29	3.74	1.91	17.33	77.02
18	M2	P040102	-	-	8.47	-	250.0	175.0	60.7	14.3	12.00	3.00	0.00	3.74	0.66	9.84	0.60	11.55	0.60	1.73	0.58	21.85	19.89	57.67
18	M6	P010300	-	-	8.47	-	250.0	149.6	89.7	10.7	12.00	3.00	0.00	0.94	0.14	6.28	0.56	17.51	0.48	2.11	6.11	4.69	18.78	70.42
18	M6	P010301	-	-	8.44	-	250.0	149.7	89.8	10.5	12.00	3.00	0.00	0.97	0.15	6.53	0.59	19.80	0.44	2.20	2.38	4.86	19.53	73.24
18	M6	P020100	-	-	8.49	-	250.0	150.4	89.6	10.0	12.00	3.00	0.00	1.39	0.21	6.68	0.60	16.21	0.54	2.18	0.38	6.98	19.93	72.71
18	M6	P020200	-	-	8.49	-	250.0	149.4	89.7	10.9	12.00	3.00	0.79	0.49	0.07	7.45	0.67	19.64	0.60	2.97	2.21	1.95	17.61	78.23
18	M6	P020201	-	-	8.44	-	250.0	149.5	89.7	10.8	12.00	3.00	0.79	0.49	0.07	7.37	0.66	20.77	0.57	2.94	3.13	1.93	17.44	77.50
19	M2	P040102	Lime (10%)	1.88	7.95	8.49	250.0	165.3	57.3	27.4	6.50	1.63	0.00	2.09	0.34	5.48	0.31	3.27	1.11	0.91	3.44	21.22	19.32	56.01
19	M6	P010300	-	-	7.93	-	250.0	143.5	86.1	20.5	6.50	1.63	0.00	0.55	0.08	3.65	0.31	5.08	0.93	1.18	3.26	4.84	19.35	72.55
19	M6	P010301	-	-	7.93	-	250.0	143.7	86.2	20.1	6.50	1.63	0.00	0.54	0.08	3.63	0.31	5.40	0.87	1.17	3.90	4.78	19.23	72.09
19	M6	P020100	-	-	7.96	-	250.0	144.6	86.1	19.3	6.50	1.63	0.00	0.78	0.11	3.74	0.32	4.77	0.99	1.17	0.95	6.94	19.82	72.29
19	M6	P020200	-	-	7.98	-	250.0	143.1	85.9	20.9	6.50	1.63	0.79	0.34	0.05	5.04	0.43	7.34	1.05	1.92	0.49	1.98	17.92	79.60
19	M6	P020201	-	-	7.95	-	250.0	143.3	85.9	20.8	6.50	1.63	0.79	0.33	0.05	4.94	0.42	7.16	1.05	1.89	2.46	1.94	17.56	78.04
20	M2	P040102	-	-	8.41	-	150.0	105.9	36.7	7.4	6.20	0.93	0.00	1.80	0.19	4.74	0.17	6.23	0.32	0.50	6.55	20.54	18.70	54.21
20	M6	P010300	-	-	8.39	-	150.0	90.3	54.2	5.5	6.20	0.93	0.00	0.50	0.05	3.33	0.18	10.30	0.26	0.68	3.15	4.84	19.37	72.64
20	M6	P010301	-	-	8.43	-	150.0	90.4	54.2	5.5	6.20	0.93	0.00	0.50	0.05	3.37	0.18	10.81	0.25	0.68	1.97	4.88	19.61	73.54
20	M6	P020100	-	-	8.41	-	150.0	90.7	54.0	5.2	6.20	0.93	0.00	0.71	0.06	3.42	0.18	8.66	0.31	0.67	0.66	6.96	19.88	72.51
20	M6	P020200	-	-	8.43	-	150.0	89.7	54.1	6.2	6.20	0.93	0.47	0.31	0.03	4.58	0.25	13.71	0.32	1.10	1.95	1.96	17.66	78.43
20	M6	P020201	-	-	8.40	-	150.0	90.2	54.1	5.6	6.20	0.93	0.47	0.29	0.03	4.45	0.24	13.29	0.32	1.07	4.84	1.89	17.13	76.14
21	M2	P040102	Lime (10%)	1.52	8.00	8.44	250.0	166.4	57.7	26.0	9.00	2.25	0.00	2.84	0.47	7.47	0.43	5.10	0.98	1.25	4.36	21.02	19.14	55.48
21	M6	P010300	-	-	8.00	-	250.0	144.2	86.5	19.4	9.00	2.25	0.00	0.74	0.11	4.96	0.43	7.95	0.81	1.61	4.72	4.76	19.06	71.46
21	M6	P010301	-	-	7.99	-	250.0	144.4	86.6	19.0	9.00	2.25	0.00	0.73	0.11	4.89	0.42	7.85	0.81	1.59	6.05	4.67	18.80	70.48
21	M6	P020100	-	-	7.98	-	250.0	145.2	86.5	18.3	9.00	2.25	0.00	1.02	0.15	4.88	0.42	6.34	0.97	1.54	6.30	6.57	18.75	68.39

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH Adj. (g/L)	pH_{Before}	pH_{After}	Wastewater Volume (mL)	$Volume_{(SUP)}$ (mL)	$Volume_{(CEN)}$ (mL)	$Volume_{(SLG)}$ (mL)	$C_{Fe,in}$ *(mg/L)*	$M_{Fe,In\ Total}$ *(mg)*	$M_{Fe,Coagulant}$ *(mg)*	$C_{Fe,SUP}$ *(mg/L)*	$M_{Fe,SUP}$ *(mg)*	$C_{Fe,CEN}$ *(mg/L)*	$M_{Fe,CEN}$ *(mg)*	$C_{Fe,SLG}$ *(mg/L)*	M_{Dry} (g) *(Dry Sludge Weight)*	$M_{Fe,SLG}$ *(mg)*	$\Delta M_{Fe,Loss}$	%SUP	%CEN	%SLG
21	M6	P020200	-	-	8.02	-	250.0	143.8	86.3	19.8	9.00	2.25	0.79	0.40	0.06	5.97	0.52	8.60	1.06	2.29	5.94	1.88	16.94	75.25
21	M6	P020201	-	-	7.97	-	250.0	144.1	86.3	19.6	9.00	2.25	0.79	0.42	0.06	6.33	0.55	9.71	1.00	2.43	0.15	1.99	17.97	79.89
22	M2	P040102	Lime (10%)	1.74	8.00	8.51	150.0	101.6	35.2	13.1	15.80	2.37	0.00	5.08	0.52	13.34	0.47	11.26	0.48	1.36	0.93	21.77	19.82	57.47
22	M6	P010300	-	-	7.98	-	250.0	146.1	87.6	16.3	15.80	3.95	0.00	1.28	0.19	8.55	0.75	16.36	0.69	2.81	5.17	4.74	18.97	71.13
22	M6	P010301	-	-	8.03	-	250.0	146.3	87.7	16.0	15.80	3.95	0.00	1.29	0.19	8.66	0.76	17.10	0.67	2.85	3.92	4.78	19.22	72.08
22	M6	P020100	-	-	7.98	-	250.0	147.0	87.6	15.4	15.80	3.95	0.00	1.84	0.27	8.80	0.77	14.77	0.76	2.81	2.47	6.83	19.51	71.18
22	M6	P020200	-	-	8.01	-	250.0	145.8	87.5	16.7	15.80	3.95	0.79	0.63	0.09	9.48	0.83	17.29	0.85	3.68	2.86	1.94	17.49	77.71
22	M6	P020201	-	-	7.99	-	250.0	145.9	87.5	16.6	15.80	3.95	0.79	0.64	0.09	9.70	0.85	18.29	0.82	3.77	0.54	1.98	17.91	79.58

Notes:

- ✓ In Scenario M2, the doses applied were 8 g/L for the conventional 40% aluminum sulfate coagulant and 4 g/L for PAM, whereas in Scenario M6, fixed doses of 2.8 g/L for the hybrid coagulants and 1.88 g/L for PAM were used for all formulations.
- ✓ The theoretical iron content in 100 g of solution for the products P040102, P010300, P010301, P020100, P020200, and P020201 was 0.00, 0.00, 0.00, 0.00, 113.08, and 113.08 mg, respectively.
- ✓ For sludge samples, ICP-OES results represent the concentration in the digested solution (prepared from 0.1 g dry sludge in 25 mL acid). Therefore, ppm values converted to mg/g based on the original dry mass before use in mass balance calculations.

APPENDIX I: MASS BALANCE CALCULATIONS FOR TOTAL CHROMIUM (Cr)

Table I.1. Mass balance calculations for total Chromium (Cr).

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{Cr,in}$ (mg/L)	$M_{Cr,In\ Total}$ (mg)	$C_{Cr,SUP}$ (mg/L)	$M_{Cr,SUP}$ (mg)	$C_{Cr,CEN}$ (mg/L)	$M_{Cr,CEN}$ (mg)	$C_{Cr,SLG}$ (mg/L)	M_{Dry} (g) (Dry Sludge Weight)	$M_{Cr,SLG}$ (mg)	$\Delta M_{Cr,Loss}$	Cr Removal (%)
1	M2	P040102	Lime (10%)	3.68	7.39	8.46	250.0	168.3	58.3	23.4	21.80	5.45	2.44	0.41	11.75	0.68	35.54	0.48	4.25	1.96	79.90
1	M6	P010300	-	-	7.41	-	250.0	145.4	87.2	17.5	21.80	5.45	0.41	0.06	2.73	0.24	54.82	0.37	5.09	1.25	94.56
1	M6	P010301	-	-	7.41	-	250.0	145.6	87.3	17.2	21.80	5.45	0.65	0.10	2.62	0.23	53.37	0.36	4.85	5.08	94.06
1	M6	P020100	-	-	7.39	-	250.0	146.4	87.2	16.5	21.80	5.45	0.84	0.12	4.18	0.36	45.65	0.43	4.90	1.20	91.06
1	M6	P020200	-	-	7.37	-	250.0	144.5	87.1	18.4	21.80	5.45	0.27	0.04	1.80	0.16	41.60	0.50	5.24	0.30	96.40
1	M6	P020201	-	-	7.41	-	250.0	145.2	87.1	17.8	21.80	5.45	0.27	0.04	1.76	0.15	42.74	0.48	5.09	3.17	96.48
2	M2	P040102	Lime (10%)	5.28	7.07	8.59	250.0	159.4	55.2	35.4	40.50	10.13	4.20	0.67	20.21	1.12	37.39	0.86	8.06	2.80	82.37
2	M6	P010300	-	-	7.08	-	250.0	139.8	83.8	26.4	40.50	10.13	0.36	0.05	2.42	0.20	58.63	0.64	9.32	5.45	97.50
2	M6	P010301	-	-	7.07	-	250.0	140.1	84.0	25.9	40.50	10.13	0.67	0.09	2.68	0.23	58.77	0.62	9.17	6.28	96.85
2	M6	P020100	-	-	7.07	-	250.0	141.1	84.0	24.9	40.50	10.13	1.07	0.15	5.35	0.45	50.26	0.71	8.97	5.52	94.07
2	M6	P020200	-	-	7.09	-	250.0	139.3	83.6	27.0	40.50	10.13	0.11	0.01	0.70	0.06	45.25	0.86	9.74	3.13	99.28
2	M6	P020201	-	-	7.09	-	250.0	139.5	83.7	26.9	40.50	10.13	0.10	0.01	0.67	0.06	53.07	0.73	9.63	4.16	99.30
3	M2	P040102	Lime (10%)	2.94	7.61	8.54	150.0	103.5	35.9	10.6	26.40	3.96	2.58	0.27	12.42	0.45	44.05	0.28	3.04	5.35	82.01
3	M6	P010300	-	-	7.62	-	150.0	88.8	53.3	7.9	26.40	3.96	0.31	0.03	2.08	0.11	58.30	0.25	3.57	6.25	96.50
3	M6	P010301	-	-	7.59	-	150.0	88.9	53.3	7.8	26.40	3.96	0.57	0.05	2.30	0.12	62.64	0.24	3.68	2.67	95.62
3	M6	P020100	-	-	7.61	-	150.0	89.3	53.2	7.4	26.40	3.96	0.78	0.07	3.90	0.21	51.31	0.27	3.50	4.63	92.99
3	M6	P020200	-	-	7.60	-	150.0	88.5	53.2	8.3	26.40	3.96	0.15	0.01	0.99	0.05	47.94	0.30	3.61	7.11	98.33
3	M6	P020201	-	-	7.62	-	150.0	88.7	53.2	8.0	26.40	3.96	0.16	0.01	1.05	0.06	53.03	0.28	3.74	3.86	98.23
4	M2	P040102	Lime (10%)	5.12	7.03	8.51	250.0	159.3	55.2	35.5	41.60	10.40	4.76	0.76	22.90	1.26	38.89	0.85	8.30	0.77	80.56
4	M6	P010300	-	-	7.05	-	250.0	139.7	83.8	26.4	41.60	10.40	0.62	0.09	4.17	0.35	53.64	0.70	9.44	5.05	95.81
4	M6	P010301	-	-	7.02	-	250.0	140.0	84.0	26.0	41.60	10.40	1.12	0.16	4.48	0.38	60.23	0.65	9.79	0.77	94.88

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	C Cr, in (mg/L)	M Cr, In Total (mg)	C Cr, SUP (mg/L)	M Cr, SUP (mg)	C Cr, CEN (mg/L)	M Cr, CEN (mg)	C Cr, SLG (mg/L)	M Dry (g) (Dry Sludge Weight)	M Cr, SLG (mg)	ΔM Cr, Loss	Cr Removal (%)
4	M6	P020100	-	-	7.01	-	250.0	141.1	84.0	24.9	41.60	10.40	1.43	0.20	7.11	0.60	46.23	0.80	9.19	3.94	92.32
4	M6	P020200	-	-	7.06	-	250.0	139.2	83.6	27.2	41.60	10.40	0.35	0.05	2.34	0.20	44.16	0.87	9.56	5.73	97.65
4	M6	P020201	-	-	7.05	-	250.0	139.4	83.6	26.9	41.60	10.40	0.36	0.05	2.36	0.20	47.45	0.81	9.62	5.17	97.62
5	M2	P040102	Lime (10%)	2.72	7.62	8.41	250.0	165.3	57.3	27.4	25.20	6.30	3.08	0.51	14.81	0.85	21.66	0.92	4.99	-0.81	78.47
5	M6	P010300	-	-	7.63	-	250.0	143.5	86.1	20.5	25.20	6.30	0.57	0.08	3.84	0.33	31.88	0.74	5.88	0.06	93.46
5	M6	P010301	-	-	7.60	-	250.0	143.7	86.2	20.1	25.20	6.30	0.94	0.13	3.75	0.32	31.84	0.74	5.86	-0.32	92.73
5	M6	P020100	-	-	7.61	-	250.0	144.6	86.1	19.3	25.20	6.30	1.09	0.16	5.43	0.47	26.68	0.84	5.59	1.37	90.08
5	M6	P020200	-	-	7.61	-	250.0	143.1	85.9	20.9	25.20	6.30	0.41	0.06	2.68	0.23	25.21	0.92	5.83	2.88	95.41
5	M6	P020201	-	-	7.60	-	250.0	143.2	85.9	20.8	25.20	6.30	0.40	0.06	2.65	0.23	24.69	0.93	5.71	4.80	95.47
6	M2	P040102	Lime (10%)	3.08	7.52	8.40	250.0	165.5	57.4	27.1	24.80	6.20	3.02	0.50	14.54	0.83	23.56	0.83	4.91	-0.77	78.48
6	M6	P010300	-	-	7.51	-	250.0	143.6	86.1	20.2	24.80	6.20	0.55	0.08	3.73	0.32	31.93	0.71	5.69	1.72	93.54
6	M6	P010301	-	-	7.53	-	250.0	143.9	86.3	19.9	24.80	6.20	0.93	0.13	3.71	0.32	33.68	0.69	5.81	-0.95	92.69
6	M6	P020100	-	-	7.54	-	250.0	144.7	86.2	19.0	24.80	6.20	1.09	0.16	5.45	0.47	30.89	0.73	5.64	-1.13	89.87
6	M6	P020200	-	-	7.53	-	250.0	143.3	86.0	20.7	24.80	6.20	0.41	0.06	2.71	0.23	29.86	0.80	5.97	-1.08	95.30
6	M6	P020201	-	-	7.51	-	250.0	143.4	86.0	20.6	24.80	6.20	0.41	0.06	2.69	0.23	30.60	0.77	5.91	-0.07	95.32
7	M2	P040102	Lime (10%)	2.44	7.68	8.38	250.0	169.8	58.8	21.3	24.40	6.10	2.95	0.50	14.22	0.84	31.71	0.61	4.82	-0.91	78.06
7	M6	P010300	-	-	7.71	-	250.0	146.3	87.8	15.9	24.40	6.10	0.58	0.08	3.88	0.34	44.09	0.51	5.61	1.01	93.04
7	M6	P010301	-	-	7.71	-	250.0	146.5	87.8	15.6	24.40	6.10	0.93	0.14	3.71	0.33	47.90	0.46	5.48	2.53	92.43
7	M6	P020100	-	-	7.66	-	250.0	147.3	87.7	15.0	24.40	6.10	1.07	0.16	5.36	0.47	39.03	0.55	5.34	2.20	89.70
7	M6	P020200	-	-	7.66	-	250.0	145.7	87.7	16.6	24.40	6.10	0.43	0.06	2.84	0.25	36.15	0.63	5.71	1.21	94.89
7	M6	P020201	-	-	7.68	-	250.0	146.1	87.7	16.2	24.40	6.10	0.43	0.06	2.84	0.25	40.10	0.57	5.72	1.05	94.88
8	M2	P040102	Lime (10%)	2.47	7.85	8.57	150.0	105.6	36.6	7.7	20.00	3.00	1.90	0.20	9.13	0.33	42.50	0.22	2.36	3.55	82.18
8	M6	P010300	-	-	7.86	-	150.0	89.8	54.1	6.1	20.00	3.00	0.20	0.02	1.34	0.07	66.69	0.17	2.82	3.01	96.98
8	M6	P010301	-	-	7.84	-	150.0	90.2	54.1	5.7	20.00	3.00	0.35	0.03	1.38	0.07	64.33	0.17	2.70	6.51	96.46
8	M6	P020100	-	-	7.83	-	150.0	90.6	54.0	5.4	20.00	3.00	0.51	0.05	2.57	0.14	54.36	0.19	2.60	7.33	93.83
8	M6	P020200	-	-	7.85	-	150.0	90.0	54.1	5.9	20.00	3.00	0.07	0.01	0.45	0.02	49.90	0.22	2.76	6.92	98.98
8	M6	P020201	-	-	7.84	-	150.0	90.2	54.0	5.8	20.00	3.00	0.07	0.01	0.44	0.02	53.34	0.20	2.73	8.10	99.01

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	$C_{Cr,in}$ (mg/L)	$M_{Cr,In\ Total}$ (mg)	$C_{Cr,SUP}$ (mg/L)	$M_{Cr,SUP}$ (mg)	$C_{Cr,CEN}$ (mg/L)	$M_{Cr,CEN}$ (mg)	$C_{Cr,SLG}$ (mg/L)	M_{Dry} (g) (Dry Sludge Weight)	$M_{Cr,SLG}$ (mg)	$\Delta M_{Cr,Loss}$	Cr Removal (%)
9	M2	P040102	Lime (10%)	2.12	7.90	8.51	250.0	165.6	57.4	27.0	28.32	7.08	3.08	0.51	14.83	0.85	23.08	0.97	5.59	1.78	80.77
9	M6	P010300	-	-	7.90	-	250.0	143.7	86.2	20.1	28.32	7.08	0.42	0.06	2.81	0.24	31.40	0.83	6.54	3.38	95.74
9	M6	P010301	-	-	7.92	-	250.0	143.9	86.3	19.8	28.32	7.08	0.71	0.10	2.83	0.24	34.85	0.74	6.41	4.55	95.10
9	M6	P020100	-	-	7.88	-	250.0	144.8	86.2	19.0	28.32	7.08	0.97	0.14	4.82	0.42	29.38	0.87	6.40	1.74	92.15
9	M6	P020200	-	-	7.88	-	250.0	143.0	86.1	20.9	28.32	7.08	0.25	0.04	1.63	0.14	28.83	0.95	6.82	1.22	97.52
9	M6	P020201	-	-	7.92	-	250.0	143.5	86.1	20.5	28.32	7.08	0.23	0.03	1.52	0.13	28.43	0.90	6.42	6.98	97.69
10	M2	P040102	Lime (10%)	0.80	8.31	8.53	250.0	158.5	54.9	36.6	38.60	9.65	4.13	0.65	19.89	1.09	18.15	1.63	7.39	5.30	81.90
10	M6	P010300	-	-	8.29	-	250.0	139.2	83.5	27.3	38.60	9.65	0.50	0.07	3.35	0.28	25.51	1.37	8.71	6.07	96.38
10	M6	P010301	-	-	8.30	-	250.0	139.5	83.6	26.8	38.60	9.65	0.89	0.12	3.58	0.30	26.35	1.33	8.79	4.51	95.61
10	M6	P020100	-	-	8.31	-	250.0	140.5	83.7	25.7	38.60	9.65	1.23	0.17	6.12	0.51	21.01	1.62	8.49	4.96	92.91
10	M6	P020200	-	-	8.29	-	250.0	138.8	83.3	27.9	38.60	9.65	0.26	0.04	1.73	0.14	19.74	1.84	9.07	4.18	98.13
10	M6	P020201	-	-	8.32	-	250.0	138.9	83.3	27.8	38.60	9.65	0.28	0.04	1.81	0.15	22.06	1.69	9.34	1.26	98.04
11	M2	P040102	-	-	8.37	-	250.0	164.9	57.1	28.0	48.80	12.20	6.14	1.01	29.55	1.69	29.83	1.29	9.64	-1.14	77.86
11	M6	P010300	-	-	8.36	-	150.0	85.9	51.5	12.5	48.80	7.32	1.20	0.10	8.05	0.41	40.32	0.66	6.63	2.32	92.93
11	M6	P010301	-	-	8.39	-	150.0	86.1	51.6	12.3	48.80	7.32	1.95	0.17	7.80	0.40	44.42	0.60	6.62	1.72	92.20
11	M6	P020100	-	-	8.40	-	150.0	86.6	51.6	11.8	48.80	7.32	2.24	0.19	11.20	0.58	35.04	0.74	6.45	1.29	89.45
11	M6	P020200	-	-	8.38	-	150.0	85.7	51.5	12.8	48.80	7.32	0.93	0.08	6.11	0.31	33.86	0.83	7.04	-1.55	94.62
11	M6	P020201	-	-	8.35	-	150.0	86.0	51.5	12.5	48.80	7.32	0.91	0.08	6.01	0.31	35.84	0.76	6.85	1.12	94.70
12	M2	P040102	Lime (10%)	2.00	8.02	8.59	250.0	158.9	55.1	36.0	50.00	12.50	5.18	0.82	24.94	1.37	27.75	1.44	9.97	2.70	82.43
12	M6	P010300	-	-	8.02	-	250.0	139.5	83.7	26.9	50.00	12.50	0.42	0.06	2.81	0.23	40.47	1.12	11.37	6.73	97.66
12	M6	P010301	-	-	8.02	-	250.0	139.8	83.8	26.4	50.00	12.50	0.82	0.11	3.27	0.27	41.37	1.11	11.44	5.40	96.89
12	M6	P020100	-	-	8.00	-	250.0	140.8	83.9	25.3	50.00	12.50	1.28	0.18	6.40	0.54	36.41	1.20	10.93	6.83	94.27
12	M6	P020200	-	-	8.01	-	250.0	139.1	83.5	27.5	50.00	12.50	0.10	0.01	0.67	0.06	34.13	1.38	11.74	5.53	99.44
12	M6	P020201	-	-	7.99	-	250.0	139.2	83.5	27.3	50.00	12.50	0.12	0.02	0.77	0.06	35.10	1.37	12.06	2.90	99.36
13	M2	P040102	Lime (10%)	3.84	7.46	8.56	250.0	159.3	55.2	35.4	33.40	8.35	3.49	0.56	16.79	0.93	21.96	1.18	6.49	4.50	82.24
13	M6	P010300	-	-	7.48	-	250.0	139.8	83.8	26.4	33.40	8.35	0.37	0.05	2.51	0.21	35.32	0.88	7.78	3.65	96.85
13	M6	P010301	-	-	7.47	-	250.0	140.1	84.0	26.0	33.40	8.35	0.64	0.09	2.54	0.21	34.67	0.85	7.40	7.77	96.38

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	C Cr, in (mg/L)	M Cr, In Total (mg)	C Cr, SUP (mg/L)	M Cr, SUP (mg)	C Cr, CEN (mg/L)	M Cr, CEN (mg)	C Cr, SLG (mg/L)	M Dry (g) (Dry Sludge Weight)	M Cr, SLG (mg)	ΔM Cr, Loss	Cr Removal (%)
13	M6	P020100	-	-	7.43	-	250.0	141.1	84.0	24.9	33.40	8.35	0.99	0.14	4.96	0.42	30.35	0.99	7.52	3.28	93.34
13	M6	P020200	-	-	7.46	-	250.0	139.3	83.6	27.0	33.40	8.35	0.15	0.02	0.96	0.08	27.66	1.12	7.74	6.08	98.79
13	M6	P020201	-	-	7.47	-	250.0	140.8	83.7	25.5	33.40	8.35	0.15	0.02	1.02	0.09	28.82	1.10	7.92	3.82	98.72
14	M2	P040102	Lime (10%)	3.47	7.36	8.37	150.0	101.0	35.0	14.0	32.50	4.88	3.55	0.36	17.09	0.60	32.90	0.47	3.83	1.83	80.38
14	M6	P010300	-	-	7.36	-	250.0	145.4	87.2	17.4	32.50	8.13	0.57	0.08	3.83	0.33	49.81	0.65	8.07	-4.50	94.87
14	M6	P010301	-	-	7.37	-	250.0	145.6	87.3	17.1	32.50	8.13	0.96	0.14	3.84	0.34	55.55	0.57	7.96	-3.85	94.15
14	M6	P020100	-	-	7.37	-	250.0	146.4	87.2	16.4	32.50	8.13	1.17	0.17	5.84	0.51	43.27	0.68	7.36	1.04	91.62
14	M6	P020200	-	-	7.37	-	250.0	145.1	87.1	17.8	32.50	8.13	0.35	0.05	2.31	0.20	41.74	0.78	8.14	-3.25	96.90
14	M6	P020201	-	-	7.36	-	250.0	145.2	87.1	17.7	32.50	8.13	0.33	0.05	2.17	0.19	40.12	0.76	7.64	3.11	97.08
15	M2	P040102	Lime (10%)	2.72	7.59	8.37	250.0	170.7	59.2	20.1	35.90	8.98	4.12	0.70	19.83	1.17	73.71	0.38	6.99	1.21	79.10
15	M6	P010300	-	-	7.58	-	250.0	146.9	88.1	15.0	35.90	8.98	0.74	0.11	4.99	0.44	103.77	0.31	8.12	3.41	93.89
15	M6	P010301	-	-	7.58	-	250.0	147.1	88.2	14.8	35.90	8.98	1.22	0.18	4.87	0.43	111.71	0.29	8.03	3.76	93.22
15	M6	P020100	-	-	7.58	-	250.0	147.8	88.0	14.2	35.90	8.98	1.48	0.22	7.38	0.65	94.44	0.34	7.99	1.27	90.33
15	M6	P020200	-	-	7.60	-	250.0	146.6	88.0	15.4	35.90	8.98	0.53	0.08	3.47	0.31	89.93	0.36	8.19	4.43	95.73
15	M6	P020201	-	-	7.60	-	250.0	147.0	88.0	15.0	35.90	8.98	0.55	0.08	3.61	0.32	95.59	0.36	8.69	-1.22	95.56
16	M2	P040102	Lime (10%)	1.68	7.92	8.40	250.0	163.2	56.6	30.2	38.10	9.53	4.71	0.77	22.69	1.28	24.24	1.26	7.61	-1.45	78.45
16	M6	P010300	-	-	7.93	-	250.0	142.2	85.3	22.5	38.10	9.53	0.83	0.12	5.56	0.47	35.32	0.97	8.53	4.25	93.79
16	M6	P010301	-	-	7.94	-	250.0	142.4	85.4	22.2	38.10	9.53	1.38	0.20	5.51	0.47	37.50	0.92	8.64	2.33	93.00
16	M6	P020100	-	-	7.90	-	250.0	143.4	85.4	21.2	38.10	9.53	1.62	0.23	8.09	0.69	30.41	1.10	8.34	2.72	90.31
16	M6	P020200	-	-	7.91	-	250.0	141.8	85.1	23.1	38.10	9.53	0.60	0.09	3.99	0.34	29.75	1.19	8.84	2.77	95.54
16	M6	P020201	-	-	7.91	-	250.0	142.1	85.1	22.8	38.10	9.53	0.61	0.09	4.04	0.34	30.87	1.17	8.99	1.05	95.48
17	M2	P040102	Lime (10%)	2.20	7.72	8.39	250.0	168.9	58.5	22.5	27.87	6.97	3.17	0.54	15.26	0.89	29.60	0.71	5.28	3.76	79.49
17	M6	P010300	-	-	7.74	-	150.0	87.5	52.5	10.1	27.87	4.18	0.60	0.05	4.04	0.21	43.53	0.35	3.85	1.65	93.67
17	M6	P010301	-	-	7.72	-	150.0	87.6	52.5	9.9	27.87	4.18	0.98	0.09	3.93	0.21	43.07	0.35	3.79	2.41	93.01
17	M6	P020100	-	-	7.75	-	150.0	88.1	52.4	9.5	27.87	4.18	1.17	0.10	5.82	0.31	37.50	0.39	3.70	1.84	90.24
17	M6	P020200	-	-	7.69	-	150.0	87.3	52.4	10.3	27.87	4.18	0.44	0.04	2.87	0.15	34.57	0.46	3.95	0.97	95.49
17	M6	P020201	-	-	7.70	-	150.0	87.4	52.4	10.3	27.87	4.18	0.43	0.04	2.80	0.15	36.65	0.41	3.79	4.82	95.60

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH	pH Before	pH After	Wastewater Volume (mL)	Volume (SUP) (mL)	Volume (CEN) (mL)	Volume (SLG) (mL)	C Cr, in (mg/L)	M Cr, In Total (mg)	C Cr, SUP (mg/L)	M Cr, SUP (mg)	C Cr, CEN (mg/L)	M Cr, CEN (mg)	C Cr, SLG (mg/L)	M Dry (g) (Dry Sludge Weight)	M Cr, SLG (mg)	ΔM Cr, Loss	Cr Removal (%)
18	M2	P040102	-	-	8.47	-	250.0	175.0	60.7	14.3	36.30	9.08	4.02	0.70	19.33	1.17	47.72	0.60	7.15	0.53	79.33
18	M6	P010300	-	-	8.47	-	250.0	149.6	89.7	10.7	36.30	9.08	0.69	0.10	4.65	0.42	69.42	0.48	8.38	1.96	94.26
18	M6	P010301	-	-	8.44	-	250.0	149.7	89.8	10.5	36.30	9.08	1.15	0.17	4.62	0.41	75.26	0.44	8.35	1.49	93.53
18	M6	P020100	-	-	8.49	-	250.0	150.4	89.6	10.0	36.30	9.08	1.41	0.21	7.02	0.63	60.36	0.54	8.12	1.23	90.74
18	M6	P020200	-	-	8.49	-	250.0	149.4	89.7	10.9	36.30	9.08	0.47	0.07	3.11	0.28	55.74	0.60	8.42	3.39	96.15
18	M6	P020201	-	-	8.44	-	250.0	149.5	89.7	10.8	36.30	9.08	0.49	0.07	3.21	0.29	62.06	0.57	8.78	-0.73	96.02
19	M2	P040102	Lime (10%)	1.88	7.95	8.49	250.0	165.3	57.3	27.4	23.80	5.95	2.56	0.42	12.34	0.71	16.38	1.11	4.56	4.44	80.99
19	M6	P010300	-	-	7.93	-	250.0	143.5	86.1	20.5	23.80	5.95	0.38	0.05	2.55	0.22	23.48	0.93	5.45	3.78	95.39
19	M6	P010301	-	-	7.93	-	250.0	143.7	86.2	20.1	23.80	5.95	0.64	0.09	2.56	0.22	24.70	0.87	5.36	4.72	94.75
19	M6	P020100	-	-	7.96	-	250.0	144.6	86.1	19.3	23.80	5.95	0.84	0.12	4.19	0.36	21.50	0.99	5.30	2.86	91.89
19	M6	P020200	-	-	7.98	-	250.0	143.1	85.9	20.9	23.80	5.95	0.23	0.03	1.51	0.13	20.96	1.05	5.50	4.91	97.26
19	M6	P020201	-	-	7.95	-	250.0	143.3	85.9	20.8	23.80	5.95	0.24	0.03	1.55	0.13	21.29	1.05	5.61	2.95	97.20
20	M2	P040102	-	-	8.41	-	150.0	105.9	36.7	7.4	23.20	3.48	2.45	0.26	11.81	0.43	33.68	0.32	2.73	1.72	80.08
20	M6	P010300	-	-	8.39	-	150.0	90.3	54.2	5.5	23.20	3.48	0.39	0.04	2.63	0.14	48.93	0.26	3.21	2.67	94.90
20	M6	P010301	-	-	8.43	-	150.0	90.4	54.2	5.5	23.20	3.48	0.65	0.06	2.60	0.14	49.73	0.25	3.15	3.84	94.27
20	M6	P020100	-	-	8.41	-	150.0	90.7	54.0	5.2	23.20	3.48	0.82	0.07	4.11	0.22	39.58	0.31	3.08	2.88	91.47
20	M6	P020200	-	-	8.43	-	150.0	89.7	54.1	6.2	23.20	3.48	0.25	0.02	1.65	0.09	40.23	0.32	3.23	3.85	96.78
20	M6	P020201	-	-	8.40	-	150.0	90.2	54.1	5.6	23.20	3.48	0.25	0.02	1.65	0.09	40.01	0.32	3.22	4.27	96.79
21	M2	P040102	Lime (10%)	1.52	8.00	8.44	250.0	166.4	57.7	26.0	30.70	7.68	3.32	0.55	15.99	0.92	24.09	0.98	5.90	3.93	80.79
21	M6	P010300	-	-	8.00	-	250.0	144.2	86.5	19.4	30.70	7.68	0.48	0.07	3.26	0.28	33.66	0.81	6.81	6.71	95.42
21	M6	P010301	-	-	7.99	-	250.0	144.4	86.6	19.0	30.70	7.68	0.88	0.13	3.52	0.30	35.78	0.81	7.23	0.12	94.38
21	M6	P020100	-	-	7.98	-	250.0	145.2	86.5	18.3	30.70	7.68	1.12	0.16	5.59	0.48	28.80	0.97	6.99	0.51	91.58
21	M6	P020200	-	-	8.02	-	250.0	143.8	86.3	19.8	30.70	7.68	0.30	0.04	2.01	0.17	26.31	1.06	7.00	5.95	97.17
21	M6	P020201	-	-	7.97	-	250.0	144.1	86.3	19.6	30.70	7.68	0.31	0.05	2.06	0.18	28.71	1.00	7.19	3.44	97.09
22	M2	P040102	Lime (10%)	1.74	8.00	8.51	150.0	101.6	35.2	13.1	42.90	6.44	4.50	0.46	21.68	0.76	40.40	0.48	4.89	5.08	81.02
22	M6	P010300	-	-	7.98	-	250.0	146.1	87.6	16.3	42.90	10.73	0.69	0.10	4.66	0.41	57.51	0.69	9.88	3.16	95.25
22	M6	P010301	-	-	8.03	-	250.0	146.3	87.7	16.0	42.90	10.73	1.19	0.17	4.76	0.42	59.61	0.67	9.92	1.96	94.48

Day	Scenario (M1–M6)	Formulation Code	pH Adjustment Chemical	Chemical Dose for pH	pH_{Before}	pH_{After}	Wastewater Volume (mL)	$Volume_{(SUP)}$ (mL)	$Volume_{(CEN)}$ (mL)	$Volume_{(SLG)}$ (mL)	$C_{Cr,in}$ *(mg/L)*	$M_{Cr,In\ Total}$ *(mg)*	$C_{Cr,SUP}$ *(mg/L)*	$M_{Cr,SUP}$ *(mg)*	$C_{Cr,CEN}$ *(mg/L)*	$M_{Cr,CEN}$ *(mg)*	$C_{Cr,SLG}$ *(mg/L)*	M_{Dry} (g) *(Dry Sludge Weight)*	$M_{Cr,SLG}$ *(mg)*	$\Delta M_{Cr,Loss}$	Cr Removal (%)
22	M6	P020100	-	-	7.98	-	250.0	147.0	87.6	15.4	42.90	10.73	1.51	0.22	7.54	0.66	50.14	0.76	9.55	2.77	91.77
22	M6	P020200	-	-	8.01	-	250.0	145.8	87.5	16.7	42.90	10.73	0.43	0.06	2.83	0.25	46.95	0.85	10.00	3.84	97.11
22	M6	P020201	-	-	7.99	-	250.0	145.9	87.5	16.6	42.90	10.73	0.43	0.06	2.81	0.25	48.21	0.82	9.94	4.41	97.12

Notes:

- ✓ In Scenario M2, the doses applied were 8 g/L for the conventional 40% aluminum sulfate coagulant and 4 g/L for PAM, whereas in Scenario M6, fixed doses of 2.8 g/L for the hybrid coagulants and 1.88 g/L for PAM were used for all formulations.
- ✓ The theoretical iron content in 100 g of solution for the products P040102, P010300, P010301, P020100, P020200, and P020201 was 0.00, 0.00, 0.00, 0.00, 113.08, and 113.08 mg, respectively.
- ✓ For sludge samples, ICP-OES results represent the concentration in the digested solution (prepared from 0.1 g dry sludge in 25 mL acid). Therefore, ppm values converted to mg/g based on the original dry mass before use in mass balance calculations.

APPENDIX J: BIOWIN MODEL OUTPUTS FOR BIODEGRADABILITY ASSESSMENT

Figure J.1. BIOWIN prediction results for N-methylmethanamine (Dimethylamine).

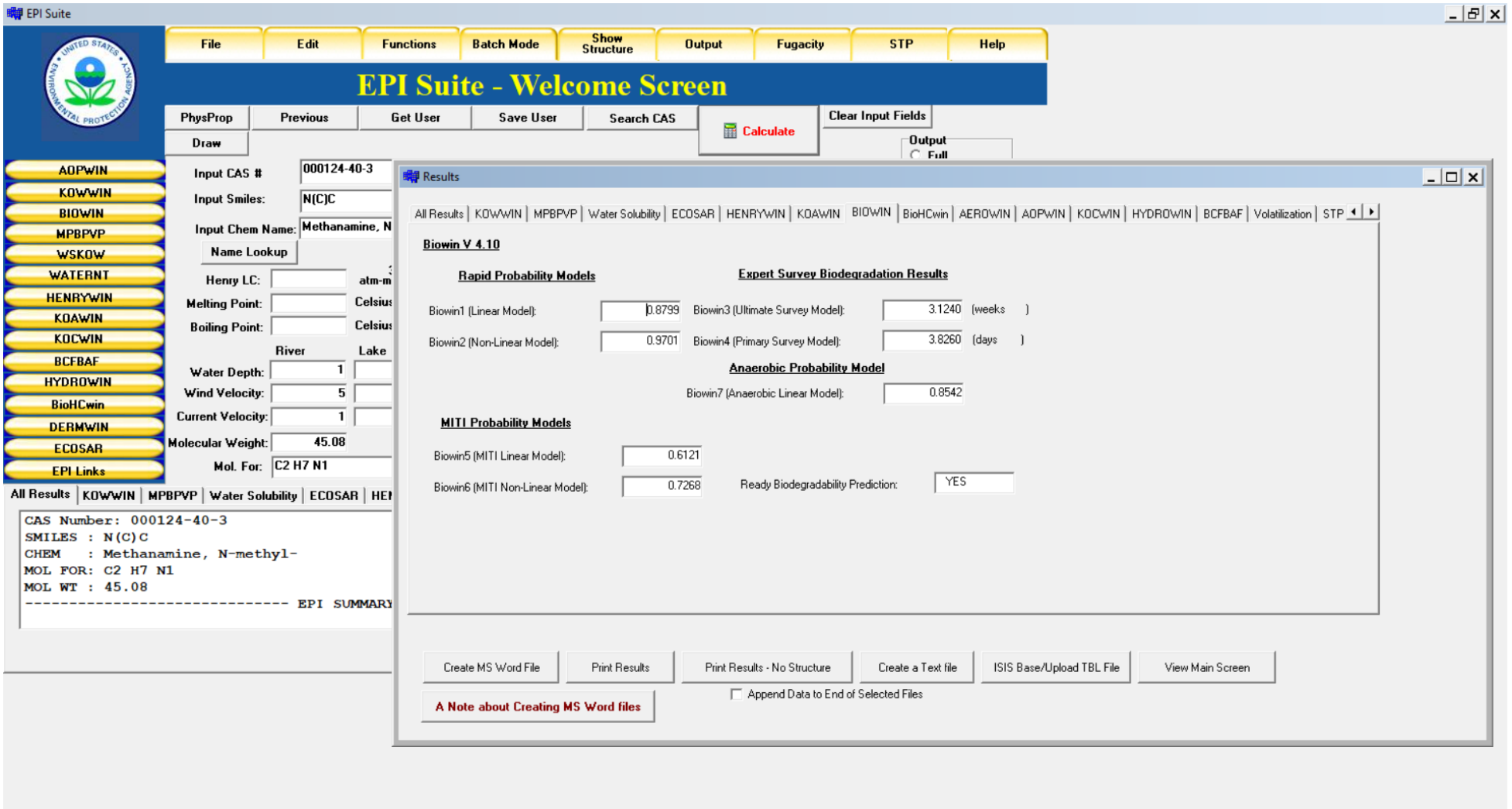


Figure J.2. BIOWIN prediction results for Oxirane, chloromethyl- (Epichlorohydrin).

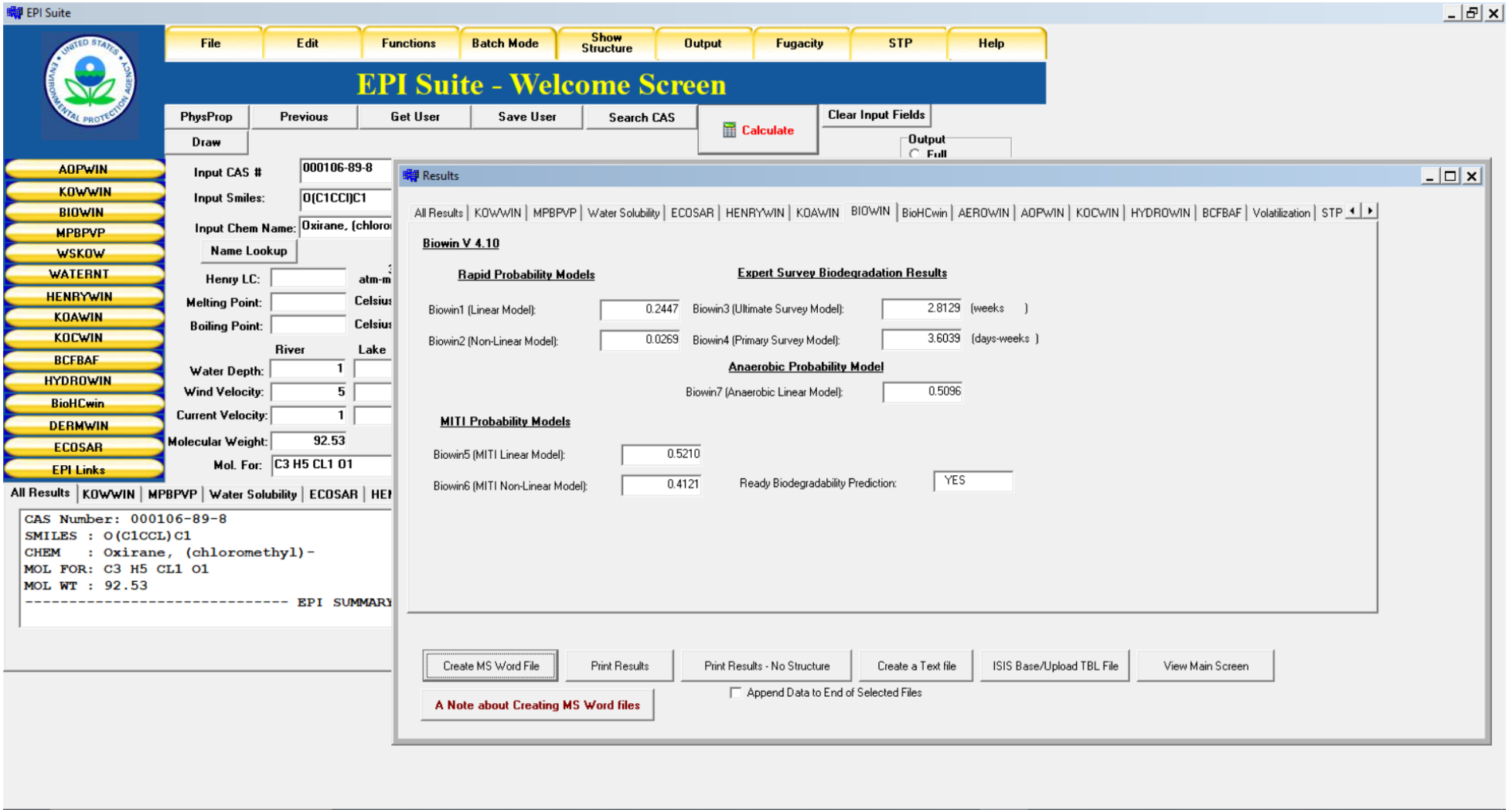


Figure J.3. BIOWIN prediction results for 2-Propenamide (Acrylamide).

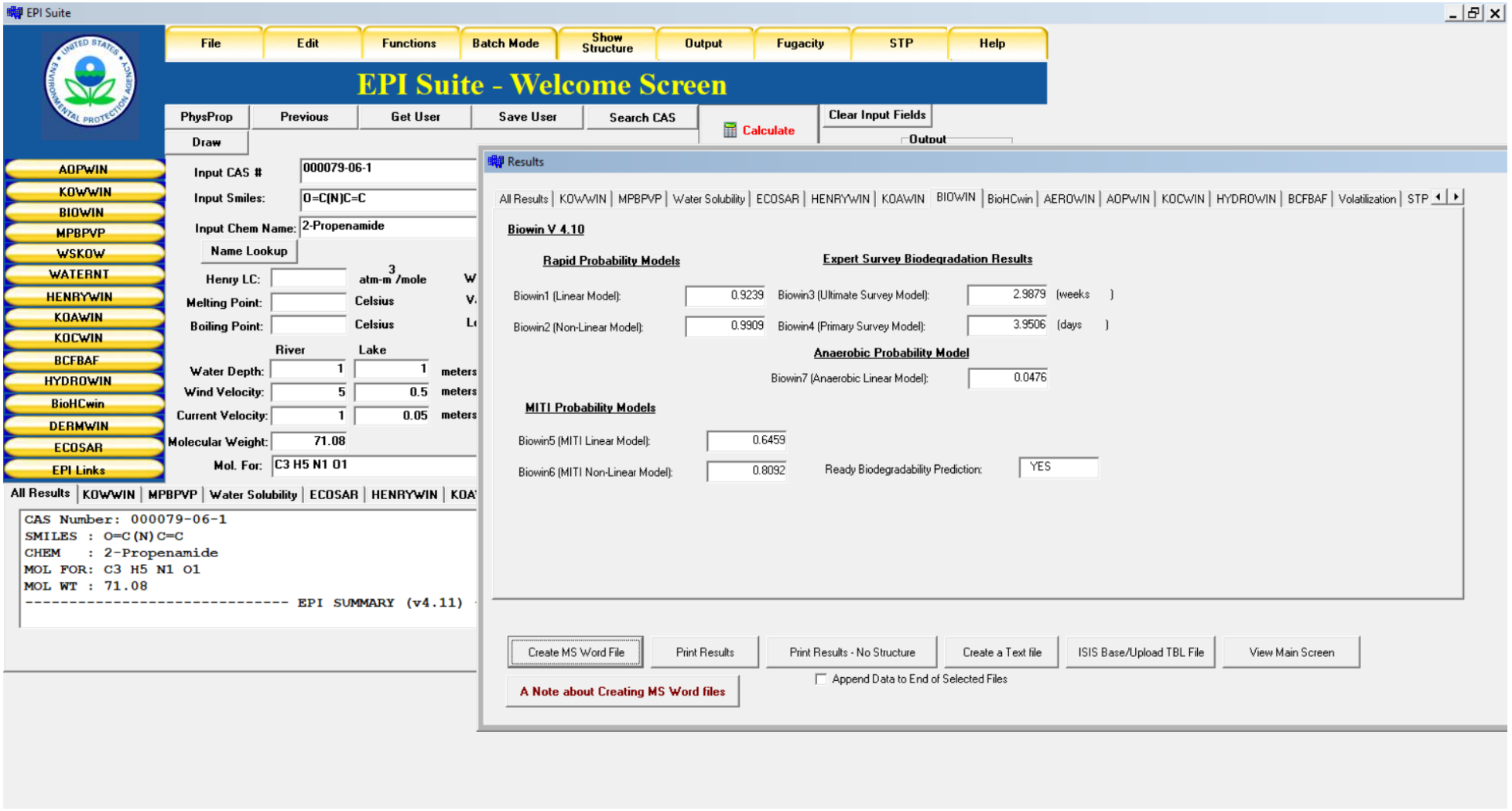


Figure J.4. BIOWIN prediction results for 2-Propenoic acid (Acrylic acid).

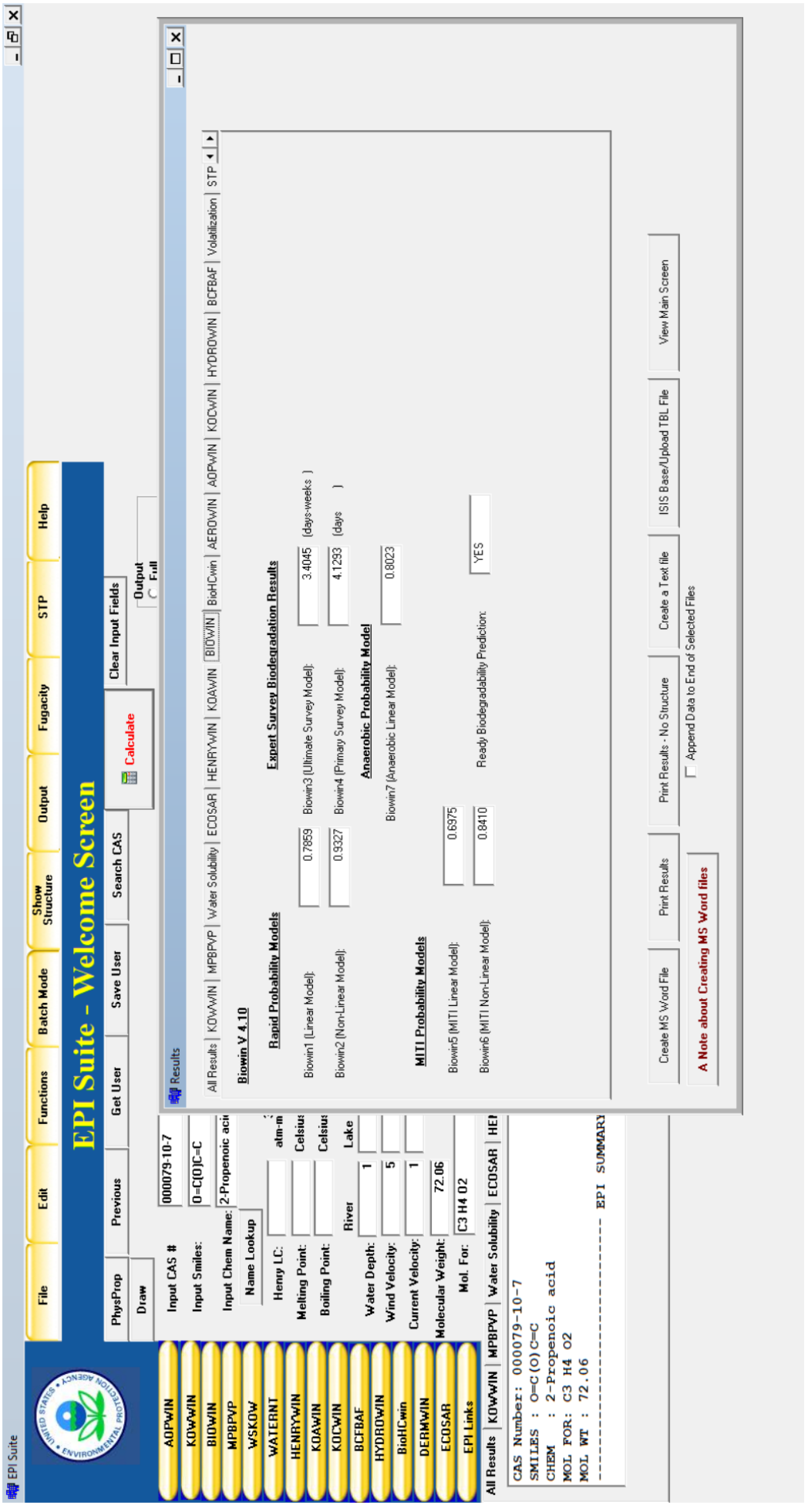
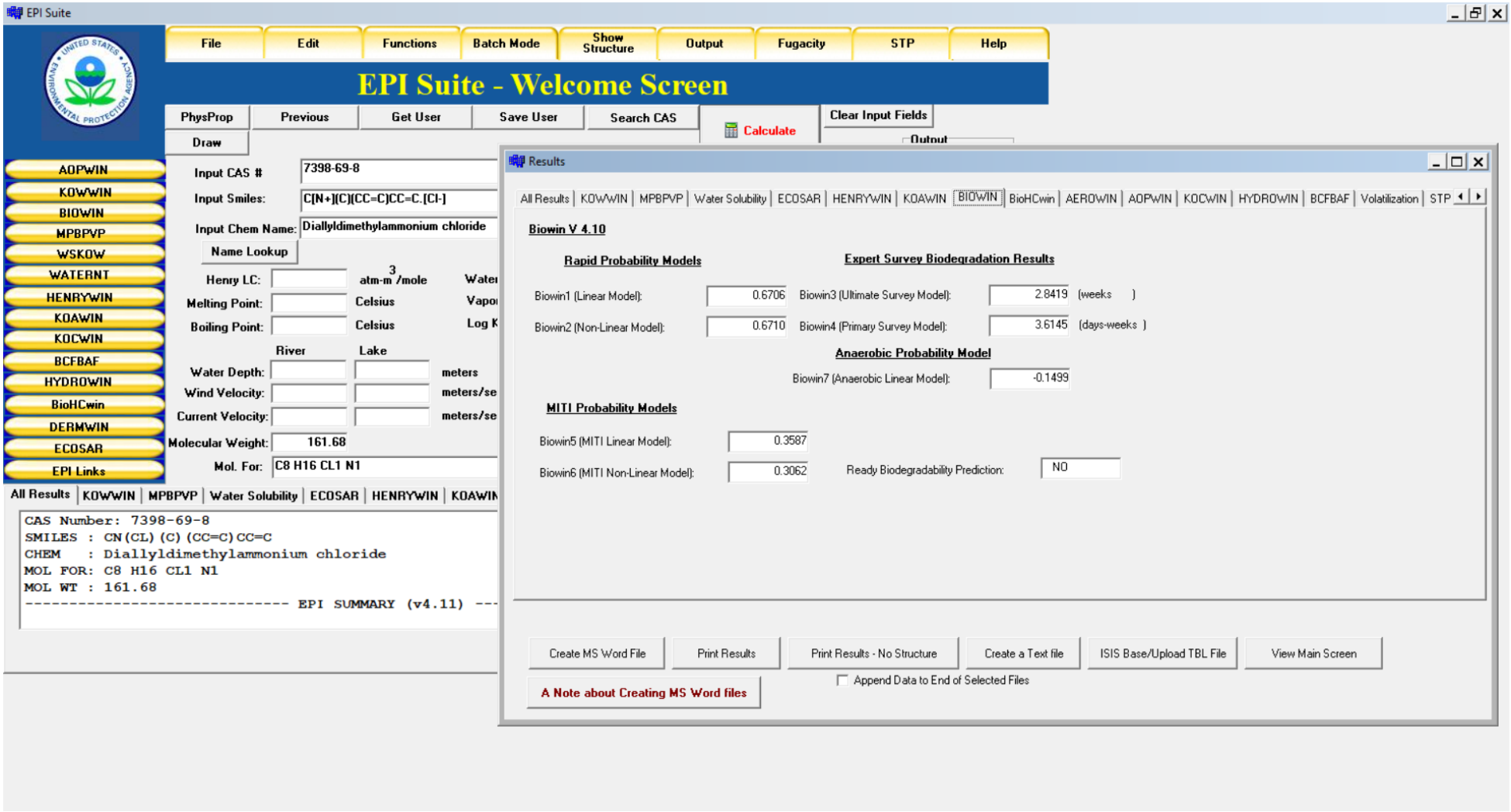


Figure J.5. BIOWIN prediction results for Diallyldimethylammonium chloride (PolyDADMAC monomer unit).



APPENDIX K: ENVIRONMENTAL IMPACT MATRIX COMPUTATIONAL RESULTS

Table K.1. Raw decision matrix prior to entropy weighting.

Scenario & Coagulant Code	Sludge Management & Disposal Impact				Chemical Burden & Toxicity						Treatment Efficiency & Organic Load Management			Systemic & Long-term Environmental Robustness			
	Sludge Volume	Moisture Content	Dry Solid Yield	Disposal Compatibility	Active Aluminum Dose	Residual Al in Effluent	Residual Fe in Effluent	Residual Total Cr in Effluent	pH Regulator Requirement	Total Coagulant Dose	COD Removal	TOC Removal	TSS Removal	Metal Residual Persistence and Toxicity (Al, Fe, Cr)			Polymer Biodegradability
														Residual Al in Sludge	Residual Fe in Sludge	Residual Total Cr in Sludge	
M2 - P040102	10.22	70.27	3.47	0.39	25920000.00	19.09	3.38	3.61	0	8000.00	68.14	65.46	81.77	260.39	7.36	32.67	N/A
M6 - P010300	7.63	58.41	2.82	0.59	9328032.00	4.74	0.89	0.54	1	2800.00	81.60	80.83	85.48	117.83	11.68	47.20	0.31
M6 - P010301	7.49	57.29	2.69	0.58	9328032.00	4.73	0.88	0.92	1	2800.00	79.38	78.47	86.07	124.12	12.31	49.42	0.44
M6 - P020100	7.18	54.63	3.14	0.71	12595800.00	8.62	1.24	1.17	1	2800.00	84.69	84.12	87.84	140.52	10.28	41.03	0.31
M6 - P020200	7.84	57.96	3.51	0.60	14359212.00	4.81	0.46	0.34	1	2800.00	74.69	73.22	89.13	153.06	13.31	38.66	0.31
M6 - P020201	7.71	56.79	3.35	0.59	14359212.00	4.78	0.46	0.34	1	2800.00	72.36	71.26	89.73	161.38	14.14	40.85	0.57
∑	**48.07**	**355.34**	**18.98**	**3.45**	**85890288.00**	**46.79**	**7.31**	**6.92**	**5**	**22000.00**	**460.86**	**453.35**	**520.01**	**957.31**	**69.08**	**249.84**	**1.93**

Notes:

1. The qualitative criteria — *Disposal Compatibility*, *Polymer Biodegradability*, and *pH Regulator Requirement* — were converted into numerical form through scale normalization as described in the relevant sections. (For *Polymer Biodegradability*, BIOWIN$_6$ model outputs were used to obtain normalized biodegradation scores.)
2. For the Residual Heavy Metal in Effluent criterion, values were evaluated based on the supernatant (sup) phase to represent the concentration of metals remaining in the treated effluent.
3. The Active Aluminum Dose was calculated using the theoretical aluminum content of each coagulant and its applied dosage, thereby representing the actual environmental aluminum load rather than nominal coagulant concentration.

Table K.2. Normalized decision matrix derived from raw criterion values.

Scenario & Coagulant Code	Sludge Management & Disposal Impact				Chemical Burden & Toxicity						Treatment Efficiency & Organic Load Management			Systemic & Long-term Environmental Robustness			
														Metal Residual Persistence and Toxicity (Al, Fe, Cr)			
	Sludge Volume	Moisture Content	Dry Solid Yield	Disposal Compatibility	Active Aluminum Dose	Residual Al in Effluent	Residual Fe in Effluent	Residual Total Cr in Effluent	pH Regulator Requirement	Total Coagulant Dose	COD Removal	TOC Removal	TSS Removal	Residual Al in Sludge	Residual Fe in Sludge	Residual Total Cr in Sludge	Polymer Biodegradability
M2 - P040102	0.213	0.198	0.183	0.113	0.302	0.408	0.462	0.521	0.000	0.364	0.148	0.144	0.157	0.272	0.107	0.131	N/A
M6 - P010300	0.159	0.164	0.149	0.170	0.109	0.101	0.121	0.078	0.200	0.127	0.177	0.178	0.164	0.123	0.169	0.189	0.159
M6 - P010301	0.156	0.161	0.142	0.168	0.109	0.101	0.121	0.133	0.200	0.127	0.172	0.173	0.166	0.130	0.178	0.198	0.227
M6 - P020100	0.149	0.154	0.166	0.206	0.147	0.184	0.170	0.169	0.200	0.127	0.184	0.186	0.169	0.147	0.149	0.164	0.159
M6 - P020200	0.163	0.163	0.185	0.173	0.167	0.103	0.063	0.049	0.200	0.127	0.162	0.162	0.171	0.160	0.193	0.155	0.159
M6 - P020201	0.160	0.160	0.176	0.170	0.167	0.102	0.063	0.049	0.200	0.127	0.157	0.157	0.173	0.169	0.205	0.164	0.296

Table K.3. Entropy values, divergence measures, and final criterion weights (Equations 4.2–4.5).

Scenario & Coagulant Code	Sludge Management & Disposal Impact				Chemical Burden & Toxicity						Treatment Efficiency & Organic Load Management			Systemic & Long-term Environmental Robustness			
														Metal Residual Persistence and Toxicity (Al, Fe, Cr)			
	Sludge Volume	Moisture Content	Dry Solid Yield	Disposal Compatibility	Active Aluminum Dose	Residual Al in Effluent	Residual Fe in Effluent	Residual Total Cr in Effluent	pH Regulator Requirement	Total Coagulant Dose	COD Removal	TOC Removal	TSS Removal	Residual Al in Sludge	Residual Fe in Sludge	Residual Total Cr in Sludge	Polymer Biodegradability
M2 - P040102	-0.329	-0.321	-0.310	-0.246	-0.362	-0.366	-0.357	-0.340	0.000	-0.368	-0.283	-0.279	-0.291	-0.354	-0.239	-0.266	N/A
M6 - P010300	-0.292	-0.297	-0.283	-0.301	-0.241	-0.232	-0.256	-0.199	-0.322	-0.262	-0.307	-0.307	-0.297	-0.258	-0.300	-0.315	-0.292
M6 - P010301	-0.290	-0.294	-0.277	-0.300	-0.241	-0.232	-0.255	-0.268	-0.322	-0.262	-0.303	-0.304	-0.298	-0.265	-0.307	-0.321	-0.337
M6 - P020100	-0.284	-0.288	-0.298	-0.326	-0.282	-0.312	-0.301	-0.301	-0.322	-0.262	-0.311	-0.313	-0.300	-0.282	-0.283	-0.297	-0.292
M6 - P020200	-0.296	-0.296	-0.312	-0.304	-0.299	-0.234	-0.174	-0.148	-0.322	-0.262	-0.295	-0.294	-0.302	-0.293	-0.317	-0.289	-0.292
M6 - P020201	-0.293	-0.293	-0.306	-0.301	-0.299	-0.233	-0.174	-0.149	-0.322	-0.262	-0.291	-0.291	-0.303	-0.300	-0.325	-0.296	-0.360
$\sum$	-1.784	-1.788	-1.787	-1.777	-1.723	-1.608	-1.517	-1.404	-1.609	-1.680	-1.789	-1.788	-1.791	-1.752	-1.772	-1.783	-1.574
e_j	0.996	0.998	0.997	0.992	0.962	0.898	0.847	0.784	0.898	0.937	0.998	0.998	1.000	0.978	0.989	0.995	0.879
d_j	0.004	0.002	0.003	0.008	0.038	0.102	0.153	0.216	0.102	0.063	0.002	0.002	0.000	0.022	0.011	0.005	0.121
w_j	0.005	0.002	0.003	0.009	0.045	0.120	0.179	0.253	0.119	0.073	0.002	0.002	0.000	0.026	0.013	0.006	0.142

Note:

1. e_j denotes the entropy value of the jth criterion, d_j represents its divergence measure, and w_j indicates the final entropy-based weight reflecting the relative importance of that criterion.
2. The total divergence across all criteria was calculated as $\sum d_j = 0.855$ and the normalization constant as $\frac{1}{\ln(6)} = 0.558$.

Table K.4. Aggregated entropy-based weights of thematic groups (Equation 4.6).

Sludge Management & Disposal Impact	0.020
Chemical Burden & Toxicity	0.789
Treatment Efficiency & Organic Load Management	0.004
Systemic & Long-term Environmental Robustness	0.187
Σ	1

Table K.5. Normalized decision matrix for TOPSIS analysis (Equation 4.7) – r_{ij} Calculation I.

Scenario & Coagulant Code	Sludge Management & Disposal Impact				Chemical Burden & Toxicity						Treatment Efficiency & Organic Load Management			Systemic & Long-term Environmental Robustness			
														Metal Residual Persistence and Toxicity (Al, Fe, Cr)			
	Sludge Volume	Moisture Content	Dry Solid Yield	Disposal Compatibility	Active Aluminum Dose	Residual Al in Effluent	Residual Fe in Effluent	Residual Total Cr in Effluent	pH Regulator Requirement	Total Coagulant Dose	COD Removal	TOC Removal	TSS Removal	Residual Al in Sludge	Residual Fe in Sludge	Residual Total Cr in Sludge	Polymer Biodegradability
M2 – P040102	104.416	4937.925	12.006	0.151	671846400000000.000	364.549	11.417	13.008	0.000	64000000.000	4643.365	4284.815	6685.825	67805.166	54.152	1067.553	N/A
M6 – P010300	58.230	3411.335	7.966	0.343	87012180993024.000	22.497	0.785	0.292	1.000	7840000.000	6658.427	6533.549	7306.380	13884.481	136.313	2227.968	0.094
M6 – P010301	56.080	3282.349	7.234	0.336	87012180993024.000	22.400	0.777	0.844	1.000	7840000.000	6301.272	6156.764	7407.447	15405.709	151.559	2442.826	0.192
M6 – P020100	51.582	2983.946	9.873	0.508	158654177640000.000	74.348	1.541	1.368	1.000	7840000.000	7173.113	7076.639	7715.937	19745.179	105.596	1683.171	0.094
M6 – P020200	61.477	3359.686	12.343	0.357	206186969260944.000	23.159	0.213	0.116	1.000	7840000.000	5578.283	5360.908	7944.804	23428.372	177.174	1494.436	0.094
M6 – P020201	59.387	3224.599	11.193	0.346	206186969260944.000	22.869	0.213	0.117	1.000	7840000.000	5235.611	5077.563	8050.918	26042.883	200.076	1669.023	0.324
$\sum$	391.171	21199.840	60.616	2.041	141689887814794000.000	529.822	14.946	15.745	5.000	103200000.000	35590.071	34490.238	45111.31	166311.791	824.870	10584.977	0.797
$\sqrt{(\sum)}$	19.778	145.602	7.786	1.428	37641717.258	23.018	3.866	3.968	2.236	10158.740	188.653	185.715	212.394	407.813	28.721	102.883	0.893

Table K.6. Normalized decision matrix for TOPSIS analysis (Equation 4.7) – r_{ij} Calculation II.

Scenario & Coagulant Code	Sludge Management & Disposal Impact				Chemical Burden & Toxicity						Treatment Efficiency & Organic Load Management			Systemic & Long-term Environmental Robustness			
														Metal Residual Persistence and Toxicity (Al, Fe, Cr)			
	Sludge Volume	Moisture Content	Dry Solid Yield	Disposal Compatibility	Active Aluminum Dose	Residual Al in Effluent	Residual Fe in Effluent	Residual Total Cr in Effluent	pH Regulator Requirement	Total Coagulant Dose	COD Removal	TOC Removal	TSS Removal	Residual Al in Sludge	Residual Fe in Sludge	Residual Total Cr in Sludge	Polymer Biodegradability
M2 – P040102	0.517	0.483	0.445	0.272	0.689	0.829	0.874	0.909	0.000	0.787	0.361	0.352	0.385	0.639	0.256	0.318	N/A
M6 – P010300	0.386	0.401	0.363	0.410	0.248	0.206	0.229	0.136	0.447	0.276	0.433	0.435	0.402	0.289	0.407	0.459	0.343
M6 – P010301	0.379	0.393	0.345	0.406	0.248	0.206	0.228	0.232	0.447	0.276	0.421	0.423	0.405	0.304	0.429	0.480	0.490
M6 – P020100	0.363	0.375	0.404	0.499	0.335	0.375	0.321	0.295	0.447	0.276	0.449	0.453	0.414	0.345	0.358	0.399	0.343
M6 – P020200	0.396	0.398	0.451	0.418	0.381	0.209	0.119	0.086	0.447	0.276	0.396	0.394	0.420	0.375	0.463	0.376	0.343
M6 – P020201	0.390	0.390	0.430	0.412	0.381	0.208	0.119	0.086	0.447	0.276	0.384	0.384	0.422	0.396	0.492	0.397	0.638

Table K.7. Weighted normalized decision matrix (Equation 4.8).

Scenario & Coagulant Code	Sludge Management & Disposal Impact				Chemical Burden & Toxicity						Treatment Efficiency & Organic Load Management			Systemic & Long-term Environmental Robustness			
														Metal Residual Persistence and Toxicity (Al, Fe, Cr)			
	Sludge Volume	Moisture Content	Dry Solid Yield	Disposal Compatibility	Active Aluminum Dose	Residual Al in Effluent	Residual Fe in Effluent	Residual Total Cr in Effluent	pH Regulator Requirement	Total Coagulant Dose	COD Removal	TOC Removal	TSS Removal	Residual Al in Sludge	Residual Fe in Sludge	Residual Total Cr in Sludge	Polymer Biodegradability
M2 – P040102	0.00251	0.00111	0.00144	0.00257	0.03075	0.09935	0.15655	0.23004	0.00000	0.05763	0.00064	0.00080	0.00012	0.01668	0.00332	0.00183	N/A
M6 – P010300	0.00188	0.00093	0.00118	0.00388	0.01107	0.02468	0.04105	0.03447	0.05324	0.02017	0.00077	0.00099	0.00013	0.00755	0.00527	0.00265	0.04872
M6 – P010301	0.00184	0.00091	0.00112	0.00383	0.01107	0.02463	0.04084	0.05860	0.05324	0.02017	0.00075	0.00096	0.00013	0.00795	0.00556	0.00277	0.06967
M6 – P020100	0.00177	0.00087	0.00131	0.00472	0.01495	0.04487	0.05751	0.07460	0.05324	0.02017	0.00080	0.00103	0.00013	0.00900	0.00464	0.00230	0.04872
M6 – P020200	0.00193	0.00092	0.00146	0.00396	0.01704	0.02504	0.02138	0.02169	0.05324	0.02017	0.00070	0.00089	0.00013	0.00980	0.00601	0.00217	0.04872
M6 – P020201	0.00190	0.00090	0.00139	0.00389	0.01704	0.02488	0.02139	0.02180	0.05324	0.02017	0.00068	0.00087	0.00013	0.01034	0.00638	0.00229	0.09061

Table K.8. Determination of positive (A^+) and negative (A^-) ideal solutions for TOPSIS (Equation 4.9a, Equation 45.9).

			PIS	NIS
Sludge Management & Disposal Impact	Sludge Volume		0.00177	0.00251
	Moisture Content		0.00087	0.00111
	Dry Solid Yield		0.00112	0.00146
	Disposal Compatibility		0.00472	0.00257
Chemical Burden & Toxicity	Active Aluminum Dose		0.01107	0.03075
	Residual Al in Effluent		0.00190	0.09935
	Residual Fe in Effluent		0.02138	0.15655
	Residual Total Cr in Effluent		0.02169	0.23004
	pH Regulator Requirement		0.05324	0.00000
	Total Coagulant Dose		0.02017	0.05763
Treatment Efficiency & Organic Load Management	COD Removal		0.00080	0.00064
	TOC Removal		0.00103	0.00080
	TSS Removal		0.00013	0.00012
Systemic & Long-term Environmental Robustness	Metal Residual Persistence and Toxicity (Al, Fe, Cr)	Residual Al in Sludge	0.00755	0.01668
		Residual Fe in Sludge	0.00332	0.00638
		Residual Total Cr in Sludge	0.00183	0.00277
	Polymer Biodegradability		0.09061	0.04872

Note: PIS (*Positive Ideal Solution*) represents the optimal environmental performance scenario, where benefit-type criteria take their maximum values and cost-type criteria take their minimum values. NIS (*Negative Ideal Solution*) represents the least desirable environmental performance scenario, where benefit-type criteria take their minimum values and cost-type criteria take their maximum values.

Table K.9. Distance of each alternative from the positive ideal solution (S^+) (Equation 4.10a).

Scenario & Coagulant Code	Sludge Management & Disposal Impact				Chemical Burden & Toxicity						Treatment Efficiency & Organic Load Management			Systemic & Long-term Environmental Robustness				S_i^+
	Sludge Volume	Moisture Content	Dry Solid Yield	Disposal Compatibility	Active Aluminum Dose	Residual Al in Effluent	Residual Fe in Effluent	Residual Total Cr in Effluent	pH Regulator Requirement	Total Coagulant Dose	COD Removal	TOC Removal	TSS Removal	Metal Residual Persistence and Toxicity (Al, Fe, Cr)			Polymer Biodegradability	
														Residual Al in Sludge	Residual Fe in Sludge	Residual Total Cr in Sludge		
M2 - P040102	5.57984E-07	6.15661E-08	1.04436E-07	4.587E-06	0.000388	0.009498	0.018271	0.043407	0.002834	0.001403	2.41435E-08	5.17494E-08	1.35709E-10	8.33825E-05	0	0	N/A	0.2755
M6 - P010300	1.21891E-08	3.59617E-09	3.06867E-09	7.03757E-07	0	0.000519	0.000387	0.000163	0	0	8.44178E-10	1.6103E-09	3.86782E-11	0	3.79546E-06	6.6316E-07	0.001755	0.0532
M6 - P010301	5.68766E-09	1.78817E-09	0	7.75496E-07	0	0.000517	0.000379	0.001362	0	0	2.48823E-09	4.75516E-09	2.86969E-11	1.6218E-07	4.99558E-06	8.81698E-07	0.000439	0.0520
M6 - P020100	0	0	3.55817E-08	0	1.50333E-05	0.001847	0.001305	0.002799	0	0	0	0	7.6225E-12	2.1113E-06	1.73352E-06	2.1923E-07	0.001755	0.0879
M6 - P020200	2.62542E-08	2.80146E-09	1.17847E-07	5.7793E-07	3.56363E-05	0.000536	0	0.000000	0	0	8.82366E-09	1.76644E-08	7.53875E-13	5.09232E-06	7.21622E-06	1.1253E-07	0.001755	0.0484
M6 - P020201	1.66308E-08	1.17361E-09	7.47461E-08	6.78792E-07	3.56363E-05	0.000528	4.54424E-11	1.23729E-08	0	0	1.34121E-08	2.45897E-08	0	7.77962E-06	9.38068E-06	2.10254E-07	0	0.0241

Table K.10. Distance of each alternative from the negative ideal solution (S^-) (Equation 4.10b).

Scenario & Coagulant Code	Sludge Management & Disposal Impact				Chemical Burden & Toxicity						Treatment Efficiency & Organic Load Management			Systemic & Long-term Environmental Robustness				S_i^-
														Metal Residual Persistence and Toxicity (Al, Fe, Cr)				
	Sludge Volume	Moisture Content	Dry Solid Yield	Disposal Compatibility	Active Aluminum Dose	Residual Al in Effluent	Residual Fe in Effluent	Residual Total Cr in Effluent	pH Regulator Requirement	Total Coagulant Dose	COD Removal	TOC Removal	TSS Removal	Residual Al in Sludge	Residual Fe in Sludge	Residual Total Cr in Sludge	Polymer Biodegradability	
M2 - P040102	0	0	4.04957E-10	0	0	0	0	0	0	0	0	0	0	0	9.38068E-06	8.816978E-07	N/A	0.0032
M6 - P010300	4.052373E-07	3.540311E-08	8.288276E-08	1.697366E-06	0.0003876	0.0055758	0.0133397	0.0382456	0.0028340	0.0014033	1.595855E-08	3.510244E-08	2.948776E-11	8.33825E-05	1.242302E-06	1.553555E-08	0	0.2487
M6 - P010301	4.510022E-07	4.236944E-08	1.178477E-07	1.590399E-06	0.0003876	0.0055838	0.0133896	0.0293914	0.0028340	0.0014033	1.113022E-08	2.513099E-08	3.959544E-11	7.619E-05	6.851002E-07	0	0	0.2313
M6 - P020100	5.579844E-07	6.156611E-08	2.391901E-08	4.587E-06	0.0002499	0.0029686	0.0098102	0.0241615	0.0028340	0.0014033	2.414355E-08	5.174944E-08	7.900633E-11	5.89574E-05	3.049006E-06	2.216202E-07	0.0004387	0.2037
M6 - P020200	3.421699E-07	3.810116E-08	0	1.908558E-06	0.0001882	0.0055221	0.0182713	0.0434066	0.0028340	0.0014033	3.775778E-09	8.944902E-09	1.162344E-10	4.72627E-05	1.417402E-07	3.642502E-07	0	0.2677
M6 - P020201	3.819502E-07	4.573911E-08	4.884855E-09	1.736711E-06	0.0001882	0.0055455	0.0182695	0.0433603	0.0028340	0.0014033	1.565866E-09	4.994811E-09	1.357009E-10	4.02236E-05	0	2.308335E-07	0.0017546	0.2709

Table K.11. Calculation of the closeness coefficient (C_i) and final ranking of alternatives (Equation 4.11).

Scenario & Coagulant Code	C_i
M2 - P040102	0.0115
M6 - P010300	0.8238
M6 - P010301	0.8165
M6 - P020100	0.6986
M6 - P020200	0.8470
M6 - P020201	0.9182