



**REPUBLIC OF TÜRKİYE
ADANA ALPARSLAN TÜRKES SCIENCE AND TECHNOLOGY
UNIVERSITY**

**GRADUATE EDUCATION INSTITUTE
DEPARTMENT OF FOOD ENGINEERING**

**ASSESSMENT OF PROCESSING OF SOME FRUIT AND VEGETABLE
PRODUCTS USING EXERGY AND LIFE CYCLE ANALYSES**

**SAMIYE ADAL
PhD THESIS**

ADANA 2024



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**THESIS ADVISOR
PROF.DR. ZAFER ERBAY**

ADANA, 2024

ABSTRACT

ASSESSMENT OF PROCESSING OF SOME FRUIT AND VEGETABLE PRODUCTS USING EXERGY AND LIFE CYCLE ANALYSES

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PhD, Department of Food Engineering

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Food processing is a highly energy-consuming procedure that frequently has environmental effects that cannot properly identified or measured. The food business, particularly food processing, is widely recognized for its significant dependency on resources and energy, resulting in notable environmental consequences. On the other hand, food is an essential necessity for humans, and the adoption of sustainable practices in food production has gained significant importance in contemporary times. Identifying and quantifying the inefficiencies in food production processes and proposing improvements that can lead to more sustainable production practices by combining exergy analysis with life cycle analysis (LCA), which can provide a more detailed understanding of the environmental impacts and energy efficiency of food processing operations is a relatively new, effective and feasible approach. This thesis presents a comprehensive assessment of the production processes of selected products in the fruit and vegetable processing sector using cumulative energy, exergy, carbon dioxide (CO₂) emissions, and LCA with a farm to fork and cradle to gate approach. In order to achieve these goals, a thorough analysis of the different stages of production, such as the farming, processing, and packaging and transportation processes, is carried out. Energy, exergy, CO₂ emissions, and LCA metrics have been calculated as a base case, for each stage of production in order to identify hotspots for energy, exergy consumption, and environmental impact. The two most widely consumed raw materials, tomato and sweet red pepper (SRP), were selected as representatives of the global fruit and vegetable sector. The study examined the processed tomato products, including retail tomatoes, tomato juice, tomato paste, and sweet red pepper products such as retail SRP, SRP paste, roasted SRP, and dried SRP. Of all the calculated parameters, the farming and packaging-transportation steps emerged as the primary contributors among the production steps. Diesel consumption, electricity, natural gas,

fertilizer use, steel, and glass packaging as inputs; evaporation, sterilization, and aseptic filling as equipment have been determined to be the major contributors of all evaluated metrics among all components examined in the study. Abiotic (fossil) depletion (AFDP), global warming potential, fresh water aquatic ecotoxicity, and human toxicity potentials were determined to have the highest environmental implications among the life cycle impact categories. It is observed that the base case exhibits the highest values for cumulative energy consumption (CEnC), cumulative exergy consumption (CExC), and cumulative carbon dioxide emission (CCO₂C) and LCA. Conversely, the biodiesel scenario (BD) demonstrates the lowest values, followed by the precision farming scenario (PF). The application of BD has resulted in a decrease in the cumulative energy value from 3320.12 MJ/ton to 1380.40 MJ/ton in retail tomato production. Considering the application of PF in tomato farming, there is a reduction of 14.7% in the CEnC value. Global warming potential required to produce one metric ton of fresh tomato in study is 120 kg CO₂-eq. On the other hand, the primary factor contributing to all evaluated metrics of retail SRP is the utilization of fertilizers possessing CEnC, CExC, and CCO₂C values of 87%, 71%, and 32% respectively. One ton of fresh SRP results in the emission of 39.82 kg/ton of CO₂, with CEnC and CExC values of 2742.20 MJ/ton and 1387.91 MJ/ton, respectively. It is recommended to increase the use of biodiesel in factory processing and transportation. Increasing consumer awareness of the adverse impacts that various farming methods and packaging materials have on the environment can stimulate the market for sustainably produced goods. The implications of these findings are significant for industry stakeholders who want to improve energy efficiency and lessen their environmental impact. By illustrating how energy and life cycle analyses can be used practically to identify and mitigate inefficiencies in food production processes, this study promote the field of sustainable food production. Subsequent investigations ought to concentrate on the execution of the suggested enhancements and their enduring consequences on production effectiveness and ecological implications. To further improve process sustainability, future studies should apply these techniques to a wider range of products and investigate cutting-edge technologies.

Keywords: Energy efficiency, Environmental impact, Exergy analysis, Fruit and vegetable processing, Life cycle analysis

ÖZET

BAZI MEYVE VE SEBZE ÜRÜNLERİNİN İŞLENMESİNİN EKSERJİ VE YAŞAM DÖNGÜSÜ ANALİZLERİ KULLANILARAK DEĞERLENDİRİLMESİ

Samiye ADAL

Doktora, Gıda Mühendisliği Anabilim Dalı

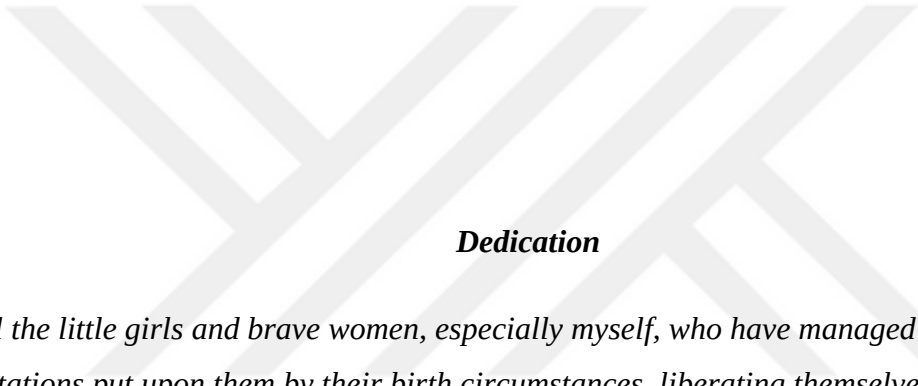
Danışman: Prof. Dr. Zafer ERBAY

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Gıda işleme, yüksek oranda enerji tüketimine dayanan ve çevresel etkileri sıklıkla doğru şekilde tanımlanamayan veya ölçülemeyen bir süreçtir. Gıda sektörü, özellikle de gıda işleme, kaynaklara ve enerjiye olan önemli bağımlılığı ile bilinmektedir ve bu da kayda değer çevresel sonuçlara yol açmaktadır. Öte yandan, gıda insanoğlunun en hayati ihtiyaçlarından birisidir ve gıdaların üretimi sırasında sürdürülebilirlik yaklaşımı günümüzde oldukça önem kazanmıştır. Ekserji analizini yaşam döngüsü analizi (YDA) ile birleştiren yaklaşım, gıda üretim süreçlerindeki verimsizlikleri belirlemek ve ölçmek ve daha sürdürülebilir üretim uygulamalarına yol gösterici iyileştirmeler önermek, gıda işleme operasyonlarının çevresel etkileri ve enerji verimliliği hakkında daha ayrıntılı bir anlayış sağlayabilecek görece yeni, etkili ve uygulanabilirdir. Bu tez çalışmasında, meyve ve sebze işleme sektöründe belirli ürünlerin üretim süreçlerinin tarladan sofraya ve beşikten kapıya yaklaşımıyla kümülatif enerji, ekserji ve YDA kullanılarak, kapsamlı bir değerlendirme yapılmıştır. Bu hedeflere ulaşmak için, tarım, işleme, paketlenme ve nakliye süreçleri gibi üretimin farklı aşamalarının geniş ölçekte analizi gerçekleştirilmiştir. Enerji, ekserji, karbondioksit (CO₂) emisyonları ve YDA değerleri; enerji, ekserji tüketimi ve çevresel etki için kritik noktaları belirlemek amacıyla, üretimin her aşaması için temel durum baz alınarak hesaplanmıştır. Çalışmada, küresel meyve ve sebze sektörünün temsilcileri olarak en yaygın tüketilen iki hammadde olan domates ve tatlı kırmızı biber (TKB) incelenmiştir. Çalışma, perakende domates, domates suyu, domates salçası ve perakende TKB, TKB salçası, közlenmiş TKB ve kurutulmuş TKB gibi tatlı kırmızı biber ürünleri dahil olmak üzere, işlenmiş domates ve tatlı kırmızı biber ürünlerini incelemiştir. Hesaplanan tüm parametreler arasında, tarla üretimi ve paketlenme-nakliye aşamaları, üretim aşamaları arasında birincil katkıda bulunanlar olarak ortaya çıkmıştır. Girdi olarak dizel tüketimi, elektrik, doğal gaz, gübre kullanımı, çelik ve cam

ambalaj; ekipman olarak buharlaştırma, sterilizasyon ve aseptik dolum, çalışmada incelenen tüm bileşenler arasında değerlendirilen tüm göstergelerin başlıca katkı sağlayıcıları olarak belirlenmiştir. Abiyotik (fossil) tükenme potansiyeli, küresel ısınma potansiyeli, tatlı su sucul ekotoksitesi, ve insan toksisitesi potansiyellerinin yaşam döngüsü etki kategorileri arasında en yüksek çevresel etkilere sahip olduğu belirlenmiştir. Temel senaryoda (TS), kümülatif enerji tüketimi (CEnC), kümülatif ekserji tüketimi (CExC) ve kümülatif karbondioksit tüketimi (CCO₂C) ve YDA için en yüksek değerlerin elde edildiği gözlemlenmiştir. Buna karşılık, biyodizel senaryosu (BS) en düşük değerleri gösterirken, bunu hassas uygulamalı tarım senaryosu (HUT) takip etmektedir. BS uygulaması, perakende domates üretiminde kümülatif enerji değerinin 3320.12 MJ/ton'dan 1380.40 MJ/ton'a düşmesini sağlamıştır. Domates tarımında HUT uygulaması dikkate alındığında, CEnC değerinde %14,7'lik bir azalma gerçekleşmiştir. Çalışmada bir metrik ton taze domates üretiminden kaynaklanan küresel ısınma potansiyeli değeri 120 kg CO₂ eşdeğeridir. Öte yandan, perakende TKB'nin değerlendirilen tüm ölçümlerine katkıda bulunan birincil faktör, sırasıyla %87, %71 ve %32 CEnC, CExC ve CCO₂C değerlerine sahip gübrelerin kullanılmasıdır. Bir ton taze TKB, sırasıyla 2742.20 MJ/ton ve 1387.91 MJ/ton CEnC ve CExC değerleri ile 39.82 kg/ton CO₂ emisyonuna neden olmaktadır. Fabrika işlemlerinde ve taşımacılıkta biyodizel kullanımının artırılması önerilmektedir. Çeşitli tarım yöntemleri ve ambalaj malzemelerinin çevre üzerindeki olumsuz etkileri konusunda tüketici bilincinin artırılması, sürdürülebilir şekilde üretilen ürünler için pazarı teşvik edebilir. Bu bulguların sonuçları, enerji verimliliğini artırmak ve çevresel etkilerini azaltmak isteyen endüstri paydaşları için önemli sonuçlar sunmaktadır. Enerji ve yaşam döngüsü analizlerinin gıda üretim süreçlerindeki verimsizlikleri tespit etmek ve azaltmak için pratikte nasıl kullanılabileceğini gösteren bu çalışma, sürdürülebilir gıda üretimi alanını desteklemektedir. Gelecekteki araştırmalar, önerilen iyileştirmelerin uygulanmasına ve bunların üretim etkinliği ve ekolojik etkileri üzerindeki kalıcı sonuçlarına odaklanmalıdır. Süreç sürdürülebilirliğini daha da iyileştirmek için, gelecekteki çalışmalar bu teknikleri daha geniş bir ürün yelpazesine uygulamalı ve en yeni teknolojileri araştırmalıdır.

Anahtar Kelimeler: Enerji verimliliği, Ekserji analizi, Çevresel etki, Meyve ve sebze işleme, Yaşam döngüsü analizi



Dedication

To all the little girls and brave women, especially myself, who have managed to overcome the limitations put upon them by their birth circumstances, liberating themselves from societal constraints and achieving self-actualization...

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LIST OF ABBREVIATIONS

ADP	: Abiotic depletion potential (kg Sb-eq),
AFDP	: Abiotic (fossil) depletion potential (MJ),
AP	: Acidification potential (kg SO ₂ -eq),
BC	: Base case
BD	: Biodiesel scenario
CCASAP	: Climate Change Adaptation Strategy and Action Plan
CCMSAP	: Climate Change Mitigation Strategy and Action Plan
CEnC	: Cumulative energy consumption
CExC	: Cumulative exergy consumption
CCO₂C	: Cumulative carbon dioxide emission
CFC	: Trichlorofluoromethane
C₂H₄	: Ethylene
CO₂	: Carbon dioxide
CO₂-eq	: Carbon dioxide equivalent
DB	: Dichlorobenzene
EIPRO	: Environmental Impact of products
EP	: Eutrophication potential (kg PO ₄ -eq)
EU	: European Union
FAO	: Food and Agriculture Organization
FU	: Functional unit
FWEP	: Fresh water aquatic ecotoxicity potential (kg 1.4 DB-eq)
GDP	: Gross Domestic Product
GHG	: Greenhouse gas
GP	: Glass packaging
GP-BD	: Glass packaging and biodiesel combination scenario
GWP	: Global warming (GWP100a) (kg CO ₂ -eq)
H₂O	: Water
HDPE	: High density polyethylene
HTP	: Human toxicity potential (kg 1.4 DB-eq)
IEA	: International Energy Agency
25KP	: 25 kg bulk packaging

25KP-BD	: 25 kg bulk packaging and biodiesel combination scenario
25KP-BD-PF	: 25 kg bulk packaging, biodiesel and precision farming combination scenario
LCA	: Life cycle assessment
LCI	: Life cycle inventory
LCIA	: Life cycle impact assessment
LCS	: Low Carbon Stainless
LDPE	: Low density polyethylene
N	: Nitrogen
ND	: Not defined
NDC	: Nationally Determined Contribution
N₂O	: Nitrous oxide
ODP	: Ozone layer depletion (kg CFC-11-eq)
OPA	: Oriented polyamide
P	: Phosphorus
PET	: Polyethylene terephthalate
PF	: Precision farming
PF-BD	: Precision farming and biodiesel combination scenario
PLA	: Poly-lactic acid
PO	: Phosphate
POCP	: Photochemical oxidation potential (kg C ₂ H ₄ -eq)
PS	: Polystyrene
PVC	: Polyvinylchloride
Rpm	: Revolution per minute
Sb	: Antimony
SO₂	: Sulfur dioxide
SRP	: Sweet red pepper
TEP	: Terrestrial ecotoxicity potential (kg 1.4 DB-eq)
UN	: United Nations
UNFCCC	: United Nations Framework Convention on Climate Change
WSDM	: Water-soluble dry matter

1. INTRODUCTION

Global energy demand is witnessing a rapid growth, while the availability of resources remains constrained (Hadžiahmetović, Blažević, & Peco, 2021). In the 21st century, energy has emerged as an essential necessity for humanity. All production activities necessitate energy. One of the primary concerns in the field of energy that poses a threat to the future of our society is the inefficient utilization of fossil fuels, resulting in global climate change. Another significant issue is the challenge of energy supply, which has even been a catalyst for conflicts and wars.

The UN Framework Convention on Climate Change Conference of the Parties held in Paris in December 2015 sparked a significant discussion on climate change in the 21st century, and how society should respond to its effects (Senyapar, 2023). In 2019, the ‘clean energy for all Europeans package’ was released, which updated the 2030 energy policy framework to include a target of achieving a 32.5% increase in energy efficiency and a minimum of 32% renewable energy (Ozdemir, 2023). This package has incorporated legal requirements in five specific domains: energy performance in buildings, energy efficiency, renewable energy, governance of the energy union, and electricity market design (Milčiuvienė, Kiršienė, Dohejko, Urbonas, & Milčius, 2019). The European Green Deal was introduced by European Union (EU) in late 2019. It encompasses a range of initiatives aimed at promoting a sustainable green economy and addressing climate change (The European Green Deal, 2019). The International Energy Agency (IEA) published the ‘Net Zero by 2050’ report in 2021. This study provides a concise overview of the necessary policies, technologies, and behavioral modifications required to attain a net zero energy system within a span of thirty years. Furthermore, it has been asserted that, the energy sector assumes a pivotal role in the process of decarbonizing the global economy (Dechamps, 2023).

Fossil fuels account for 88.2% of Türkiye's overall energy consumption. Lowering carbon dioxide (CO₂) emissions is also of utmost significance in attaining sustainable growth in Türkiye, a prospective member of the EU that aspires to rank among the top 10 largest economies globally (Pata, 2018). Türkiye became a member of the United Nations Framework Convention on Climate Change (UNFCCC) in 2004, officially approved the Kyoto Protocol in 2009, and formally endorsed the Paris Agreement in 2016. Türkiye is quite

conscientious in fulfilling the commitments of these accords. The primary goals of Türkiye's National Climate Change Strategy (2010–2023), established in 2010, are as follows: ensuring Türkiye's compliance with its obligations under the UNFCCC, regularly monitoring greenhouse gas (GHG) emissions, and actively engaging in negotiation and collaboration initiatives aimed at combating climate change (Ozdemir, 2023). The 2017-2023 action plan aims to decrease Türkiye's main energy consumption by 14% by 2023. This will be achieved through the implementation of 55 specific measures across six categories: buildings and services, energy, transport, industry and technology, agriculture, and cross-cutting areas. Additionally, it is estimated that there will be a cumulative savings of 23.9 million ton of oil equivalent by 2023, requiring an expenditure of 10.9 billion USD (IEA, 2022). On the other hand, The Ministry of Environment, Urbanization, and Climate Change has completed the implementation period of the 2011-2023 Climate Change Strategy and Action Plan. Now, preparations have begun for a new strategy and action plan in accordance with the 2053 Net Zero Emission Target, 12th Development Plan, Medium Term Program, Nationally Determined Contribution (NDC), and Climate Summit Decisions. In order to achieve the stated NDC targets, the Directorate of Climate Change has developed two distinct strategy and action plans for the period of 2024-2030. These plans outline Türkiye's roadmaps for addressing climate change through both mitigation and adaptation measures. The purpose of these publications is to define common goals for addressing climate change and working towards a sustainable future collaboratively. The 2024-2030 Climate Change Mitigation Strategy and Action Plan (CCMSAP) and the 2024-2030 Climate Change Adaptation Strategy and Action Plan (CCASAP) were implemented concurrently. As part of CCMSAP, an analysis of needs was carried out on Türkiye's climate change policies, strategies, plans, and initiatives to reduce greenhouse gas emissions. Stakeholders actively participated in the identification of sector-specific plans and measures for reducing emissions. The Plan encompasses 49 strategies and 260 actions that specifically target several sectors such as industry, energy, buildings, transportation, agriculture, trash, land use, land use change, and forestry. Additionally, the Plan also addresses the important aspects of just transition and carbon pricing. Within the framework of CCASAP, country-specific climate change forecasts were utilized to study the future climate hazards, and the outcomes were assessed. Individual vulnerability and risk assessments were carried out for each sector at a national level, using these findings as a basis. A comprehensive analysis revealed a grand total of 40 strategies and 129 actions pertaining to various sectors including agriculture and food security, biodiversity

and ecosystem services, water resources management, tourism and cultural heritage, industry, urban areas, social development, public health, transportation and communication, energy, disaster risk reduction, and cross-cutting issues (DCC, 2024)

Energy is regarded as the primary and essential input in the production process, and it is utilized with the identical intensity as capital and labor. Given the extensive use of energy in the industrial sector, a consistent and ongoing energy supply is necessary to maintain and improve the current levels of production and living standards in any country, regardless of its status whether it is developing, emergent, prosperous or industrialized (Rehman, Ma, Ozturk, & Ulucak, 2022). Utilization of energy enables the growth of the economy. During the swift progress of the global economy, substantial amounts of CO₂ have been released through the combustion of fossil fuels for energy purposes, resulting in global warming emerging as one of the most critical concerns (Zheng, Yuan, Baninla, Zhang, Stenseth, & Ma, 2020). Improvements in energy efficiency are considered an essential means to mitigating global warming and attaining the goals of sustainable development. The global energy consumption in 2020 was predominantly driven by the 10 leading energy-consuming nations, who collectively contributed to 66.8% of the total global energy consumption (Wang, Lu, Chen, Yi, & Cui, 2024). There are three primary fossil fuels, namely coal, natural gas, and oil, which collectively contribute almost equal proportions to the global energy consumption (Reader, 2019).

Development depends on the presence of energy, and for sustainable development , the utilization of sustainable energy technology is essential. Three crucial modifications required to attain sustainable energy development encompass emissions mitigation, substitution of fossil fuel-dependent electricity generation with renewable energy sources, and enhancement of energy efficiency (Østergaard, Duic, Noorollahi, Mikulcic, & Kalogirou, 2020). Sustainable sources of energy must not release any pollutants or, at most, release them in managed amounts. This is to prevent any potential harm to the environment caused by human-induced climate change and to finally eliminate the negative consequences of using fossil fuels (Reader, 2019).

Besides energy need for economic growth, environmental pollution is a major alarming issue in both developing and prosperous economies (Rehman et al., 2022). This is attributed to its

adverse impacts on the health of people, biological diversity, the protective ozone layer, the quality of the air, natural assets (such as water, soil, and forests), and the overall economy. The primary factor contributing to environmental damage is the global upward motion of CO₂ emissions, which is closely linked to the growing demand for energy consumption (Rahman, 2020). Many nations have established strategies to mitigate environmental emissions. The issue of emissions regulation and its causes have been discussed and examined in public platforms on global climate change and warming. The implementation of emissions regulations and adherence to compliance measures has been proven to reduce the severity of pollution (Rehman et al., 2022).

Industrialization is a significant contributor to the rise in CO₂ emissions, as it leads to higher energy consumption. Economists assess the growth rates of nations by analyzing the Gross Domestic Product (GDP) per capita. They observe a strong correlation between economic growth, the proportion of the industrial sector in the GDP, and the composition of the industrial sector (Pata, 2018). Over the past decade, the food industry has had significant effects from resource scarcity, as well as food loss and waste along the whole supply chain. The agro-food system has been diligently handling various important challenges, such as food security, production traceability, the quality of products, sustainability of the environment, and human resource management. Consequently, production systems are shifting towards sustainable methodologies (Sica, Malandrino, & Supino, 2018). The increasing focus from policy makers, non-governmental groups, and scholars has compelled agri-food businesses to include sustainability into their company plans (Esposito, Sessa, Sica, & Malandrino, 2020).

Regarding European strategies for sustainable production and consumption, the agri-food sector has recently assumed a special significance (Solimene, Coluccia, & Bernardo, 2023). Agriculture and food industries are two of the most important businesses on which the Turkish economy is heavily dependent on, as well. The agricultural sector in Türkiye remains the primary driver of employment, and plays a substantial role in the country's import and export activities. There has been a growing concern in utilizing energy evaluation and modeling methodologies for the purpose of conducting energy utilization evaluations, with the aim of achieving energy conservation and subsequent financial benefits. The need to enhance energy and exergy efficiency in order to reduce energy costs in this industry is driven by high energy inputs. The impact of energy input costs on production costs is widely

recognized (Sogut, Ilten, & Oktay, 2010). For these purposes, the application of thermodynamic analysis is of utmost importance in the examination of energy efficiency within industrial processes. Moreover, exergy analysis has emerged as a crucial tool for the purpose of designing, analyzing, and optimizing thermal systems. This seeks to assess the energy that is accessible at various system points and provides helpful data that enables selecting the best operating conditions and design parameters for engineering systems (Castro, Roman, Echegaray, Mazza, & Rodriguez, 2018).

Life cycle assessment (LCA), a widely used tool for examining the environmental implications of the food system (Ghnimi, Nikkhah, Dewulf, & Van Haute, 2021). LCA (ISO, 2006a), on the other hand, is a method utilized to measure the environmental impacts across the entire life cycle of a product or process. It allows for the assessment of contributions to various impact categories and the evaluation of resource usage. Assessments of the life cycle environmental impacts of the production of food, including agriculture and processing, along the supply chain enhance knowledge of the environment and highlight crucial production systems (Ghnimi et al., 2021). From this viewpoint, conducting LCA studies can serve as an essential decision-making tool for devising suitable strategies to manage the entire life cycle of products and enhance their environmental performance. The objective is to encourage the transition towards sustainable agriculture, farming, and food production systems, ultimately promoting more sustainable patterns of food consumption (Del Borghi, Moreschi, & Gallo, 2020). The evaluation of environmental impacts and resource management throughout the whole life cycle of food items has become crucial in the production of sustainable goods (Manfredi & Vignali, 2014). This method is becoming more common for examining the environmental effects of agricultural productions. Several examples of products that have undergone LCA include tomato-based product processing (Shahvarooghi Farahani, Soheilifard, Ghasemi Nejad Raini, & Kokei, 2019), olive oil production (Espadas-Aldana, Vialle, Belaud, Vaca-Garcia, & Sablayrolles, 2019), tea production (Soheili-Fard, Kouchaki-Penchah, Raini, & Chen, 2018), whole peeled canned tomato production (Garofalo, D'Andrea, Tomaiuolo, Venezia, & Castrignanò, 2017), pasta production (Heidari, Huijbregts, Omid, Rafiee, & van Zelm, 2017), legume processing and packaging (Del Borghi, Strazza, Magrassi, Taramasso, & Gallo, 2018), and apple juice production (Khanali, Kokei, Aghbashlo, Nasab, Hosseinzadeh-Bandbafha, & Tabatabaei, 2020) .

The agricultural sector in Türkiye is of great economic importance as it contributes to the country's net foreign currency inflow through exports and also creates employment possibilities in adjacent areas such as production, packaging, and logistics. The fresh fruits and vegetables sector holds great importance as a sub-sector within agriculture. Türkiye has a prominent role in the global production and trading of fresh fruits and vegetables exporting roughly 4.7 million tons and generating around 3.5 billion dollars in revenue yearly. The primary product categories under this industry include of fresh citrus, fresh fruits, and fresh vegetables. Turkey exports to almost 160 countries, with its primary customers being the Russian Federation, Germany, Romania, Iraq, Ukraine, Poland, Bulgaria, and the Netherlands. The sector has begun expanding its export markets and has made efforts to include Far East countries as new export destinations (MEA, 2023). Upon conducting research in the thesis archive of the Turkish Higher Education Institution, only two theses related to food are discovered. One of the topics is about İzmir tulum cheese, while the other is about sugar. The present study will provide new perspectives on food industry procedures regarding the processing of fruits and vegetables. The objective of this study is to analyze and report the energy, exergy, CO₂ emission, and LCA results with a holistic approach-from an extensive investigation conducted on fruit and vegetable sector-since the food industry and food processing in particular, is well known for requiring a lot of energy and resources, energy efficiency studies as well as mitigation of the environmental effects of food processing are imperative. The objective is to comprehensively consider the complete manufacturing process and examine the energy and exergy consumption, as well as seeking to minimize the environmental impact of the products. From farm to fork and cradle to factory gate, the study has been conducted along the supply chain. The environmental hotspots of the researched items have been discovered, and various scenarios have been tested by modifying the variables that have the greatest impact on the investigated metrics. Tomato (*Solanum lycopersicum*) and sweet red pepper (*Capsicum annuum*) were chosen as raw materials for this purpose, and their fresh and processed products have been researched in terms of energy, exergy, CO₂ emission, and LCA.

2. THEORETICAL FUNDAMENTALS AND LITERATURE REVIEW

2.1. An Overview of Food Processing with an Emphasis on the Fruit and Vegetable Sector

The food processing industry is a significant and prosperous sector on a global scale. The processing of foods is a component of a manufacturing process that involves the conversion of animal, plant, and marine materials into intermediate or completed value-added food items, which are designed to be safer for consumption. The achievement of the intended transformation necessitates the utilization of labor, energy, machinery, and scientific knowledge in a single step (unit operation) or a sequence of steps (process) (Heldman & Hartel, 1998). Food products, including fruits, vegetables, fats, oils, sugars, dairy, meat, coffee, chocolate, meal, and flours, are intricate combinations of vitamins, carbohydrates, proteins, lipids, fibers, smells, colors, antioxidants, and various organic and mineral compounds. Prior to commercialization, these products must undergo processing and preservation for the purpose of being used in food ready meals, as well as extraction for use as food ingredients. There are various techniques that can be employed for this objective, such as frying, drying, filtering, and cooking (Chemat, Rombaut, Meullemiestre, Turk, Perino, Fabiano-Tixier, & Abert-Vian, 2017).

The depth of food processing encompasses several unit operations that take place from the harvest of raw materials to their transformation into food items, packaging, and subsequent transport for retail purposes. These operations can be seen as integral components of the broader scope of food processing. The majority of food processing methods employ six distinct unit operations including heat transfer, fluid movement, mass transfer, mixing, size adjustment (reduction or expansion), and separation. Food processing involves the combination of food material with various ingredients, such as sugar, preservatives, and acidity, to create a product. This product is then exposed to multiple unit operations, either in a sequential or simultaneous manner (Heldman & Hartel, 1998). These processes can be broadly classified into primary and secondary processing. Primary processing refers to the post-harvest or post-slaughter preparation of food to prepare it for consumption or use in other food products. Primary processing plays a crucial role in facilitating the transportation and

readiness of foods for sale, consumption, or transformation into various other products. For instance, following the initial stages of peeling and slicing, an apple can be consumed in its fresh form or transformed into a pie by baking. Secondary processing is the transformation of primary-processed food or ingredients into various products within the food industry. It guarantees that foods have multiple uses, do not perish rapidly, are nutritious and complete to consume, and are accessible throughout the year (such as seasonal foods) (Park, Lamsal, & Balasubramaniam, 2014).

Several food processing procedures enhance the appeal, flavor, safety, and consumability of food products. Various food-processing techniques are commonly employed in the industry. These techniques encompass pasteurization, sterilization, cooking, drying, cooling and freezing, fermentation, adding preservatives, reducing water activity, and employing multiple techniques to impede or halt chemical, biochemical, and microbiological activities. The majority of food products that are commercially available undergo various forms of thermal processing (Teixeira & Tucker, 1997). The methods of sterilization and pasteurization include the application of heat to render enzymatic and microbial activity in food inactive or eradicate it (Wang & Sun, 2012). Pasteurization and sterilization are major industrial thermal food processing procedures used to produce canned products. Pasteurization is the technique of heating liquids or solids to eliminate microorganisms that live in aerobic conditions and reduce deterioration from high acidic meals ($\text{pH} < 4.5$). To prevent spore-forming microorganisms from growing, refrigerate foods are produced by this procedure at low temperatures when $\text{pH} > 4.5$. Commercial sterilizing involves intense heat treatment to eradicate pathogens, vegetative microorganisms, and many of the spore-forming bacteria in low acid foods ($\text{pH} > 4.5$) (Tola & Ramaswamy, 2012). Cooking, which encompasses baking, roasting, and frying, is a thermal procedure employed to modify the palatability of food items and eliminate microorganism and enzymes, so ensuring food safety. Dehydration and drying are thermal procedures employed to eliminate a significant portion of water content in food products through evaporation (or sublimation in the case of freeze drying). This method aims to prolong the shelf life of food items by diminishing their water activity (Wang & Sun, 2012).

The field of food technology, particularly in harsh or non-classical situations, is currently experiencing significant growth and advancement in both applied research and industry.

Exploring alternative methods for processing, preserving and extracting can enhance production efficiency and aid in environmental conservation. This can be achieved by minimizing water and solvent usage, eliminating effluent, fossil energy consumption, and the formation of harmful compounds (Chemat et al., 2017). One of the foremost issues that lie ahead pertains to the availability of electricity, clean freshwater, and sufficient food for all individuals, while ensuring that these resources are both reasonably priced and sustainable. Food process engineering is directly or indirectly involved in all three of these primary concerns. Renewable energy sources rely on agricultural commodities, so giving rise to a novel rivalry for the utilization of farmland in the context of food production (Schubert, Schuchmann, Engel, & Knoerzer, 2013).

On the other hand, food is an essential necessity for humans, and the adoption of sustainable practices in food production has gained significant importance in contemporary times. The food business, particularly food processing, is widely recognized for its significant dependency on resources and energy, resulting in notable environmental consequences (Smith & Lal, 2022). The food industry utilizes a substantial quantity of energy for conducting diverse heating and/or cooling procedures, during which a notable portion of energy is irreversibly dissipated as waste heat. The majority of energy in the food sector is allocated towards the generation of heat energy, accounting for around 59%. This heat energy is mostly derived from fossil fuels. Around 16% and 12% of power is utilized for cooling processes and various motor drives (Josijević, Šušteršič, & Gordić, 2020). The majority of heat energy is allocated towards the processes of baking, drying, and pasteurization. Cooking and heating predominantly rely on the use of electricity, whereas cooling activities account for 31% of its usage, with the remaining portion being allocated to electric motor operations operate at a speed of 25% (Hadžiahmetović et al., 2021).

Food processing is a highly energy-consuming procedure that frequently has environmental effects that are not properly identified or measured. It consists of both organized and unorganized sectors, each with different levels of energy use and thus differing carbon footprints. Energy consumption in food production primarily occurs at four levels: agriculture, transportation, food processing, and food handling (Kumar & Chakabarti, 2019). Agriculture, which involves the cultivation of raw materials for food processing, requires energy for food production. The three primary dimensions of sustainable agriculture are

human society, economics, and environment (S. Gorjian, Fakhraei, Gorjian, Sharafkhani, & Aziznejad, 2022). In order to achieve sustainability, agriculture must be sustainable by meeting the requirements of current and future generations, while also guaranteeing profitability, environmental well-being, and social and economic fairness. Sustainable food and agriculture plays a role in all aspects of food security, including availability, access, usage, and stability. It also encompasses the dimensions of sustainability, which include environmental, social, and economic factors (FAO, 2021). Energy is expended in the processes of transportation and food processing. This suggests that there is a need to enhance the energy use efficiency during the handling and transportation processes (Gorjian et al., 2022).

The primary factors propelling the transition towards sustainable food processing encompass legislative, economic, consumer, and corporate-oriented drives (Murphy, McDonnell, & Fagan, 2014). Environmental and societal concerns have made sustainability a crucial need for food industry companies' success. Businesses feel forced to prioritize matters such as limited resources, global warming, and inequality in society and the economy due to sustainability concerns. Consequently, scholars and practitioners have shown significant interest in innovation for sustainability (Yang, Vladimirova, & Evans, 2017). A sustainable and resilient production and supply chain is vital also for a food item, such as fruits and vegetables, that cannot be stored for a long time and depend on a continuous supply (Huang, Guan, & Hammami, 2022). The growing need for sustainable products, together with environmental and social considerations, forced also the fruit and vegetable industries to transition from traditional to innovative, sustainable business models by adopting sustainability practices (Mili & Loukil, 2022). One of the major problems is to minimize water and energy consumption, while maximizing the efficiency of water and energy utilization in food sector operations (Ramírez, Castañón-Rodríguez, & Uresti-Marín, 2020).

Fruits and vegetables are fundamental elements of culinary traditions, serving a crucial function in supplying fresh, nourishing, and healthful food to consumers across various age groups globally (Wallace, Bailey, Blumberg, Burton-Freeman, Chen, Crowe-White, & Wang, 2020). The implementation of sustainable diets represents a significant global challenge in the 21st century. The current worldwide supply of fruits and vegetables is inadequate, and there is a notable surplus of high-energy foods, particularly sugar, cereals, and oils. This is despite the

fact that global agriculture sufficiently supplies enough calories for the existing global population (Kc, Dias, Veeramani, Swanton, Fraser, Steinke, & Dunfield, 2018). Due to the seasonal nature of fruits and vegetables, which are only available for a limited time, traditional post-harvest processes and processing have been focused on ensuring the long-term availability of safe fruits and vegetables. This is done to promote a more varied diet throughout the year. The utilization of traditional processing techniques has resulted in enhanced sensation, particularly in relation to texture, transportation stability, and consumer convenience. While it is theoretically possible to enhance the nutritional value through minimal processing, achieving a balance between safety, preservation of micronutrients, and energy costs poses significant challenges in practical applications (Liu, Le Bourvellec, Yu, Zhao, Wang, Tao, & Hu, 2022). Fresh fruits and vegetables are goods that are highly hydrated, perishable, and sensitive. Consequently, there is an increased need for reliable and safe preservation throughout the supply chain (Davis, Downs, & Gephart, 2021).

Over the last decade, there has been an incredible increase in the consumption of fruits and processed items. Fruit consumption is on the rise, due to increased understanding of its health advantages, including fiber, antioxidants, vitamins, minerals, and phytochemicals. Year-round, food stores provide fresh and processed foreign foods in canned, frozen, dried, fermented, pickled, and jam/jelly/marmalade forms. Fruits are widely available throughout the year in developed countries, and international trade has made tropical fruits more affordable. Fruits are used in a variety of processed meals, including juice mixes, snacks, and infant food. Fruit processing technology advancements are typically driven by consumer demand or increased efficiency. Fresh, ready-to-eat fruit preparations are replacing traditional methods like canning, freezing, and dehydration. Modified atmospheres and irradiation can extend the shelf life of products (Oke, Jacob, & Paliyath, 2012).

Vegetables and fruits share numerous similarities in composition, harvesting, storage, and processing. In the context of botany, numerous vegetables are classified as fruits. Therefore, tomatoes, cucumbers, eggplant, peppers, and other similar plants can be classified as fruits, as fruits are the plant parts that contain seeds. However, the crucial differentiation between fruits and vegetables is predicated upon their respective use. Vegetables are commonly regarded as botanical components that be consumed alongside the primary course of a meal, while fruits are typically consumed autonomously or as a final indulgence. Vegetables can be processed

through several methods, including canning, freezing, freeze-drying, pickling, and dehydrating. The procedures employed in the processing are contingent upon the specific vegetable variety and the chosen methodology. Following the harvest, the canning process encompasses several essential steps. These steps include washing, sorting and grading, peeling, cutting and sizing, blanching, filling and brining (with brining playing a crucial role in ensuring proper filling weight and heat transfer), exhausting (which aids in maintaining a high vacuum; the exhaust temperature in the center of the can should be approximately 71 °C, sealing, cooling, labeling, and storage (Oke & Paliyath, 2006). One of the main categories of processed vegetable products is vegetable juices and blends. These are liquid foods that are mostly made from vegetables as the primary ingredient. Juices are typically classified into three categories: clear juice, cloudy juice, and pulpy juice. These categories are based on the appearance of the juice, which is determined by the amount and size of insoluble solids.

Tomatoes are a major agricultural crop worldwide. *Lycopersicum esculentum*, the cultivated tomato plant, is a member of the *Solanaceae* family of nightshades. Although technically a yearly plant, it is commonly planted as an annual. Tomatoes, while technically classified as a fruit, are widely regarded as a vegetable by consumers (Shen & Wu, 2018). In 2021, global fruit and vegetable production increased to 910 million tonnes (+1.1 percent from 2020) and 1.2 billion tons (+1.4 percent). Between 2000 and 2021, global fruit output increased by 59 percent, reaching 910 million tonnes. In 2021, bananas produced the most fruit (125 million tonnes), followed by watermelons (102 million tonnes), apples (93 million tonnes), oranges (76 million tonnes), and grapes (74 million tonnes). Vegetable production increased by 68% worldwide, reaching 1.15 billion tons by 2021. In 2021, tomatoes were the most produced vegetable (189 million tonnes), followed by onions (107 million tonnes, including shallots), cucumbers (93 million tonnes, including gherkins), cabbages (71 million tonnes), and eggplants (59 million tonnes). Tomatoes were the most popular vegetable, with a steady share of 16 percent across the time (FAO, 2022). The tomato, globally farmed crop, holds significance as a valuable vegetable, thanks to its pleasing flavor and substantial nutritional content (Wu, Si, Yan, Wu, Zhao, Zhang, & Fan, 2023). Tomatoes are widely used in human diets, due to their rich content of lycopene (Alda, Gogoasa, Bordean, Gergen, Alda, Moldovan, & Nita, 2009) vitamins A, B, and C, as well as minerals iron, calcium, and magnesium (Srivastava & Kulshreshtha, 2013). Additionally, tomatoes are a good source of dietary fiber (Frusciante, Carli, Ercolano, Pernice, Di Matteo, Fogliano, & Pellegrini, 2007).

This vegetable has the potential to be consumed either in its raw state or after undergoing various culinary preparations (Chen, Shi, Xue, & Ma, 2009).

In 2021, China emerged as the foremost global producer of fresh fruits and vegetables, with a staggering production volume of 853.9 million tons. China accounts for 41% of global fresh fruit and vegetable production. India (245.8 million tons), Türkiye (51.6 million tons), the US (50.7 million tons), and Brazil (48.3 million tons) are the next four countries in order of production, after China. Türkiye is ranked third globally in terms of production, with a total output of 51.6 million tons. Additionally, it has achieved the highest position in the international rankings. Türkiye accounts for 2.5% of the global production rate of fresh fruits and vegetables. The tomato is the highest yielding crop globally, with a staggering production of 189 million metric tons. The top tomato-producing countries globally are the People's Republic of China with 67.5 million tons, India with 21 million tons, Türkiye with 13 million tons, and the USA with 10.4 million tons (MEA, 2023). In 2021, Türkiye produced a total of 51.6 million tons of fresh fruits and vegetables on 2 million hectares of land. Tomatoes were the most produced crop, with 13 million tons, followed by apples with 4.5 million tons, and grapes came third with 3.67 million tons (MEA, 2023).

The tomato is classified as the second most prominent vegetable crop, behind the potato (Pishgar-Komleh, Akram, Keyhani, Raei, Elshout, Huijbregts, & van Zelm, 2017). However, due to its high water content, fresh harvested tomatoes are perishable. Tomatoes are not solely consumed in their raw state as a nutritious meal owing to their favorable nutritional and sensory attributes, but they are also utilized in the production of diverse processed foods (Motamedzadegan & Tabarestani, 2018). Therefore, a large portion of the tomatoes grown around the world are processed to create new durable-longer shelf life-products like tomato paste, tomato pulp, tomato juice, diced tomatoes, tomato powder, well-known ketchup, dried tomato, etc. (Soufiyan, Dadak, Hosseini, Nasiri, Dowlati, Tahmasebi, & Aghbashlo, 2016). Tomatoes undergo several unit operations throughout preprocessing, including grading, washing, sorting and trimming, coring, and peeling (Motamedzadegan & Tabarestani, 2018).

Pepper (*Capsicum annuum* L.) is a vegetable in the *Solanaceae* family that belongs to the *Capsicum* genus. It contributes significantly to human nutrition due to its antioxidant characteristics, vitamins (primarily A, C, and E), mineral elements, polyphenols, and carotene.

Red-Kapia-peppers, which have a long conical form, fleshy, red, and sweet structure, are eaten fresh, dried, powdered, pasted, or canned. Furthermore, peppers are frequently used to provide color and aroma to sauces, soups, pickles, and pizzas, and a substantial number of red peppers are ingested as powders (Sharma, Joshi, & Kaushal, 2015). Peppers rank in the top ten most produced vegetables globally due to their distinctive taste and high nutritional content. Peppers include high levels of phenols, flavonoids, and capsaicinoids (Loizzo, Pugliese, Bonesi, Menichini, & Tundis, 2015). Pepper holds a significant position among the widely consumed vegetable varieties worldwide, including Türkiye. In 2021, the worldwide production of peppers reached to 36.29 million metric tons (Shahbandeh, 2023).

Sweet red pepper (SRP) is cultivated either in open fields or in under cover. China holds the top position in global pepper production, with a total output of 16023500 tons grown across 709150 hectares. Mexico follows closely in second position producing 2379736 tons of pepper on an area of 136132 hectares. Based on the data from Turkish Statistical Institute, Türkiye's pepper production amounts to 3020000 tons, cultivated on an area of 9.8% of total cultivated agricultural area. (TUIK, 2022), The contributions of the provinces such as Şanlıurfa, Gaziantep, Kilis, Kahramanmaraş and Hatay for the production ratios were 35.28%, 30.62%, 16.45%, 9.82%, and 1.94%, respectively.

2.2. Energy and Environmental Consequences of Food Industry with a Special Emphasis on Fruit and Vegetable Processing Industry

The food industry is one of the major consumers of energy in processes as well as fossil fuels, which emit a substantial amount of greenhouse gases into the water and air, thereby contributing to environmental contamination. The food industry has been reported to be responsible in between 20% to 33% of the overall GHG emissions. The specific distribution of emissions from various stages in the life cycle of food products is illustrated in Figure 2.1. Approximately 33% of the overall GHG emissions in the food chain are estimated to be related to energy usage (Crippa, Solazzo, Guizzardi, Monforti-Ferrario, Tubiello, & Leip, A., 2021). However, the food systems' influence on sustainability extends beyond GHG emissions. Furthermore, it has adverse effects on desertification, land degradation, water scarcity, and the depletion of biodiversity. Due to their role in exacerbating global warming, the emissions of GHG emissions must be decreased (Groth et al., 2023; Smith, Nkem, Calvin, Campbell, Cherubini, Grassi, & McElwee, 2019).

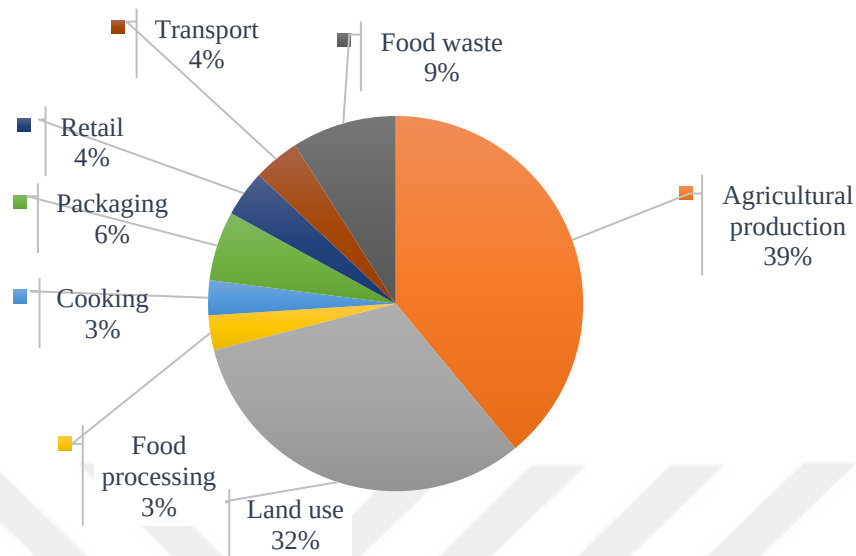


Figure 2.1. Emissions of greenhouse gases from the food chain (Groth, Wegmann, & Meyerding, 2023)

The food industry includes energy-intensive operations, with energy-related expenses accounting for 20% to 50% of the total production costs. Furthermore, the food industry accounts for a significant proportion (about 12%) of the overall electricity consumption in the industrial sector. Nevertheless, the energy in the food sector is often misused as a result of numerous inefficiencies that are evident in food processing technologies (Clairand, Briceño-León, Escrivá-Escrivá, & Pantaleo, 2020). The fruit and vegetable processing industry consumes around 6000 terajoules of energy annually, ranking sixth in terms of energy consumption among other sectors such as sugar, dairy products, meat, fish, and baked items. Simultaneously, within the consumption structure of final energy in this sector, electric energy comprises 11.6%. Refrigeration can cause the electrical energy consumption in certain plants to exceed 50%. The diverse range of processes and unitary operations, fluctuating operating circumstances, and non-simultaneous operation of installations, along with the specific profile of raw materials processing and the seasonal nature of production, lead to significant fluctuations in the consumption of electrical energy (Wojdalski, Drozd, & Lubach, 2007). Industrial plants, due to their large energy consumption, present an opportunity for power utilities to effectively regulate electricity usage. Energy efficiency programs allow major industries to decrease their consumption and enhance their operational production, hence boosting their advantages. Nevertheless, industrial processes are

predominantly inflexible, as a result of the production limitations imposed by the plants, which dissuade certain industries from embracing these initiatives.

The primary environmental consequences associated with the food processing industry encompass the formation of aquatic, atmospheric, and solid waste. These impacts are contingent upon the amount of resources employed, the amount of waste generated, and the transportation methods employed within the processing system. The appropriate administration of water and energy resources in the context of food processing plays a crucial role in implementing cost-efficient sustainability strategies (Murphy et al., 2014). Environmental sustainability can be attained by the development and implementation of alternative environmental technologies and products that optimize resource utilization, result in cost reductions, and minimize adverse effects on both humans and the environment (Matlack, 2010).

The food industry is a significant contributor to atmospheric emissions, primarily attributed to its substantial energy use. The energy consumption in the food sector is significant, encompassing many activities such as building heating, processing and supplying processed water, refrigeration, and the transportation of raw materials and products (Murphy et al., 2014). This type of energy use contributes to the release of GHG emissions, particularly carbon dioxide emissions. The food production industry faces a significant challenge in terms of GHG emissions, due to its heavy reliance on transportation and fertilizer usage. However, there is a growing emphasis on energy conservation and management in food processing, driven by economic and legal pressures. In recent years, the food industry has made significant advancements in the reduction of its energy consumption by implementing process optimization and control, establishing energy recovery and recycling systems, and adopting effective production practices. This tendency is expected to persist as a result of the compliance with regulations in carbon trading schemes, such as the EU emissions trading system (Sellahewa & Martindale, 2010).

Food production has a vital role in the utilization of resources and has notable environmental effects. The environmental impact of products (EIPRO) study conducted at the European level has revealed that, food products contribute to 20-30% of the overall environmental consequences caused by consumption. Furthermore, food products are responsible for over

50% of eutrophication (Tukker, Huppes, Guinée, Heijungs, Koning, Oers, & Jansen, 2006). Similar to all industrial processes, the agri-food sector has an environmental impact throughout every step of the manufacturing process, starting from the cultivation phase, through food processing and distribution, all the way to the end-of-life stage. Internationally, it is widely acknowledged that, a comprehensive sustainability assessment should be conducted using a life cycle approach. This approach enables a thorough analysis of the entire system or supply chain, thereby preventing the transfer of burdens (Del Borghi, Gallo, Strazza, & Del Borghi, 2014).

Environmental concerns and fossil fuel depletion are driving initiatives to limit GHG emissions. Renewable energies, including solar and wind power, are widely chosen as viable alternatives. Nevertheless, fossil fuels account for 80% of the overall global energy consumption, with fossil fuel-powered plants generating half of all electricity (Halpin, 2013; Li & Tao, 2017). Another strategy handles the issue of industrial energy efficiency, which is of great importance, especially in developing nations. It is defined as the ratio of the service output of a process to the energy input into that process. The objective of industries may be to optimize the production of valuable outputs or decrease the use of energy inputs. Energy efficiency can be utilized, especially on a larger scale, to examine industrial activity and its effectiveness. Energy efficiency indicators can be categorized into four main types: thermodynamic, thermophysical, thermoeconomic and economic (Clairand et al., 2020).

To establish a sustainable agri-food supply chain, it is crucial to possess techniques and resources that allow companies to evaluate the ecological efficiency of their products. The quantification of the environmental performance of food and drink products also seeks to convey this information throughout the supply chain and to consumers, with the goal of enhancing companies' competitiveness and guiding consumers towards more sustainable choices (Jungbluth, Tietje, & Scholz, 2000). By employing LCA, it becomes possible to identify the key contributors to each impact; thus, improvement opportunities can be targeted more effectively (Sieti, Schmidt Rivera, Stamford, & Azapagic, 2019). Applying LCA for food items consumed at a global level bears additional importance, as the avoided or mitigated impacts would have positive effects on a large, rather than a limited, population (Del Borghi et al., 2020). In addition to academic studies, LCA can also be used for the eco-design of food products. Eco-design can be summarized as the idea of thinking about a

product and its whole life cycle from design to destruction, focusing on reducing its impacts on the environment (Rousseaux, Gremy-Gros, Bonnin, Henriel-Ricordel, Bernard, Floury, Staigre, & Vincent, 2017). Another application of LCA in the food business is creating product environmental footprints. These footprints are used to assist consumers in making well-informed choices when selecting between various products and brands (Gül, Üçtuğ, & Güngörmüşler, 2021). The research on tomato products and sweet red pepper products that have been carried out in the literature is presented in Tables 2.1 and 2.2. Studies on energy, exergy, CO₂, and LCA related to tomato products are shown in Table 2.1, whereas studies on energy, exergy, CO₂, and LCA related to sweet red pepper products are shown in Table 2.2. CML-IA baseline method is often used in agricultural and food supply analysis. The impact categories studied in the context of this study are defined below.

Abiotic Depletion is one of the impact categories that is utilized in standard CML evaluation. Abiotic resources refer to natural resources, including energy resources, such as iron ore and crude oil that are considered to be non-living. Various alternative approaches are employed to evaluate abiotic resource depletion. Various methodologies have been devised based on different definitions, which also encompass different definitions of impact categories. Abiotic resource depletion refers to the reduction of both non-renewable and renewable abiotic resources, such as wind and flowing water, in certain situations. Abiotic depletion is a significant factor that must be considered in LCA. Additionally, it is one of the impact categories that is frequently discussed. Energy generation is typically associated with the utilization of natural resources. The depletion of abiotic resources is heavily influenced by the specific methods used for electricity generation (Pikoń, 2012).

Eutrophication is a worldwide environmental problem resulting from the excessive release of nutrients, specifically nitrogen (N) and phosphorus (P), into the ecosystem. These nutrients primarily come from the application of fertilizers in agricultural production systems. The surplus nutrients introduced to the field as fertilizers infiltrate the water bodies via leaching, runoff, and precipitation, resulting in eutrophication in both freshwater and marine ecosystems (Huang, Xu, Ridoutt, Wang, & Ren, 2017). Additional factors contributing to eutrophication include the release of pollutants from various industries, such as food manufacturing, desalination, oil and gas, and textile industries. Municipal wastewater treatment plants, livestock production, fossil fuel combustion, and energy consumption also play a role in eutrophication (Balasuriya, Ghose, Gheewala, & Prapasongsa, 2022; Khan &

Mohammad, 2014; Panagopoulos, 2021a, 2021b). Excessive nutrients expedite the proliferation of algae and aquatic vegetation, resulting in the formation of a harmful algal bloom. This bloom diminishes water clarity, impeding the penetration of sunlight into the deeper layers of the water. The absence of sunlight inhibits photosynthesis, leading to the demise of algae and aquatic plants due to a lack of nutrients. Bacterial decomposition of deceased organic matter leads to a decrease in oxygen levels in the lower layers of water, resulting in the formation of a hypoxic zone (Ibisch, 2016). As a consequence, the application of fertilizers in agricultural production leads to the release of excessive amounts of nitrogen and phosphorus, which in turn causes eutrophication in the aquatic ecosystem.

Acidification refers to the process of emissions that raise the concentration of acidity (lowering the potential of hydrogen) in water and soils. Acidification occurs as a consequence of atmospheric pollution caused by nitrogen and sulfur, which are present in the form of nitrogen oxides (NO_x) or ammonia. Acidification is a significant current global environmental threat that has a direct impact on the ecosystem. Acid rain primarily consists of sulfur dioxide (SO₂) and NO_x, which can result in the mortality of certain species. It causes significant destruction to structures (Dahlgren, Strippel, & Oliveira, 2015). As the level of acidification increases, the severity of environmental damages also increases. Acidification and eutrophication affect 6-15% and 7-18% of the entire natural ecosystem. Multiple studies have demonstrated that, the acidification potential is influenced by atmospheric conditions and regional characteristics (Bouwman, 1999; Kameni Nematchoua, 2022).

Global warming potential is a measure of the cumulative radiative forcing caused by a single emission of a specific component, compared to the radiative forcing caused by an equal mass emission of CO₂ (Myhre, Shindell, Bréon, Collins, Fuglestad, Huang, & Mendoza, 2014). Various climate pollutants of diverse origins contribute to anthropogenic climate change. Climate pollutants are frequently quantified using a standardized measure that is based on CO₂. This means that, emissions other than CO₂ are usually expressed and combined as quantities equivalent to carbon dioxide (CO₂-e). The GWP is the most commonly used metric for measuring the equivalence of CO₂. It is defined as the total change in radiative forcing, which is the disruption of the Earth's atmospheric energy balance, causing warming, over a specific time period after emitting a certain amount of a climate pollutant, compared to emitting the same quantity of CO₂. The GWP100, which represents the 100-year variant of the Global Warming Potential, has been officially accepted in international climate policy,

specifically in the Kyoto Protocol and the draft text of the Paris Agreement. It is also used in standardized LCA and carbon-footprinting methods (Lynch, Cain, Pierrehumbert, & Allen, 2020).

The ozone depletion potential is a measure of the worldwide reduction in ozone caused by the release of a specific molecule compared to a reference molecule, typically CFC-11 or CFC1 (Solomon, Mills, Heidt, Pollock, & Tuck, 1992). Ozone depletion arises, when the equilibrium between the generation and elimination of stratospheric ozone is disrupted. While natural phenomena can contribute to ozone depletion, it is widely acknowledged that human activities, specifically the use of chlorofluorocarbons (CFCs), are the primary cause of this depletion (Angell & Korshover, 1973). Every chemical that causes ozone depletion contains both chlorine and bromine (Andersen & Sarma, 2012). CFCs possess high volatility and are non-combustible, allowing them to rapidly evaporate and easily ascend to the stratosphere, where ozone is present. In this region, they initiate the depletion of ozone molecules. These CFCs also have detrimental effects on human health. Rocket launches are a significant contributor to the widespread depletion of the ozone layer. Research has shown that, unregulated rocket launches can cause significantly greater ozone depletion compared to CFCs. The emission of nitrogenous compounds such as NO, N₂O, and NO₂ from human activities is believed to have a significant impact on the depletion of the ozone layer. Global warming contributes to the depletion of the ozone layer. As a result of global warming and the greenhouse effect, a significant portion of the troposphere, which is the layer below the stratosphere, contains trapped heat (Anwar, Chaudhry, Nazeer, Zaman, & Azam, 2015).

The human toxicity potential (HTP) is a quantitative measure that assesses the potential harm caused by the release of a chemical into the environment. It takes into account both the inherent toxicity of the compound and the potential dose of exposure. This tool is employed to quantify the emissions that are recorded as part of a LCA or in the toxics release inventory, and to combine the emissions in relation to a specific reference compound. Emissions can be assessed by measuring their benzene equivalence, which represents the amount of carcinogens present, and their toluene equivalents, which represent the amount of noncarcinogens present. HTP provides assessments of hazards by considering the toxic potency of a substance and the potential dose. As it is commonly referred to the measure of toxicity, known as the risk assessment value, is quantified by cancer potency factors $q1^*$ or the reciprocal of the

permissible daily intake or reference dose. The exposure is determined through the utilization of CalTOX (Maddalena, McKone, Layton, & Hsieh, 1995; McKone, 1992), a risk assessment model that combines a multimedia environmental fate model with a multiple pathway exposure model. The HTP offers a more accurate risk assessment compared to other methods, without the need for specific data related to the site (Hertwich, Mateles, Pease, & McKone, 2001).

Freshwater ecotoxicity serves as a representative measure for both marine and terrestrial ecotoxicity at an intermediate stage, as certain substances can exhibit high toxicity regardless of the ecosystem they are introduced to. Nevertheless, it remains an imperfect representation as the destiny of freshwater, marine water, and soil compartments can vary significantly for the same elementary flow and emission compartment. The occupation and transformation of land have significant effects on terrestrial biodiversity and are commonly used as indicators for the overall impact of land use on ecosystem services (Bulle, Margni, Patouillard, Boulay, Bourgault, De Bruille, & Jolliet, 2019).

Photochemical oxidation potential is formed when reactive substances in the air combine with emissions to create particles. This smog can harm agricultural crops, human health, and the ecosystem. It is reported that photochemical fog can be detrimental to the environment. The measurement is quantified in terms of C₂H₄ equivalence. The increased presence of motor vehicles in cities is a primary contributor to this category (Kaynak-Duman, 2020).

Table 2.1. Energy, exergy and LCA studies conducted on tomato products

Food Product	Methodology	System boundaries/Aim	Software/Impact assesment method*	References
Chopped tomato	LCA and energy analysis	Ohmic heating and appetization line	SimaPro 8.1.0 Analyst, Ecoinvent 3.2 database, IMPACT 2002+	(Ghnimi et al., 2021)
Tomato paste	Exergy analysis	Whole process analysis with double effect evaporator	ND	(Soufiyan et al., 2016)
Tomato puree	LCA	Whole supply chain	Simapro 8.1.1.16, Impact 2002+	(Ingrao, Faccilongo, Valenti, De Pascale, Di Gioia, Messineo, & Arcidiacono, C., 2019)
Tomato puree	LCA	Whole supply chain	ILCD method	(Bacenetti, Duca, Negri, Fusi, & Fiala, 2015)
Fresh tomato, paste, whole peeled, diced, juiced tomato	Energy analysis, CO ₂ analysis	Production processes- whole supply chain	ND	(Karakaya & Özilgen, 2011)
Tomato products (tomato paste, chopped tomato, peeled tomato)	LCA	Whole system approach	CML 2001	(Del Borghi et al., 2014)
Tomato paste; cold break, hot break	LCA	Whole system approach	eFootprint, CLCD-China-ECER 0.8.1 database	(Ding, Li, Liu, Qi, Liu, & Dong, 2023)
Fresh tomato and cucumber production	LCA	Open field and greenhouse comparison	SimaPro 8.03.14	(Zarei, Kazemi, & Marzban, 2019)
Whole peeled tomato	LCA	Whole supply chain	CML-IA baseline method SimaPro, ILCD 2011 Midpoint, Ecoinvent (v 3.1)	(Garofalo et al., 2017)
Fresh tomato and cucumber	LCA	Open field and greenhouse comparison	SimaPro, Ecoinvent 2.0, CML 2 baseline 2000 V2/world, 1990	(Khoshnevisan, Rafiee, Omid, Mousazadeh, & Clark, 2014)
Fresh tomato and potato products	LCA	Cradle to grave	SimaPRO-9 ReCiPe 2016 (E) Midpoint method	(Parajuli, Matlock, & Thoma, 2021)

Table 2.1. Energy, exergy and LCA studies conducted on tomato products (continue)

Food Product	Methodology	System boundaries/Aim	Software/Impact assessment method*	References
Tomato ketchup	LCA	Different packaging and farming practices effects	Ecoinvent 3.5, Product Environmental Footprint	(Wohner, Gabriel, Krenn, Krauter, & Tacker, 2020)
Cherry tomatoes	LCA	Fertilizer and pesticide reduction effects	REET, USEtox_2.12	(Guo, Zhao, Zhuang, Wang, & Zhang, 2021)
Fresh tomato	LCA	Organic and conventional farming comparison in greenhouse	EDIP97, CML01 method, IPCC, 2001	(He, Qiao, Liu, Dendler, Yin, & Martin, 2016)
Tomato (crushed)	Energy, exergy analysis	Ohmic heating unit	ND	(Darvishi, Hosainpour, Nargesi, & Fadavi, 2015)
Fresh tomato	Energy analysis and LCA	Multi-tunnel greenhouse Cradle to regional distribution center	IPCC, 2006	(Neira, Montiel, Cabeza, & Reigada, 2018)
Fresh tomato	Cumulative exergy approach	Different region comparison	ND	(Yildizhan & Taki, 2018)
Fresh tomato	Energetic analysis and LCA	Farm to gate approach, organic and conventional farming comparison	IPCC, 2006	(Ronga, Galligani, Zaccardelli, Perrone, Francia, Milc, & Pecchioni, 2019)
Fresh tomato	LCA	Open field, Farm to gate	Carbon footprint	(Clavreul, Butnar, Rubio, & King, 2017)
Hydroponic tomato production	Environmental footprint analysis	Photovoltaic solar system	Ecoinvent V3.6, ILCD	(Martin-Goriz, Maestre-Valero, Gallego-Elvira, Marín-Membrive, Terrero, & Martínez-Alvarez, 2021a).
Fresh tomato consumption	LCA	Cradle to consumer gate approach	SimaPro v.9.1, Agri-footprint, CML-IA	(Urbano, Barquero, & González-Andrés, 2022)

Table 2.1. Energy, exergy and LCA studies conducted on tomato products (continue)

Food Product	Methodology	System boundaries/Aim	Software/Impact assessment method*	References
Organic fresh tomato	LCA	Organic tomato produced and distributed in Sweden	ReCiPe	(Bosona & Gebresenbet, 2018)
Tomato, cucumber, lettuce	Carbon footprint, LCA	Cradle to farm gate, two cropping system comparison	IPCC, 2006	(de Jesus Pereira, Cecílio Filho, & La Scala Jr, 2021)
Open field tomato production	Economic and energy analysis	Stake-tomato grown in open field in Tokat province	ND	(Esengun, G. Erdal, Gündüz, & Erdal, 2007)
Fresh tomato	Energy and economic analysis	Open field and greenhouse production	ND	(Yelmen, 2019)
Fresh tomato	Economic analysis	Pesticide usage investigation	ND	(Engindeniz, 2006)
Tomato paste	Energy and exergy analysis	Quadruple-effect evaporator unit	ND	(Sogut et al., 2010)
Fresh tomato	Energy and economy analysis	Tomato production comparison with input costs	ND	(Cetin & Vardar, 2008)
Fresh tomato	Energy and CO ₂ analysis	Open field-Bursa region	ND	(Demirtas, 2021)
Tomato juice	Energy and exergy performance	Microwave heating-assisted vacuum evaporation	ND	(Sofizadeh, Khodaei, Darvishi, Behroozi-Khazaei, & Koushesh Saba, 2023)
Greenhouse tomato production	LCA	Different fertilization and irrigation treatments From greenhouse construction to tomato harvest	GaBi database, literature findings	(Fan, Luo, Hao, Li, & Kang, 2022)
Open field tomato production	Carbon footprint	Different regions comparison	Ecoinvent 3.1 database	(Pishgar-Komleh et al., 2017)
Tomato	LCA	Tomato cultivation and processing	CML2001 CED ReCiPe	(Manfredi & Vignali, 2014)

* ND: Not defined

Table 2.2. Energy, exergy and LCA studies conducted on pepper products

Food Product	Methodology	System boundaries/Aim	Software/Impact assessment method*	References
Fresh pepper	LCA	Cultivation phase, Greenhouse	SimaPro, CML-IA Baseline 4.7, midpoint methodology	(García García & García García, 2022)
Fresh pepper	Environmental impact gap methodology	Plastic greenhouse, cultivation phase	Environmental impact gap methodology	(Wang, Liu, Wu, Sun, Guo, Jin, & Zou, 2018)
Fresh red pepper and green pepper	LCA and Carbon footprint analysis	Gate to gate approach Field cropping and greenhouse cropping	Ministry of Knowledge Economy Methodology	(So, Park, Huh, Shim, Ryu, Kim, & Lee, 2010)
Fresh pepper	Attributional LCA	Organic and conventional pepper cultivation comparison	SimaPro, version 8.0.1.4, ecoinvent v3.1, the ELCD and the industry, Agri-footprint	(Chatzisyneon, Foteinis, & Borthwick, 2017)
Sauceboat pepper	Energy and GHG analysis	SRP farming step	Literature survey	(Baran, Eliçin, Bellitürk, & Çelik, 2022)
Roasted capia pepper	LCA	Cradle to grave approach	CCaLC2 LCA software with Ecoinvent 2, CML 2001 method.	(Gül et al., 2021)
Cucumber				
Red pepper slices	Energy and exergy analysis	Convective type drying	ND	(Akpınar, 2011)
Red pepper drying	Energy analysis	Freeze drying-Pulsed electric field, Ultrasound treatment	ND	(Rybak, Parniakov, Samborska, Wiktor, Witrowa-Rajchert, & Nowacka, 2021)
Red pepper drying	Performance-Economic analysis	Greenhouse type of dryers	ND	(Yelmen, Çakır, & Şahin, 2019)

*ND: Not defined



3. MATERIALS AND METHODS

3.1. System Description and Process Specifications

The present investigation analyzes the evaluation of energy, exergy consumption, and CO₂ emissions within LCA in the production of tomato and sweet red pepper products. Assessing the process design and providing a thorough description of the system constitute the initial step of the investigation. The production processes are comprised of three main stages: farming step, factory processing step and packaging-transportation step. For each product, the amount of energy used, exergy, CO₂ emissions and LCA were determined independently. The research was conducted on the basis of a variety of assumptions, and its primary objective was to make an objective comparison of various processing systems. The assumptions are listed in Table 3.1.

Table 3.1. Assumptions and the limitations of the study

Resources	Harvested SRP in season come from the Samsun-Bafra region, which is 75 km away from the factory. The average distance between the factories and the customer is assumed as 500 km. The distance between the fields and the factory is doubled to calculate the total distance traveled, which is 150 km (Karakaya & Özilgen, 2011). This is because the trucks often travel from the fields to the factory empty and return loaded with SRP.
	The Brix value of SRP cultivated in the Samsun-Bafra lowland is 7 (Hekimoğlu & Altındeğer, 2018) and an average of 5.3554 kg of red peppers is assumed to yield 1 kg of pepper paste. One ton of red peppers yields 186.92 kg of SRP paste.
	The dry matter content of the paste derived from red pepper is assumed as 34 Brix (Hekimoğlu & Altındeğer, 2018).
Processing	A ripe tomato has an average dry matter content of 5-7%. An average of 5.6 kg of tomatoes is processed to get 1 kg of tomato paste (Kirkin, 2013). In this study the tomato total dry matter was assumed to be 7%. Since 95% of crushed tomatoes contain water, the density of tomatoes is often stated as 1 kg/L (Karakaya & Özilgen, 2011). According to the calculations made in this study, 1 kg of tomato juice is produced from 1.0693 kg of tomatoes.
	For the equipment, steady-state operating conditions are presumed.
	Electricity and natural gas are the primary energy sources for the base case.
Packaging and transportation	Due to the minimal impact of ink jet usage in terms of tonnage, it is ignored in the calculations.
	The new high-tech plastic pallets are fully recyclable and may be used for around 250 journeys, resulting in negligible energy usage and emissions during production.
	Heavy-duty trucks with a 10-ton capacity consume fuel at a rate of 0.287 liters per km, when going at a speed of 90 km/h. The density of diesel oil is used as 0.832 kg/l in calculations (Roy, Nei, Okadome, Nakamura, Orikasa, & Shiina, 2008)
Limitations	Due to the lack of data and the difficulties in forecasting consumer behavior, the consuming stage is not taken into account.

Table 3.2. Inputs and quantities required for 1 ton of fresh (field) tomato and SRP production

Tomato farming	Amount per ton	References
Nitrogen (N)	2.98	(Esengun et al., 2007)
Phosphorus (P ₂ O ₅)	3.04	(Esengun et al., 2007)
Potassium (K ₂ O)	1.11	(Esengun et al., 2007)
Pesticides (kg)	0.04	(Esengun et al., 2007)
Fungicides(kg)	0.08	(Esengun et al., 2007)
Herbicides(kg)	0.02	(Esengun et al., 2007)
Diesel (kg)	6.26	(Esengun et al., 2007)
Water for irrigation (kg)	30824	(Esengun et al., 2007)
Seed (kg)	7.21×10 ⁻⁴	(Esengun et al., 2007)
Electricity (MJ)	124.55	(Yelmen et al., 2019)
Human labor (h)	0.22	(Yelmen et al., 2019)
Machinery use (h)	7.37	(Yelmen et al., 2019)
Transportation (kg/150 km)	3.58	(Karakaya & Özilgen, 2011)
Sweet red pepper farming		
Nitrogen (N) (kg)	22.65	(Wang et al., 2018)
Phosphorus (P ₂ O ₅) (kg)	23.08	(Wang et al., 2018)
Potassium (K ₂ O) (kg)	14.44	(Wang et al., 2018)
Fungicides (kg)	0.115	(Chatzisyneon et al., 2017)
Herbicides (kg)	0.0825	(Chatzisyneon et al., 2017)
Insecticides (kg)	0.073	(Chatzisyneon et al., 2017)
Water for irrigation (m ³)	90	(Chatzisyneon et al., 2017)
Electricity (kwh)	27.76	(García García & García García, 2022; Martin-Gorriiz et al., 2021b)
Human labor (MJ)	0.22	(Yelmen, 2019)
Transport (Diesel) (MJ/kg)	3.58	(Karakaya & Özilgen, 2011)
Agricultural machinery (Diesel)	2.83	(García García & García García, 2022)

The inputs required for farming and packaging-transportation steps of the tomato and SRP products are presented in Table 3.2 and Table 3.3. The other inputs needed for the various processing steps of tomato and SRP products processing are provided in Appendix-F. The equipments utilized in various production stages, such as conveying, washing, sorting, mixing, concentrating, canning or bottling, sterilizing, packaging, etc., have been sourced from the websites of leading equipment providers within the tomato and sweet red pepper processing sector. When making decisions on equipment selection, various detailed factors such as capacity suitability, energy utilization, and energy source of the equipment were taken into consideration by consulting information available on websites. This information plays a significant role in the decision-making process for equipment selection. The tables presented in Appendix-F provide the brand, model, and capacity information of the all equipment utilized in manufacturing processes.

Table 3.3. Inputs and quantities required for packaging and transportation of tomato and SRP products for 1 kg functional unit

Inputs	Retail tomato	Tomato juice	Tomato paste	Retail SRP	SRP paste	Roasted SRP	Dried SRP
Paper (kg)	0.30	3.38	0.8	3.8	-	-	0.05
Cardboard (kg)	11.34	2.03	0.48	13.1	1.82	23.35	0.77
Electricity (MJ)	5.77	13.34	3.11	1.94	0.69	0.87	0.44
Steel (kg)	-	175.10	33.65	-	13.33	87.11	-
LDPE (kg)	-	-	-	-	3.45	42.02	-
Glass (kg)	-	-	-	-	77.64	980.41	-
Polyethylene (kg)	-	-	-	-	-	-	0.54
Polyethylene terephthalate (kg)	-	-	-	-	-	-	0.54

3.2. Tomato Products System Boundaries and Specifications

For the analysis in the manufacturing of tomato and SRP products, an extensive review of literature and additional data sources, including the Türkiye Development Agency reports (Doğaka, 2017; Eastern Mediterranean Development Agency, 2021; Gümüşhane Chamber of Commerce and Industry, 2021; Hacibekoğlu et al., 2013; Hekimoğlu and Altindeğer, 2018); Turkish Statistical Institute Data (2019), International Energy Agency Report (IEA, 2022), Turkish Food Codex Communique on tomatoes and red pepper paste and puree (2014), Global Market Insights (2023), Turkish Statistical Institute Data (2023), and Türkiye Institute of Economics and Policy Development (2021) reports were used. The production method for each product was divided into three key stages: fresh tomato agriculture, factory processing, and packaging-transportation.

The basis for all calculations was the production or processing of one metric ton (1000 kg) of fresh tomatoes. The functional unit (FU) for LCA was chosen as 1 kg of unit product. For the whole system and each component of the production system, mass balances based on general mass fluxes based on dry matter and water content were established. A ripe tomato has an average dry matter content of 5-7%. An average of 5.6 kg of tomatoes is processed to get 1 kg of tomato paste (Kirkin, 2013). This yield, however, may vary based on the amount of dry matter in the tomatoes utilized in tomato paste production. In this study, the tomato total dry

matter was assumed to be 7%. Since 95% of crushed tomatoes contain water, the density of tomatoes is often stated as 1 kg/l (Karakaya & Özilgen, 2011). According to the calculations made in this study, 1 kg of tomato juice is produced from 1.06931 kg of tomatoes. Figure 3.1 illustrates the system boundaries of the tomato products (retail tomato, tomato juice, and tomato paste) that were evaluated.

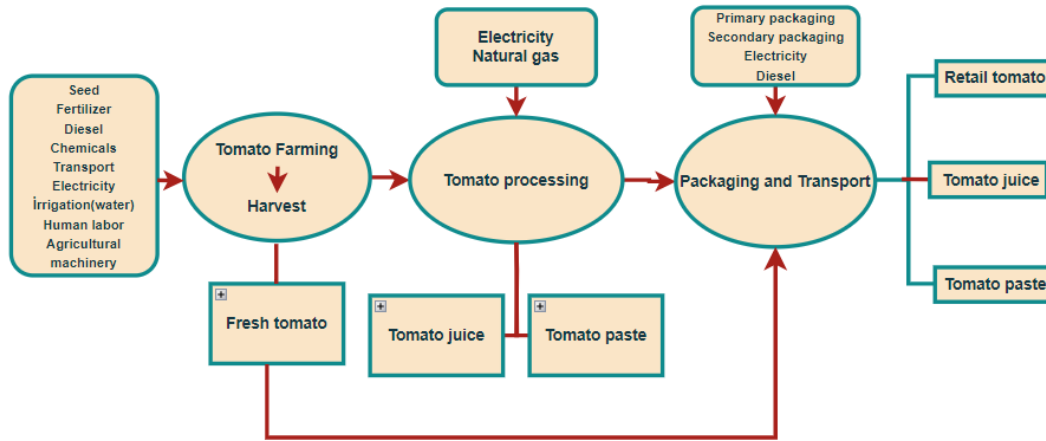


Figure 3.1. System boundaries of retail tomato, tomato juice and tomato paste production

3.2.1. Retail tomato production

3.2.1.1. *Tomato farming*

Figure 3.2 illustrates the flowchart pertaining to the cultivation and development of tomatoes intended for retail markets. The inputs necessary for the growth of a tomato plant include seeds, chemical fertilizers, chemical insecticides, water for irrigation, diesel for agricultural machinery operations, and electric power for irrigation and other electrical motors. The cultural practices pertaining to tomato cultivation in Türkiye have been documented by Engindeniz (2006), Esengun et al. (2007), and Yelmen (2019).

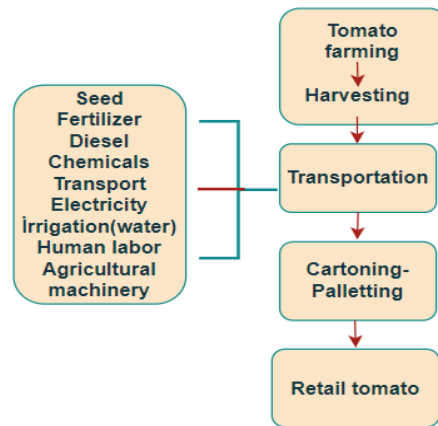


Figure 3.2. Flow diagram of fresh tomato and retail tomato production steps

3.2.1.2. Retail tomato packaging and transportation

For transportation, it is reported that trucks with a capacity of 1-1.5 tons consumed approximately 0.1667 liters of gasoline per km at a speed of 60 km per hour, while transporting fresh tomatoes from the farm to retail stores, wholesalers, or retail stores (Roy et al., 2008). As trucks frequently travel great distances, while fully loaded and continue their journey by transporting another load on their return trip one-way fuel consumption was considered in the calculations and the retail tomatoes were assumed to be delivered over an average distance of 500 km (Karakaya & Özilgen, 2011).

3.2.2. Tomato juice production

3.2.2.1. Tomato farming

Tomato farming is the main process in all tomato products evaluated in this research. As a result, detailed explanations are provided in Section 3.2.1.1. for tomato farming step.

3.2.2.2. Tomato juice factory processing

Tomato juice is the undiluted liquid obtained from mature red or reddish tomatoes, with or without boiling, and then filtered. The liquid is extracted from the tomato's flesh, removing skins, seeds, and other solid substances, while containing finely separated insoluble materials. The tomatoes undergo identical unit activities in the production of tomato juice, as similar to the process of preparing tomatoes for paste or canning (Motamedzadegan & Tabarestani, 2018). In order to produce tomato juice, the tomatoes go through several pre-processing unit

operations as well as factory processing, which includes processes like crushing, breaking, and extraction, deaeration, salting, filling, and occasionally homogenization and thermal processing. Lastly, the tomato juice is packaged and transported to retail markets (Motamedzadegan & Tabarestani, 2018). Figure 3.3 shows the flow diagram of production steps of tomato juice and tomato paste factory processing

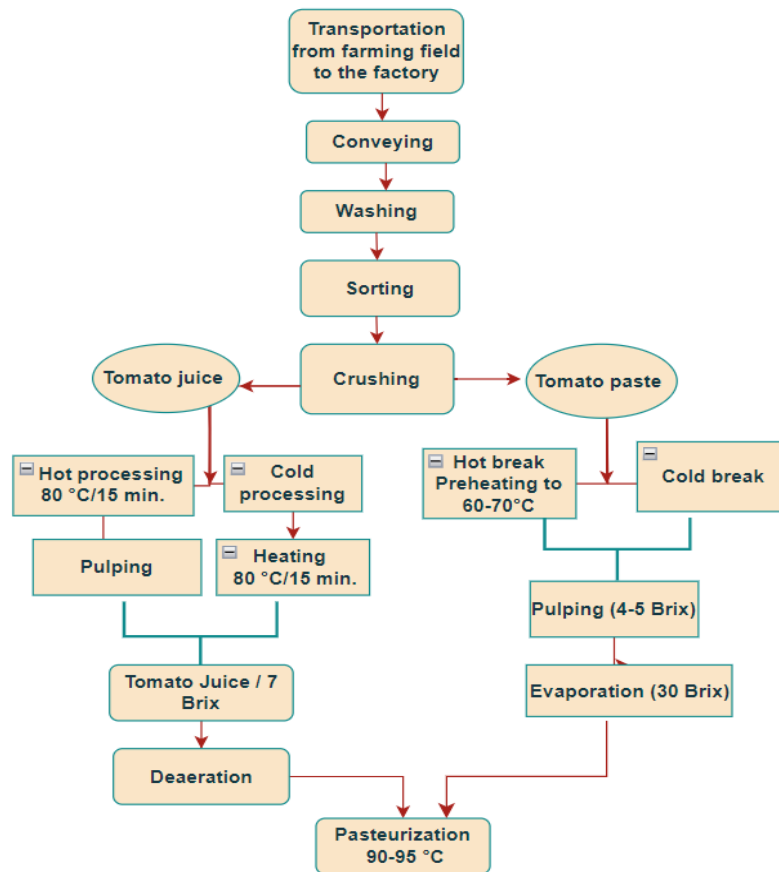


Figure 3.3. Flow diagram of production steps of tomato juice and tomato paste factory processing (Motamedzadegan & Tabarestani, 2018)

3.2.2.3. Tomato juice packaging and transportation

One ton of tomatoes yield 935.18 kg of tomato juice. The density of tomato juice is considered as 1 kg/l, as 95% of the resulting shredded tomatoes are water dense (Karakaya and Özilgen, 2011). Tomato juices are packed into 830 ml tin cans. 24 cans are packed inside a box. One kg of tomato juice is obtained from 1.06931 kg of tomatoes. Therefore, in order to produce 935.18 kg of tomato juice from one ton of fresh tomatoes, 1126.72 pieces of 830 ml cans are needed. To pack these cans, 46.95 boxes are needed. Finally, 0.7824 pallets are

needed. As trucks frequently travel great distances, while fully loaded and continue their journey by transporting another load on their return trip one-way fuel consumption was considered in the calculations, and the tomato juice was assumed to be delivered over an average distance of 500 km (Karakaya & Özilgen, 2011). Figure 3.4 illustrates the flow diagram of packaging and transportation steps of tomato juice and tomato paste.

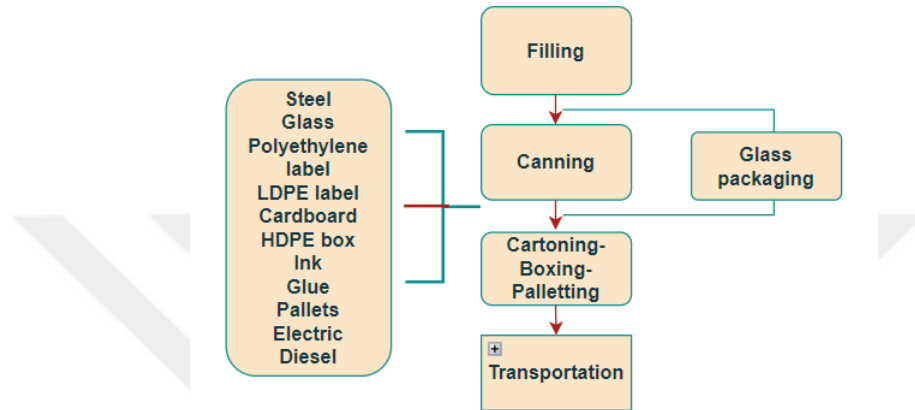


Figure 3.4. Flow diagram of the packaging and transportation step for tomato juice and tomato paste production

3.2.3. Tomato paste production

3.2.3.1. Tomato farming

Tomato farming is the main process in all tomato products evaluated in this research. As a result, detailed explanations are provided in Section 3.3.1. for tomato farming step.

3.2.3.2. Tomato paste factory processing

Tomato pulp (purée) refers to a food product that is created using one or a combination of the following ingredients: (1) the liquid derived from fully mature tomatoes of red or reddish varieties; (2) the liquid obtained from the residue left over after preparing these tomatoes for canning; (3) the liquid obtained from the residue left over after partially extracting juice from these tomatoes; and (4) salt. When considering tomato paste, the first choices (1-4) remain consistent. Furthermore, it is possible for tomato paste to incorporate spices, seasoning, and baking soda. Tomato purée or paste refers to finely distributed slurry that is obtained by removing the skins and seeds from mashed tomatoes by the use of a pulper or finisher. The distinction between tomato paste and tomato purée lies solely in the extent to which the

concentration is conveyed (Motamedzadegan & Tabarestani, 2018). For tomato paste, the product must include at least 24% natural tomato soluble solids, and for tomato pulp, it must have at least 8% salt-free tomato solids (Gould, 1974). In the process of producing tomato paste, the tomatoes go through some pre-processing unit operations as well as factory processing, which includes heating (hot or cold break), extracting and refining (filtering) the juice, concentrating (evaporating), packaging, and finally transportation for retail markets.

3.2.3.3. Tomato paste packaging and transportation step

Upon analysis of the packaging step, a total of 218.208 kg of tomato paste is produced from one ton of fresh tomatoes. The primary container for tomato paste is 12.4 kg Izvar brand conical barrels constructed of sheet (cold rolled steel), which with is filled 230 kg tomato paste after it has been aseptically filled. The production date and company name are encoded on the lateral sides of the barrels using an ink jet technology. Nevertheless, due to the minimal impact of ink jet usage in terms of volume, it is disregarded in the calculations. Secondary packaging is then carried out in 830 mL tin cans with regard to market demand. The estimations made at the can packaging step were based on the study conducted by Karakaya and Özilgen (2011).

According to Karakaya and Özilgen (2011), cans weighing 815 g (850 cm^3) are commonly utilized as packaging material in Türkiye. A standard 425 mL can (15 oz, a total surface area of 332 cm^2 and a lateral surface area of 248 cm^2) is made of 54.3 g of steel and has a paper label weighing 2.1 g. Tomato solids are concentrated from 5 to 30 Brix, and packaging material is reduced six fold, when tomatoes are turned into tomato paste rather than tomato pulp. The can with a volume of 830 mL has a total surface area of 507 cm^2 and a lateral surface area of 350 cm^2 . Assuming that the overall surface area of the steel utilized is equivalent to the edge surface area of the number of labels, one can requires 83 g of steel and 0.6 kg of paper labels. Since 1 ton of fresh tomatoes yield 218.208 kg of tomato paste, a total of 263 cans are necessary to package tomato paste obtained from one ton of fresh tomatoes. This corresponds to a total of 21.9 kg of steel and 0.8 kg of paper labels. In Türkiye, tomato paste cans are typically packaged in cartons with 24 cans each, and these cartons are then arranged in pallets with 60 cartons each pallet. A total of 263 cans necessitate 10.96 corrugated boxes and 0.182 pallets. Because 100% recyclable plastic pallets were utilized in this research, the calculations associated with pallet usage were not considered.

3.3. Sweet Red Pepper Products System Boundaries and Specifications

Figure 3.5 shows the schematic representation of system boundaries and the specific requirements of SRP products. The system encompasses the various stages of SRP farming, processing, and packaging-transportation. As described in Section 3.1, the production processes are comprised of three main stages: farming step, factory processing step and packaging-transportation step. For each product, the amount of energy used, exergy, CO₂ emissions and LCA have been determined independently.

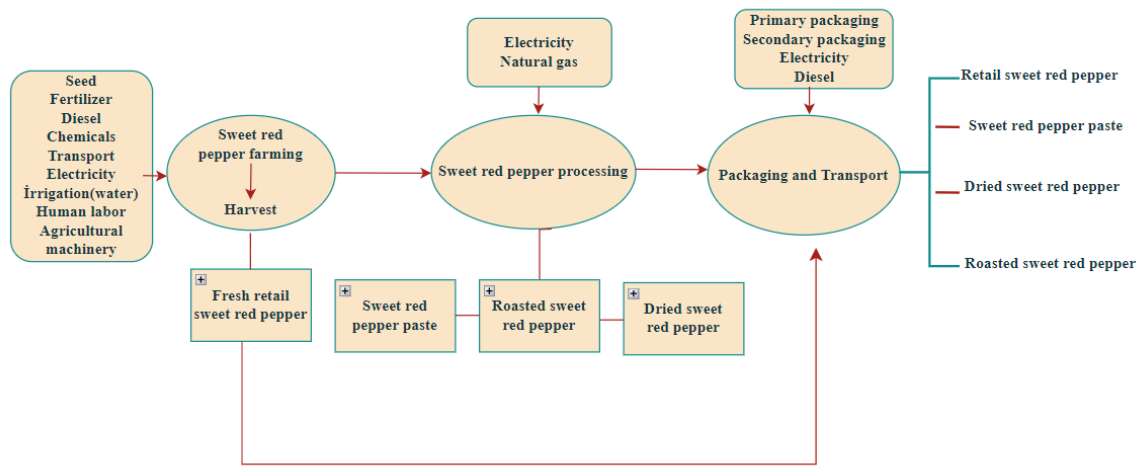


Figure 3.5. Sweet red pepper products system boundaries

3.3.1. Retail sweet red pepper production

3.3.1.1. Sweet red pepper farming

Figure 3.6 and Table 3.2 illustrate the system description and inputs for the growth of 1 ton of fresh SRP. Both the ‘hot’ and ‘sweet’ varieties of peppers are regularly consumed in both fresh and preserved versions. Peppers, whether raw or cooked, are utilized in salads, sandwiches, salsas, dips and curries in domestic and food service kitchens. Preserved peppers, such as those that have been roasted, brined, or canned, are being sold in both retail and food service industries. They are used as ingredients in sandwiches, pizzas, pastas, and other foods that are ready to cook or prepared (Uppili, LaFountain, & Johanningsmeier, 2023).

The data collected for building the life cycle inventory (LCI) revealed that, the amount of fertilizer used in the production of red peppers was more than that used in the manufacture of green peppers. The fertilizer input for red pepper was 2.55 kg per kg, whereas for green pepper it was 0.774 kg per kg. The pesticide input for red pepper was 5.38E-03 kg per kg, while for green pepper it was 2.98E-04 kg per kg. The direct emission values of CO₂, CH₄, and N₂O were 5.84E-01 kg per kg for red pepper and 2.81E+00 for green pepper, respectively (So et al., 2010). It is reported that, the average marketable yields of organic and conventional pepper fruits per 1000 m² of cultivable area are 2500 ± 500 kg and 4000 ± 1000 kg, respectively (Chatzisyneon et al., 2016). The electrical energy estimates related to the utilization of various water sources for irrigation were retrieved from Martin-Górriz et al. (2021b).

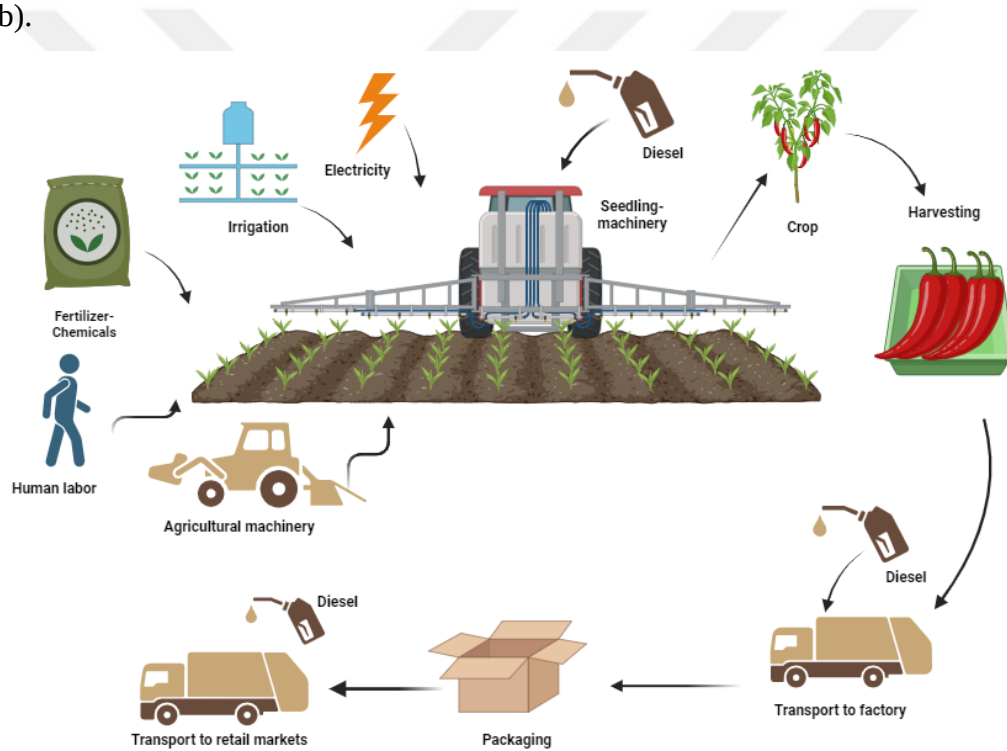


Figure 3.6. Retail fresh sweet red pepper production steps (Created with Biorender.com)

3.3.1.2. Packaging and transportation

Cardboard packages with a capacity of 5 kg were utilized to package fresh sweet red peppers. The dimensions of these packages are 25.4 mm in length, 279.4 mm in width, and 193.675 mm in height. The specs of the cardboard box have been acquired from Ümit Ambalaj, a packaging company situated in Adana, Türkiye, as well as from a survey that was conducted among several cardboard companies. Given that, each fresh SRP box has an area of 0.52 m²

and the cardboard weighs 0.126 kg/m² (Karakaya & Özilgen, 2011) and it follows that, 13.104 kg of cardboard is required to package one ton of fresh SRP. Cardboard boxes are put on a pallet that has a capacity of 100 boxes. The newly developed advanced plastic pallets are fully recyclable and have a lifespan of approximately 250 trips. As a result, the energy consumption and CO₂ emissions related to the production of these pallets are not taken into account. For one metric ton of fresh SRP, a total of 200 cardboard boxes and 2 pallets are utilized to package. According to Chow, Hackett, & Ganji (2005), the process of producing cardboard requires an energy range of 0.75 to 1.25 MJ/m². The energy and exergy use and CO₂ emissions for cardboard production were reported as 43.3 MJ/kg (Chow et al., 2005), 16.5 MJ/kg (Lattouf & Oliveira Júnior, 2003) and 1.17 kg/kg (Chow et al., 2005), respectively.

3.3.2. Sweet red pepper paste production

3.3.2.1. Sweet red pepper farming

Sweet red pepper farming is the main process in all SRP products evaluated in this research. As a result, detailed explanations are provided in Section 3.7.1 for SRP farming step.

3.3.2.2. Sweet red pepper paste factory processing

A study was conducted to assess the suitability of different varieties of domestic and foreign peppers for export and tomato paste production, as well as their ability to adapt to the region. The study found that in red peppers, the total dry matter ranged from 6.81% to 13.08%, water-soluble dry matter ranged from 6.9% to 8.3%, ash content ranged from 5.51% to 9.97%, pH level ranged from 4.2 to 5.28, reducing sugar content ranged from 28.41% to 59.57% (dry matter), and ascorbic acid content ranged from 1062 g/100 g to 1232 g/100 g on dry matter (Erdoğan, 2013).

When comparing the location based on the quantity of water-soluble dry matter (WSDM), peppers cultivated in Yenice yielded the highest value of 8.33%. The WSDM values found from pepper samples collected from the Central area and Ezine were 7.33% and 7.57%, respectively (Çiftci, Gündoğdu, & Kaynaş, 2023). In a study the impact of post-harvest treatments on red pepper to determine the effects on the quality and biochemical attributes of the pepper was assessed. They observed that, the control fruits had a WSDM value of 7.95% (Sakaldaş, Kaynaş, & Özdirek, 2014). Given the values established in the previous study, the

notable high rate of WDSM in peppers cultivated in Yenice is noteworthy. In food processing technology, a high WDSM content is a desirable attribute. Additionally, it serves as a crucial factor in assessing maturity and choosing the optimal time for harvesting (Bozkurt, 2019).

Figure 3.7 shows the production procedures of SRP paste (Doğaka, 2017; Kuleaşan & Okur, 2012; Uzel, 2017). In order to make pepper paste, fully ripe peppers that are bright red in color and contain a high percentage of soluble solids are utilized (Yıldırım & Cemek, 2013).

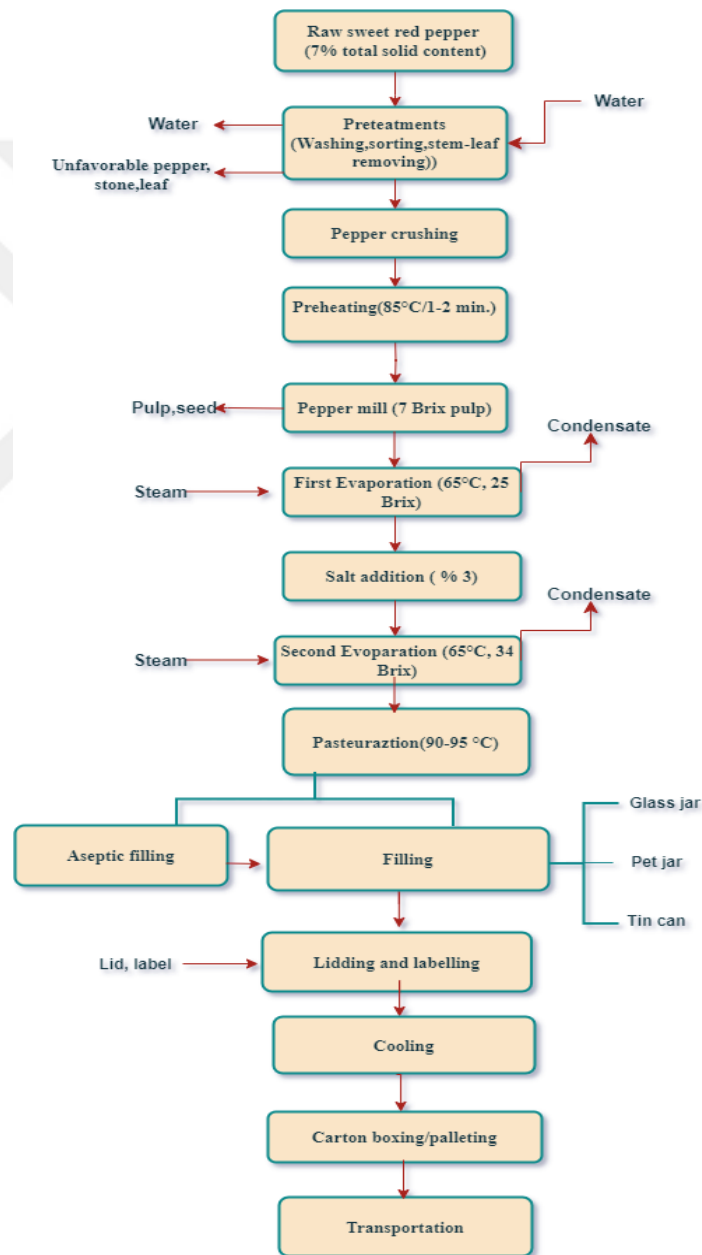


Figure 3.7. Sweet red pepper paste production steps (Doğaka, 2017; Kuleaşan & Okur, 2012; Uzel, 2017).

Peppers used in industrial manufacturing must have a WDSM value of at least 5.9% (Gök, Göçmen, & İstanbulluoğlu, 2021). The Brix value of sweet red pepper cultivated in the Samsun-Bafra lowland is 7, and 1 kg of pepper paste is obtained from 3.5-4 kg. Pepper paste is best produced using peppers that have a deep red color and a thick flesh. Smooth and shiny ones are favored for the purpose of roasting. The dry matter content of the paste derived from red pepper in the Bafra lowland ranges from 34 to 40 Brix (Hekimoğlu & Altındeğer, 2018).

3.3.2.3. Packaging and transportation

In this study it is assumed that an average of 5.3554 kg of red peppers yields 1 kg of pepper paste. One ton of red peppers yield 186.92 kg of SRP paste. The SRP paste is filled in containers constructed of 230 kg low carbon stainless (LCS) sheet, which are conical drums as primary packaging manufactured by the Izvar brand. Each drum has a weight of 12.4 kg. A total of 186.92 kg of SRP paste requires the utilization of 0.8126 barrels, which corresponds to 10.077 kg of steel. The production date and manufacturer name are coded on the barrels' side surfaces using an ink jet technology. Nevertheless, due to the minimal impact of ink jet usage in terms of tonnage, it is ignored in the calculations.

Upon analyzing the Turkish market for pepper paste, it becomes evident that, 660 cc glass jars are the prevailing choice. The 660 cc jar contains a net weight of 650 g of tomato paste. When filling a 660 cc glass jar with 186.92 kg of paste, it will require a total of 287.57 glass jars. In this study, the product specifications of 660 cc glass jars were obtained from the website of Arslan Ambalaj Ticaret ve Sanayi A.Ş., a company operating in the packaging market in Türkiye. The cylindrical glass jar with a twist-off lid has a height of 137.6 mm and a width of 82 mm. It has a capacity of 660 cc and weighs 270 g. Contact was made with "Arslan Ambalaj" to acquire lid specifications that are compatible with the product. In this case, 82 mm twist-off covers were preferred. The jars are put into a box consisting of 12 units; a total of 23.96 unit box will be used. A total of 77.64 kg of glass material will be utilized, when 287.57 glass jars are used, as each glass jar weighs 270 g. Given that, the weight of an 82 mm twist-off metal jar lid is 11.29 g, a total of 3.25 kg of steel material will be used. The surface area of a jar with a capacity of 660 cc is 0.050316 m² on average. The average surface area of a carton is 0.6037 m². Assuming that the weight of a carton is determined by a calculation of 0.126 kg/m² (Karakaya & Özilgen, 2011), the weight of a single carton is precisely 76.0662 g. Hence, a total of 1.8225 kg of cardboard will be required for 23.96 boxes.

In order to assess the impact of pet packaging within different scenarios, the product specifications of 2084 coded, 1300 cc pet jars made of PET material were obtained from the website of Teknopet Plastik Ürünleri ve Pet Ambalaj San. Tic. A.Ş. It has been established that, 1300 cc pet packaging is the accepted standard in pet packing. A 1300 cc PET jar, with a height of 137.5 mm, a width of 135.1 mm, a mouth screw size of 110 mm, and a weight of 60 g, was chosen. The jar is round in shape and is made from polyethylene terephthalate (PET) material. The net amount of red pepper paste taken by 1300 cc pet jar is 1550 g. The selected jar lid is the Marmara pet lid, which has the following parameters: it is coded as 3376, made of high density polyethylene (HDPE) material, has a mouth diameter of 110 mm, a width of 114.6 mm, a height of 25.6 mm, and weights 29 g. These lid specs were obtained from the website, the company of Teknopet Plastik Ürünleri ve Pet Ambalaj San. Tic. A.Ş. 120.6 pet jars are necessary to package 186.92 kg of red pepper paste into 1300 cc jars. Given that, each PET jar has a weight of 60 g, and each lid has a weight of 29 g, a total of 7.236 kg of PET material and total amount of 3.497 kg HDPE material will be utilized respectively to produce 120.6 PET jars with lid. One 65 × 50 mm label with a 30 µm thickness weighs 12.43 g. For 287.57 jars, a 3.574 kg PET label is thus used. 6 pet jars are loaded in a carton box. The pet jar has a surface area of 0.0870 m². The appropriate box area is 0.54 m². Thus, a box weighs 68.04 g. A total of 1.3676 g of cardboard will be needed to make 20.1 boxes.

3.3.3. Roasted sweet red pepper production

3.3.3.1. Sweet red pepper farming

Sweet red pepper farming is the main process in all SRP products evaluated in this research. As a result, detailed explanations are provided in Section 2.1.1 for SRP farming step.

3.3.3.2. Factory processing of roasted sweet red pepper

Figure 3.8 shows the main steps of roasted SRP production (Gül et al., 2021; Özdikmenli & Demirel Zorba, 2015). The roasted red peppers are carefully prepared through an intensive procedure that involves sorting, washing, and subjecting them to specialized oven processing or flame roasting in order to remove the skins (Gül et al., 2021). Flame peeling is primarily employed for removing the skin of red peppers. This method involves the use of machines with a diameter of approximately 60 cm and a length of 6 m, inclined at an angle of 10-15% and rotating at a speed of 15 rpm. The raw material is transported to the oven via a conveyor

belt, where it is exposed to temperatures exceeding 1000 °C. The product is then passed in front of the flame, which rapidly heats it, causing the peel to separate instantly. The roots and outer skins of the vegetables are incinerated in the process.

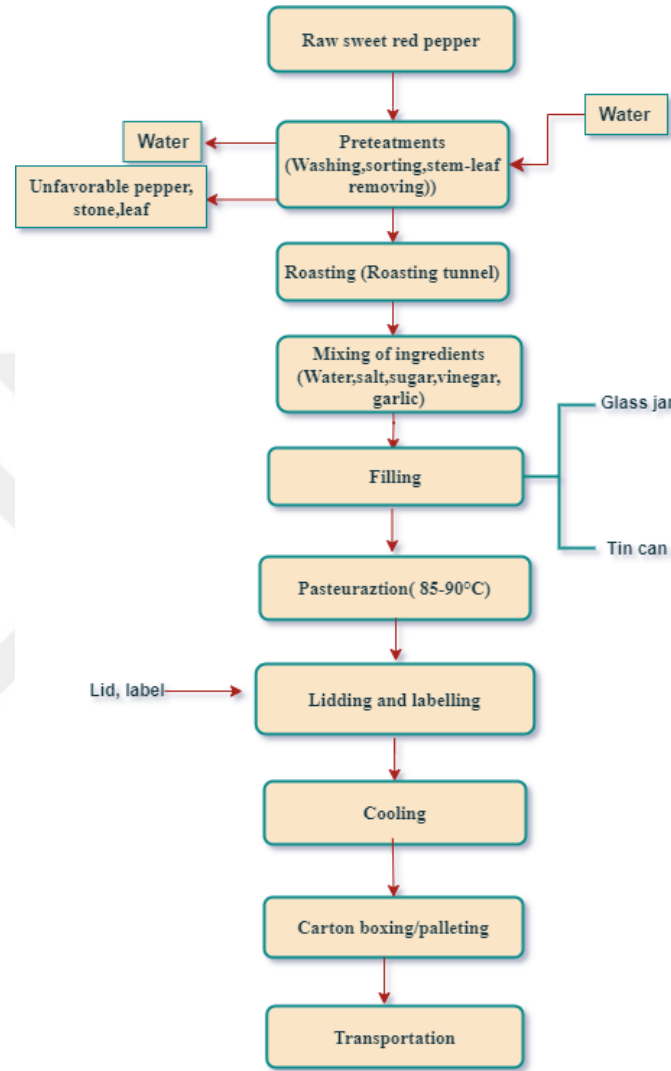


Figure 3.8. The production steps of roasted sweet red pepper (Gül et al., 2021; Özdikmenli & Demirel Zorba, 2015).

On average, a loss of 9% of the product occurs (Doğaka, 2017). The prepared peppers are thereafter filled into glass jars. Following that, water, vinegar, salt, oil, sugar, and garlic are added, and subsequently undergo pasteurization (Koca & Erdoğan, 2011). It is reported that, a 1 kg glass jar of roasted SRP contains the following ingredients: 350.1 g of roasted peppers, 258.4 g of water (specifically, drinking water sourced from ground water), 2.05 g of garlic, 10.9 g of salt, 25.8 g of sugar and 29.3 g vinegar (Gül et al., 2021).

In Turkish cuisine, the consumption and production rate of roasted peppers is significant. Therefore, employing LCA can help manufacturers comprehend the environmental impact of each processing step. This understanding can guide them in establishing environmentally friendly production units within their process flow, resulting in a substantial potential for mitigating environmental impact (Gül et al., 2021).

3.3.3.3. Packaging and transportation

The roasted SRP is filled in containers constructed of 230 kg LCS sheet, which are conical drums as primary packaging manufactured by the Izvar brand. Each drum has a weight of 12.4 kg. A total of 882.612 kg of roasted SRP requires the utilization of 3.8374 barrels, which corresponds to 47.58 kg of steel. The production date and manufacturer name are coded on the barrels' side surfaces using an ink jet technology. Nevertheless, due to the minimal impact of ink jet usage in terms of tonnage, it is ignored in the calculations. The packaging of 'Hisar Konserve' product categories, produced in Türkiye, served as the basis for selecting the packaging in the present study. Furthermore, according to the interviews conducted with the packaging companies, it was revealed that, the manufacturers predominantly favor glass jars to accentuate the visual appeal of the roasted pepper. A glass jar with a capacity of 720 cc is recommended for storing roasted peppers. The glass jar with a capacity of 720 cc contains roasted peppers with a net weight of 690 g and a filtered weight of 480 g. In this study, the product specifications of 720 cc glass jars were obtained from the website of Arslan Packaging Trade and Industry Inc., a company operating in the packaging market in Türkiye. The cylindrical glass jar with a twist-off lid has a height of 141.4 mm and a width of 89.7 mm. It has a capacity of 720 cc and weighs 280 g. A carton box contains either 12 or 24 units. The surface area of a jar with a capacity of 720 cc is 0.053 m² on average. The average surface area of a carton is 0.635 m².

Assuming that the weight of a carton is determined by a calculation of 0.126 kg/m² (Karakaya & Özilgen, 2011), the weight of a single carton is precisely 80.01 g. Hence, a total of 23.35 kg of cardboard will be required for 291.79 boxes for a quantity of 882.61 kg SRP. The weight of an 82 mm twist-off metal jar lid is 11.29 g. In this case, 82 mm twist-off covers were preferred. The jars are put into a box consisting of 12 units. A jar with a capacity of 720 cc is filled with 252.07 g of SRP. 1 ton of SRP yields 882.61 kg of roasted SRP (Table 3.4). It is calculated that 3501.45 glass jar of roasted SRP are obtained from 1 ton of fresh SRP. Thus,

980.40 kg of glass and 39.53 kg of steel will be utilized in the processing of 1 ton of fresh SRP to produce roasted SRP in glass jars.

Table 3.4. The recipe for producing roasted sweet red pepper from 1 ton of fresh SRP

Ingredients	Weight (kg/ton)
Roasted SRP	882.61
Water	651.44
Salt	27.48
Sugar	65.04
Vinegar	73.87
Garlic	5.17

Tin packaging is another type of packaging that will be examined in the context of the scenarios. Upon examining the packaging of roasted peppers in tin cans in Türkiye, it is evident that packages weighing between 3-5 kg are predominantly favored, particularly by the catering industry. Currently, there are a greater number of containers that are appropriate for these specific weights in the packaging industry. The product specifications were acquired by communication with the ‘Saribekir Packaging’ company in the present investigation. The ‘A10’ coded tin packaging has dimensions of 153 mm in width, 176 mm in height, and weighs 3100 g. It has a capacity to carry 3 kg of roasted pepper. The product has a net weight of 3 kg, and the weight of the filter is either 1750 g or 1850 g. The mass of one tin package is 265 g. It is calculated that 813.40 tin can of roasted SRP are obtained from 1 ton of fresh SRP. Thus, 215.55 kg of steel will be utilized in the processing of 1 ton of fresh SRP to produce roasted SRP in tin jars.

Cardboard boxes were designed to contain 3 kg cans, with each box containing 4 cans. The tin can has a surface area of 0.12034 m². The appropriate surface area of the cardboard box for this package is 0.54 m². The weight of a carton is precisely 68.04 g. A total of 203.35 cartons are needed, with each carton containing 4 cans. For this particular scenario, an overall amount of 13.836 kg of cardboard will be utilized.

3.3.4. Dried sweet red pepper production

3.3.4.1. Sweet red pepper farming

Sweet red pepper farming is the main process in all SRP products evaluated in this research. As a result, detailed explanations are provided in Section 2.1.1 for SRP farming step.

3.3.4.2. Factory processing step

Figure 3.9 shows the main steps of dried SRP production processing (KDA, 2019; Kuchi, Gupta, & Kachwaya, 2014; Ozturkoglu-Budak, 2017). Peppers are conventionally dehydrated through natural means, by being left in the open air and exposed directly to sunlight. Nevertheless, due to the susceptibility of this drying process to weather conditions, its drying time is prolonged, and there is a potential risk of contamination by foreign substances (such as sand, dust, etc.) and mycotoxins in the dried products, making it an unfavorable choice. Alternatively, numerous artificial drying technologies and techniques, such as hot air drying in cabins or tunnels, infrared drying, freeze drying, microwave drying, dielectric drying, and ultrasound, are used (Aras, 2022). In a study, a laboratory experiment was done to investigate the drying characteristics of red pepper in a drier. The results indicated that, the optimal drying temperature for red pepper should not exceed 60 °C, as temperatures in the range of 65-70 °C, may lead to burning. Prior to the drying process, it has been documented that taking samples of pepper and subjecting them to cutting or chopping can noticeably decrease the amount of time required for drying (Doğantan, Tunçer, & Başçetinçelik, 1987).

The effects of various drying conditions and factors (drying temperature, chopping method, and storage conditions) on the quality preservation of dried pepper samples were taken into consideration in a different study to determine the most suitable drying temperature, cutting type, and storage conditions. The optimal conditions were found to be 60 °C, ring shape, and cold storage (Aras, 2022). The feasibility study of a dried fruit and vegetable plant states that the end weights of the dried products will be reduced to 1/10 of the weight of tomatoes, peppers, and quinces, 1/8 of the weight of strawberries, 1/12 of the weight of peaches, and 1/5 of the weight of persimmons (Bebka, 2021). A study was conducted using a tray dryer at an air velocity of 1 m/s and a temperature of 50 °C. The drying process resulted in an increase in dry matter from 9.08% to about 88% for the pericarp section of red pepper (Yılmaz-Ozdere, 2023).

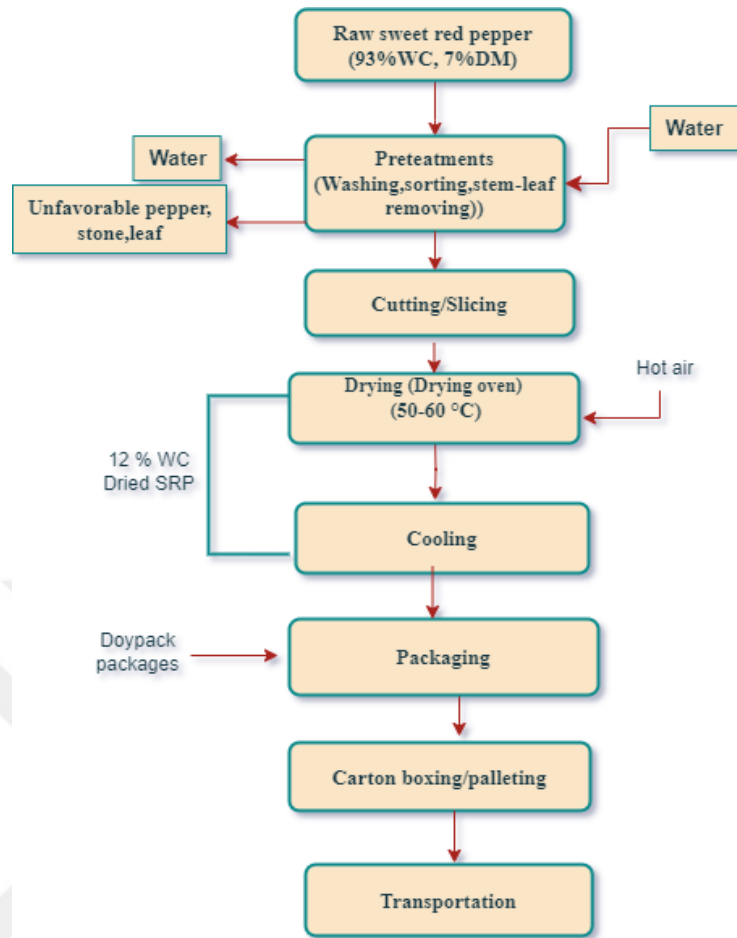


Figure 3.9. Dried sweet red pepper production steps (W.C: Wet content, D.M: Dry matter) (KDA, 2019; Kuchi, Gupta, & Kachwaya, 2014; Ozturkoglu-Budak, 2017)

3.3.4.3. Packaging and transportation

A metallized doypack package with a width of 200 mm, a height of 300 mm, and a bottom curve of 50 mm was utilized. The packaging is transparent. In order to achieve this objective, the company called ‘SC Doypack Packaging’ in the Turkish market was contacted and the specifications of the product were acquired. The weight of a single 1 kg dried SRP package of doypack packaging with dimensions of 20*30*5 cm and made of transparent metallized material is 10.8 g. A total of 1.0714 kg doypack material will be used. As it can be seen from different data provided in the literature, the most common types of doypack packaging are: combined polyethylene (55-60% of all packaging), combined polypropylene (20%), combined paper (5%), combined polypropylene with aluminum and polyethylene terephthalate; combined polyethylene with polyethylene terephthalate; as well as types of packaging where there is no marking or there is a ‘7 other’ mark (14-19%) (Borysovska &

Bovsunovsky, 2022). According to another study, the doypacks included materials like PET, oriented polyamide (OPA), and polypropylene (PP). In more detail, the doypack composition with aluminum-layer consisted of 10.81% PET, 8.11% Aluminum (ALU), 13.51% OPA, 67.57 PP (Saarniit, Lang, Kuldjarv, Laaksonen, & Rosenvald, 2023). Özilgen (2016) stated that, the energy consumption of virgin paper is 10 GJ per ton. However, when the pulp is made from recycled paper, the energy usage decreases by 64%. Based on information from literature (Borysovska & Bovsunovsky, 2022, Saarniit et al., 2023) and specifications provided by doypack companies such as ‘Morpack, KRCPACK, SC Doypack’, this study estimates that the doypack package is composed of 50% PE, 20% PP, 5% paper, and 25% PET. So the doypack composition consists of 0.53585 kg of PE, 0.21434 kg of PP, 0.267925 kg PET, and 0.053585 kg of paper. A carton box contains 12 units. The average surface area of a carton is 0.7424 m². Assuming that the weight of a carton is determined by a calculation of 0.126 kg/m² (Karakaya & Özilgen, 2011), the weight of a single carton is precisely 93.54 g. Hence, a total of 0.7728 kg of cardboard will be required for 8.261 boxes for a quantity of 99.2053 kg dried SRP.

The second scenario for dried SRP consisted of evaluating bulk dried SRP in 25 kg kraft packaging (25KP). An alternative packaging option for dried SRP in the food industry is offered for sale in 25 kg bulk kraft packaging. In order to achieve this objective, a quantity of 25 kg of kraft food packaging material was utilized. The kraft package weighs 0.6 kg and it is estimated that 8.3% of polyethylene is utilized in its production (Uçal, Yildizhan, Ameen, & Erbay, 2023). For a quantity of 99.2053 kg of dried SRP, precisely 3.97 pieces of kraft packaging will be utilized. Consequently, a total of 0.2 kg of PE and 2.18 kg of paper will be utilized to produce 2.381 kg of kraft packaging.

3.4. Analysis Methods

3.4.1. Cumulative exergy consumption method

The first law of thermodynamics emphasizes energy conservation, while the second law addresses irreversibility, quantifies energy losses, and suggests ways to reduce them. Exergy is a measure of energy quality and the degree of thermodynamic imperfection in energy transition (Szargut, 1987a; Szargut & Morris, 1987b). Exergy depends on both system and environmental factors, in contrast to energy, which is independent of environment conditions. One important shortcoming in energy analysis is that it ignores energy quality. A different

conclusion will be drawn, if the analysis takes energy quality into account. Energy analysis thus results in less-than-ideal decisions. With the use of exergy analysis, ‘quality’ as well as ‘quantity’ of energy flows is taken into account. Consequently, exergy offers a general technique for the ‘rational use of resources’ (Frangopoulos, 2009). Dincer and Rosen (1999) established the attributes of exergy in a publication. Several noteworthy properties of exergy may be identified:

- The state in which a system is in full equilibrium with the reference system is referred to as the ‘dead state’. The system's exergy is equal to zero, when it is in the dead state,
- The exergy of a system increases, as it moves further away from the surrounding conditions,
- The exergy and energy of electricity are equivalent, similar to shaft work,
- The estimated chemical exergy values for gaseous, liquid, and solid fuels are 0.95–0.98, 0.98–1, and 1–1.04, respectively,
- Exergy is a measure of quality, whereas energy is a measure of quantity,
- Exergy, unlike energy, is irreversibly destroyed. In a reversible process, exergy is neither destroyed nor produced.

The thermodynamic inefficiencies of a system arise from irreversibility occurring inside the system, as well as from the destruction of exergy and the transfer of exergy to the environment (resulting in exergy loss). Thus, exergy-based analysis, which relies on the principles of the second law of thermodynamics, is employed to address the aforementioned issues in energy analysis. Beyond the scope of technical analysis, it is utilized to uncover the origins and extent of inefficiencies with the goal of minimizing them. Furthermore, exergy analysis can be applied across the full production and consumption chain, including the entire process from resource extraction to environmental emissions. As a result, it can also be utilized in the assessment of environmental impacts (Dewulf, Van Langenhove, Muys, Bruers, Bakshi, Grubb, & Sciubba, 2008; Morosuk, Tsatsaronis, & Koroneos, 2016).

Production operations, comprising multiple stages from the extraction of raw materials to the production of final products, necessitate the consumption of energy. As a result, cumulative energy consumption (CEnC) has emerged as a crucial method for examining the energy usage

throughout the production process. This analysis, known as industrial energy analysis or energy costing, is used to calculate the necessary increase in fuel extraction based on planned changes in production of products and to assess the impact of fuel price fluctuations on product costs. Nevertheless, this analysis tool has significant limitations. It fails to consider the consumption of non-energetic raw materials, the distinction between the quality of different types of energy, and the level of thermodynamic imperfection. Applying the second rule of thermodynamics and the idea of exergy can help address some of these constraints (Szargut, 1987a; Szargut & Morris, 1987b).

The application of the second law of thermodynamics has led to the development of a method called cumulative exergy consumption (CExC) analysis. This method takes into account all stages of a process, from the utilization of natural resources to the production of final products (Dewulf et al., 2008). Cumulative exergy consumption is a term that refers to the total amount of exergy consumed across all stages of a production process, encompassing the exergy of all resources utilized (Szargut, Morris, & Steward, 1988). The primary concept behind these methodologies is to view production processes as a collection of individual processes. Each stage contributes to the rise in input exergy, the destruction of exergy due to internal irreversibility, and the addition of exergy value to the end output. Hence, the ultimate outcome possesses an aggregated exergy value that can be computed after the manufacturing procedure is identified (Dewulf et al., 2008; Sciubba, Bastianoni, & Tiezzi, 2008). Because CEnC excludes non-energetic raw materials, it cannot provide an assessment of the environmental impact of the process (Özilgen & Sorgüven, 2011). The cumulative exergy methodology offers novel assessment indicators for the sustainability and renewability of manufacturing methods. CExC is a process pathway function that quantifies the whole exergy consumption for production, including raw materials, transportation, work, and heat transfer. The cumulative exergy strategy is a significant way to enhance the renewability of agricultural and manufacturing processes, due to this approach (Yildizhan & Taki, 2018). Over the past ten years, the CExC of several fuels and industrial items has been calculated but CExC calculations in the food industry are uncommon (Özilgen & Sorgüven, 2011).

The concept of exergy, which refers to the maximum amount of useful work that can be obtained from a system, as it reaches equilibrium with its surroundings, has applications in fields, such as industrial ecology and environmental engineering. It enables the more efficient

use of energy and the reduction of negative environmental impacts. Since the late 1990s, exergy analysis has been applied to resource and environmental studies, in order to establish comprehensive analytical frameworks. The features of this framework make it an intriguing analytical tool for researchers. Additionally, exergy analysis can serve as a decision-making tool for policy makers to make sustainable choices (Salehi, Mahmoudi, Bazargan, & McKay, 2018). The CExC-index estimates the total exergy values of natural resources that are supplied to the system through all the links in the manufacturing process chain, per unit of the specific product being analyzed (Szargut & Morris, 1987b).

The CExC-index adheres to the principle of conservation. The CExC of the products from each process is equal to the total of the CExC of the delivered semi-finished products and the exergy of natural resources extracted directly from the environment. Hence, the CExC-index values can be computed based on the collection of balanced equations proposed by Szargut and Morris (1987b). The graphical sequence method for the CExC-analysis was presented by Szargut and Morris (1987b), following a similar approach to the one proposed by the International Federation of Institutes for Advanced Study (1974). In order to conduct a more comprehensive study, which includes calculating exergy losses, the scheme needs to be supplemented. Figure 3.10 (Szargut, 1987a) illustrates the schematic diagram of an intermediary connection in the series of production procedures. The constituent process is identified in the prominent (topmost) rectangle. Each huge rectangle is connected to a triangle that is seamlessly integrated with a small rectangle. The exergy A and the CExC-index B of the product resulting from the constituent process are provided in the triangle. An additional ratio, $E = A/B$, can be inserted to describe the CDP (cumulative distribution function) of the intermediate product being considered. The exergy loss C and the relative exergy loss D are provided in the little rectangle located above the triangle. The rectangle that encompasses both circles contains the data C and D pertaining to transportation. The product's name and quantity are indicated within the double circle below. The distribution of the intermediate product among the subsequent operations can be illustrated in separate individual circles. If the exergy requirement for the production of machines and installations is not excluded, the name of the machines and installations can be placed inside a rhombus, connected to the higher circles that provide information about the kind and amount of the consumed semi-finished items.

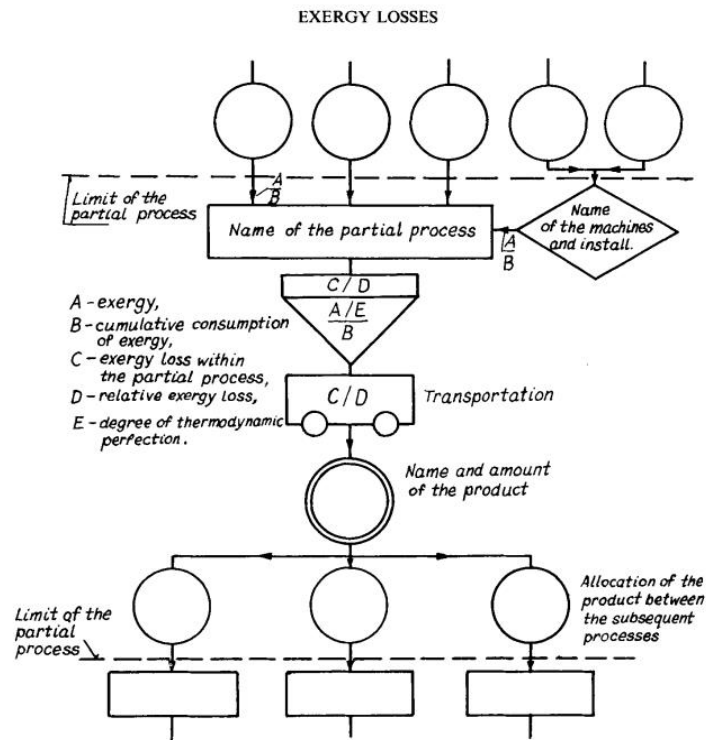


Figure 3.10. CExC-analysis scheme for an intermediate link in the production process chain (Szargut, 1987a)

The analysis of CExC should be conducted in three sequential steps. The initial stage involves determining the consumption of raw materials and semi-finished products at every stage of the production process chain. The calculation of this step should commence with the final link of the chain of industrial operations. The second stage involves calculating the CExC-indices, starting with the first linkages that represent the acquisition of raw materials. The exergy losses and CDP values can be determined in the third phase. The results of the CExC-analysis suggest that certain raw materials, semi-finished products, or energy carriers should be removed from the production process chain as much as possible due to their negative impact on the overall efficiency of the production processes (Szargut, 1987a). In this study, a comprehensive analysis of mass (Appendix-A), energy (Appendix-B), and exergy (Appendix-B) balance is conducted for every operation. In Appendix-F, the specific CEnC, CExC and CCO₂C values of inputs for each step are illustrated. The following are the governing equations for this steady-flow system:

Mass balance equation:

$$\sum(\dot{m})_{in} - \sum(\dot{m})_{out} = 0$$

Energy balance equation:

$$\sum(\dot{m}h)_{out} - \sum(\dot{m}h)_{in} = Q - W$$

Exergy balance equation:

$$\sum(\dot{m}b)_{in} - \sum(\dot{m}b)_{out} - \sum_k Q_k \left(1 - \frac{T_o}{T_k} \right) - W = X_{loss}$$

3.4.2. Life cycle assessment

The LCA methodology is used to assess the environmental implications of a process across its entire life cycle. According to ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), the four fundamental stages of LCA include goal and scope definition, life cycle inventory, life cycle impact assessment, and improvement assessment. LCA analysis enables the correlation of a comprehensive range of data pertaining to the life cycle of a product or process. Its primary objective is to identify the specific phases of the process that possess significant environmental implications. The following subsections provide an outline of the major stages involved in a LCA analysis.

3.4.2.1. Definition of the goal and scope, functional unit and system boundaries

Goal definition is one of the most significant stages of the LCA approach, as the decisions taken at this step have an impact on the entire study. The purpose of this research is to assess the environmental implications of retail tomato, tomato juice, tomato paste, retail SRP, roasted SRP, SRP paste, and dried SRP. All steps of production are considered, including farming, factory processing, packaging and transport stages. This allows us to compute the values of the various impact categories and determine which input is the primary cause of these consequences. Due to the lack of data and the difficulties in forecasting consumer behavior, the consuming stage is not taken into account. Additionally, another important objective is to evaluate the potential impact of different strategies in enhancing the overall environmental sustainability of the entire supply chain. For this purpose, many scenarios were investigated, as well as the impact of various characteristics on impact categories. The entire life cycle has been classified into three major stages: tomato cultivating, tomato processing,

packaging and transport. The system was designed using a cradle-to-gate methodology. For the base case, the functional units were selected as one kg of packaged product for each raw material.

3.4.2.2. Life cycle inventory

Each research has its own inventory, which is generated via collecting the data required to accomplish the study's objectives in order to fulfill those objectives. An extensive review of literature and additional data sources were collected as the first step. The backdrop system data, which included agrochemical manufacturing, electricity (medium voltage), transportation was obtained from the Agribalyse 3.1 and Ecoinvent 3.9.1 databases. Life cycle inventories of each specific processing step and inputs and quantities required for packaging and transportation of tomato and SRP products for 1 kg functional unit are provided in Table 3.2 and Table 3.3.

3.4.2.3. Life cycle impact assessment

Life cycle impact assessment (LCIA) is the stage, where the inventory analysis results, particularly the inventory table, are analyzed and interpreted in relation to their environmental effects. An impact score is derived by aggregating the various elementary flows that contribute to a specific impact category, based on an evaluation (van Oers, Guinée, & Heijungs, 2020). During the impact assessment phases, the findings of the inventory analysis are converted into contributions to predetermined impact categories that are relevant. The inventory analysis involves identifying all the inputs from the environment, such as raw materials and fuels, as well as the outputs to the environment, such as energy and emissions, which enter and exit a power generation facility (Pikoń, 2012).

The LCA study was carried out using OpenLCA 1.11.0 (Green Delta GMBH, Berlin, 2021) software, and the impact assessment categories were chosen as CML-IA baseline technique (Guinée, 2002). Abiotic depletion (ADP), Abiotic (fossil) depletion (AFDP), acidification (AP), eutrophication (EP), global warming potential (GWP), ozone layer depletion (ODP), human toxicity (HTP), freshwater aquatic ecotoxicity (FWEP), terrestrial ecotoxicity (TEP), and photochemical oxidation (POCP) are the impact categories calculated via CML-IA baseline method. Table 3.5 presents the primary impact categories that are discussed in this study.

Table 3.5. Life cycle impact categories and their units

Impact category	Reference unit
Abiotic depletion	kg Sb-eq
Abiotic depletion (fossil fuels)	MJ
Acidification	kg SO ₂ -eq
Eutrophication	kg PO ₄ -eq
Fresh water aquatic ecotoxicity	kg 1.4 DB-eq
Global warming	kg CO ₂ -eq
Human toxicity	kg 1.4 DB-eq
Ozone layer depletion	kg CFC 11-eq
Photochemical oxidation	kg C ₂ H ₄ -eq
Terrestrial ecotoxicity	kg 1.4 DB-eq

3.4.2.4. Life cycle improvement scenarios and sensitivity analysis

A sensitivity test was carried out to determine how the output parameter (environmental impact) varies, when the input values change. Morris one-at-a-time strategy was used to modify input parameters (Groen, Heijungs, Bokkers, & de Boer, 2014; Shimako, Tiruta-Barna, de Faria, Ahmadi, & Sperandio, 2018; Sun, Newham, Croke, & Norton, 2012; Szargut et al., 1988). This is based on changing each input factor independently of the others and seeing how the results changed. The assessment involved evaluating the impacts of modifications in farming methods, the availability of renewable fuel choices, and the utilization of different packaging materials on the observed changes in outcomes. Upon examining the results of the base case, it was observed that, the excessive application of fertilizer played a significant role in the impact categories associated with tomato and SRP cultivation. Precision farming, also known as precision agriculture, involves the adoption of potential adjustments of fertilizers based on findings from the literature. Precision agriculture technology may convert farming data into valuable information, potentially improving the efficient utilization of agricultural resources and enhancing sustainability (Liu, Langemeier, Small, Joseph, Fry, Ristaino, & Preckel, 2018).

Furthermore, throughout the packaging and transportation step, steel, glass and diesel emerged as the primary factors influencing impact categories. In addition, diesel, electricity, and natural gas played a significant role in both the production and transportation steps. Several studies suggest that, electricity generated from non-fossil fuel sources, has the

potential to yield substantial cost reductions in comparison to conventional energy production methods (Peng, Lu, & Yang, 2013). The following scenarios presented in Table 3.6 were used in the study to conduct sensitivity analysis in the context of tomato and SRP products.

Table 3.6. Scenarios carried out in tomato and SRP products processing

Tomato products	Definition
Base case (BC)	Tin packaging, diesel usage,
Precision farming (PF)	50% less fertilizer use
Biodiesel utilization (BD)	Biodiesel usage
Glass packaging (GP)	Glass packaging
SRP products	Definition
Base case (BC)	Glass packaging, diesel usage,
Biodiesel utilization (BD)	Biodiesel usage
PET packaging (PET)	PET packaging
Precision farming (PF)	50% less fertilizer use
PF-BD	Combination of 50% less fertilizer and biodiesel use
PET-BD-PF	Combination of PET packaging, biodiesel and 50% less fertilizer

4. RESULTS AND DISCUSSION

4.1. Cumulative Energy, Exergy and CO₂ Results of Tomato Products

4.1.1. Retail tomato

The retail tomato production results are illustrated in Figure 4.1, Figure 4.2, Figure 4.3, Figure 4.4, Figure 4.5, and Table 4.1. According to Figure 4.1, the primary factors that have the greatest impact on tomato farming step are diesel use, chemical fertilizer application, and electricity consumption respectively. Diesel consumption accounted for 41% of the CEnC value in field tomato production, whereas fertilizer, agricultural machinery, electricity, and water for irrigation contributed 23%, 13%, and 3%, respectively. In accordance with the study conducted, Esengun et al. (2007) reported in their study that, the largest rate of energy consumption among the entire amount was attributed to diesel oil, with fertilizer usage being the subsequent source of energy, and the primary factor contributing to the highest level of diesel oil energy consumption was the extensive utilization of machinery for activities; such as soil preparation, cultivation, and transportation in tomato farming. They claimed that, this was a result of excessive usage of chemical fertilizers because farming fertilizer procedures are typically not based on soil analysis. Similarly, Karakaya and Özilgen (2011) stated that, the main energy consumers in agriculture are diesel-powered trucks and chemical fertilizers. They offered that, diesel oil consumption can be minimized by utilizing energy-efficient trucks and improving delivery routes.

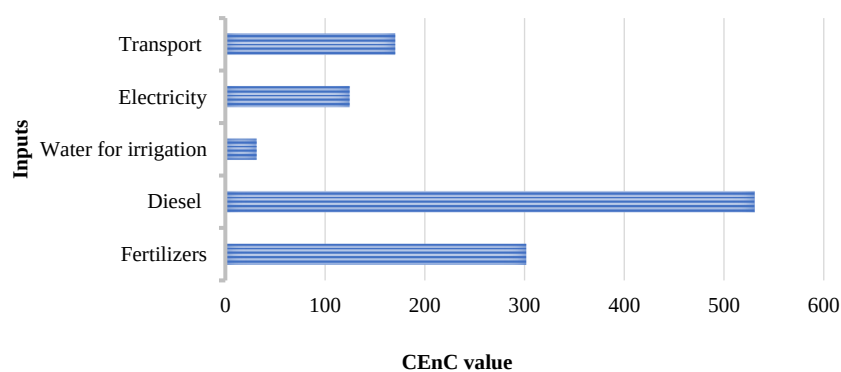


Figure 4.1. The top contributors to cumulative energy consumption (MJ/ton) of 1 ton fresh tomato production for the base case

Yıldızhan and Taki (2018) claimed that, diesel fuel, irrigation, fertilizer, and chemicals were identified as the primary inputs influencing all cumulative metrics assessed in both open field and greenhouse tomato production for the base case. Within the context of greenhouse tomato farming, a different study revealed that, diesel fuel constitutes the most significant share of total energy use, amounting to 34.35% of all inputs. The primary application of diesel energy was for powering tractors and facilitating various greenhouse operations. The use of diesel fuel is later followed by the use of fertilizer energy, specifically with the use of manure (Hatirli, Ozkan, & Fert, 2006). It is reported that, the energy consumption associated with fertilizer production constitutes around 40% of the overall energy usage in agricultural output within developed nations. The majority of the energy was utilized in the manufacturing process of nitrogen, phosphorous, and potassium fertilizers (Singh, Singh, Mittal, & Pannu, 1998). Therefore, in this context, the results of the research are consistent with studies in the literature.

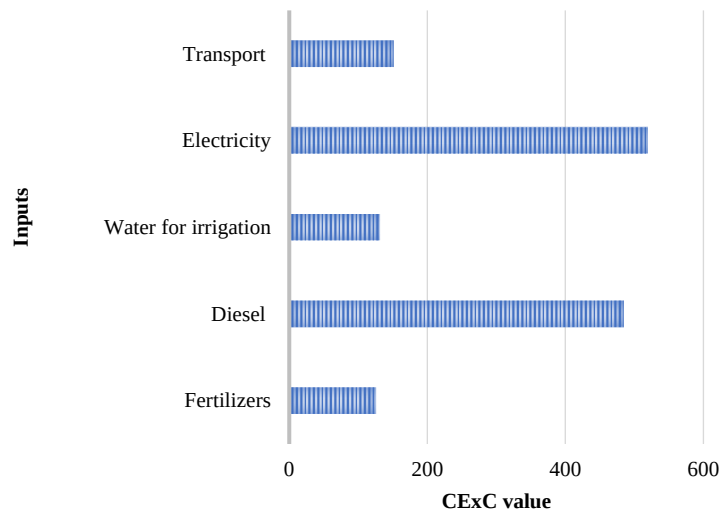


Figure 4.2. The top contributors to cumulative exergy consumption (MJ/ton) of 1 ton fresh tomato production for the base case

In their study, Yıldızhan and Taki (2018) found that, water for irrigation accounts for around 55% of the total CE_{ExC} in the south Marmara region, followed by diesel fuel and fertilizer. Electricity and diesel fuel made the greatest contributions to the overall CE_{ExC} in Antalya and Tokat regions, respectively. Nevertheless, the CE_{ExC} of chemicals is consistently low across all regions. In the present study analysis, similar to the findings in Antalya and Tokat regions,

the main factors contributing to the results are electricity and diesel fuel, accounting for 37% and 34% respectively.

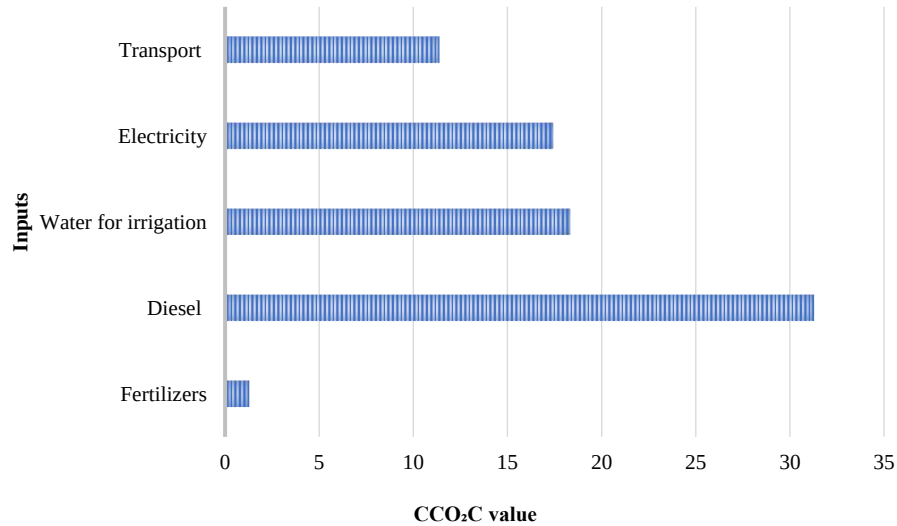
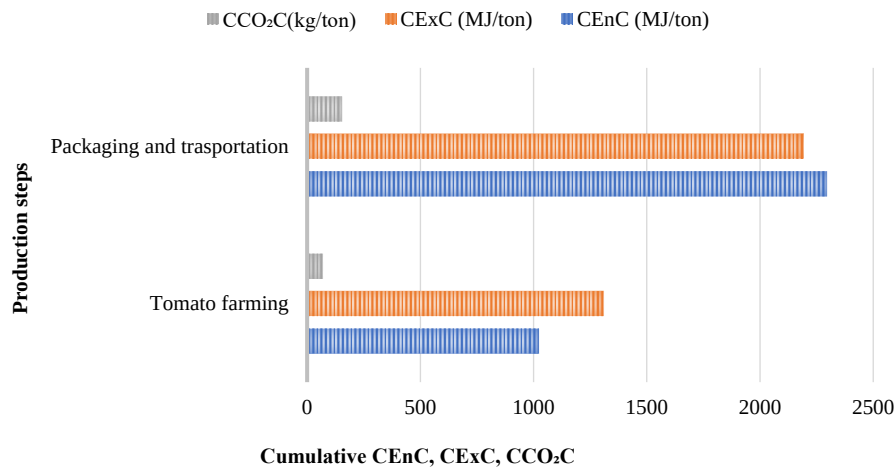


Figure 4.3. The top contributors to cumulative CO₂ emission (kg/ton) of 1 ton fresh tomato production for the base case

In packaging and transportation step the largest energy, exergy and CO₂ emission values were observed in diesel consumption and cardboard usage in this study. Since the product delivery trucks are regarded as making one-way trip merely because, in actuality, they frequently transport additional goods on the way back, the packaged tomatoes are assumed to be transported to 500 km distance from plant to the market. Diesel oil has a density of about 0.832 kg/L (Gnansounou & Raman, 2016), and it has an energy equivalent of 57.5 MJ/kg (Wittmus, Olson, & Lane, 1975) and 53.2 MJ/kg (Cengel & Boles, 2006), respectively. The diesel oil's carbon dioxide emission factor is 3.18 kg CO₂/kg (Kalnes, Marker, & Shonnard, 2007). Similarly for biodiesel energy equivalent is 37 MJ/kg (Carraretto, Macor, Mirandola, Stoppato, & Tonon, 2004), exergy equivalent is 8.8 MJ/kg (Sorguven & Ozilgen, 2010) and carbon dioxide emission factor is 0.97 kg CO₂/kg (Coronado, de Carvalho Jr, & Silveira, 2009). When comparing the fuel economy of diesel and biodiesel, It is reported that, at 60 km/h, 1-1.5 ton capacity trucks utilize 0.1667 l/km of diesel fuel and 0.06022 l/km of biodiesel fuel (Gnansounou & Raman, 2016).

Table 4.1. Cumulative energy, exergy and CO₂ results of retail tomato

Product	Scenario	CEnC (MJ/ton)	CExC (MJ/ton)	CCO ₂ C (kg/ton)
Tomato agriculture	BC	1023.54	1309.21	69.24
	PF	872.76	1246.52	68.59
	BD	632.30	857.83	41.59
	GP	1023.54	1309.21	69.24
Packaging and transportation	BC	2296.59	2192.32	154.96
	PF	2296.59	2192.32	154.96
	BD	748.10	392.45	25.10
	GP	2296.59	2192.32	154.96
Whole process	BC	3320.12	3501.53	224.20
	PF	3169.35	3438.84	223.55
	BD	1380.40	1250.27	66.69
	GP	3320.12	3501.53	224.20

**Figure 4.4.** Cumulative energy, exergy and CO₂ emission results related to the production of 1 ton retail fresh tomato

From Figure 4.4, it can be observed that, the packaging and transport stage has emerged as the most important contributor, when taking into account the various stages of retail tomato production. From Figure 4.5 and Table 4.1, when examining the separate impacts of each stage on established parameters in tomato farming and packaging and transportation, it is

observed that, the BC exhibits the highest values for CEnC, CExC, and CCO₂C. Conversely, the BD scenario demonstrates the lowest values, followed by the PF scenario. It is clear that, the BD scenario resulted in a great decrease in energy and exergy consumption, as well as a reduction in CO₂ emissions. Based on the present study and the aforementioned studies, it is evident that, the utilization of diesel has a significant impact on cumulative energy, exergy consumption, and CO₂ emissions. Therefore, it is reasonable to consider replacing diesel with a more environmentally and economically sustainable fuel alternative like biodiesel.

The current global energy crisis, as well as rising GHG emissions, necessitates an energy transition away from fossil-based fuels and toward alternative and sustainable biofuels (Raj, Sajith, Sreenikethanam, Vadlamani, Satheesh, Ganguly, & Bajhaiya, 2023). Biofuel is a non-fossil fuel created from renewable organic biomass, such as animals, microorganisms, plants, and waste (Rai et al., 2022). Numerous literary studies have been conducted on the substitution of diesel fuel with biodiesel in the context of food industry application (Karakaya & Özilgen, 2011; Özilgen & Sorgüven, 2011; Sorgüven & Özilgen, 2012; Uçal et al., 2023). Consequently, the utilization of biodiesel has the most significant effect on CEnC, CExC, and CCO₂C, resulting in a reduction of 58.4%, 64.3%, and 70.3%, respectively. According to Özilgen and Sorguven (2011), adopting effective agricultural practices and replacing diesel with biodiesel made from renewable sources can reduce the overall energy consumption in vegetable oil manufacturing. This reduction is particularly significant at the farming stage, where raw materials are obtained. In line with their study and as previously stated, the application of BD has resulted in a decrease in the cumulative energy value from 3320.12 MJ/ton to 1380.40 MJ/ton in retail tomato production.

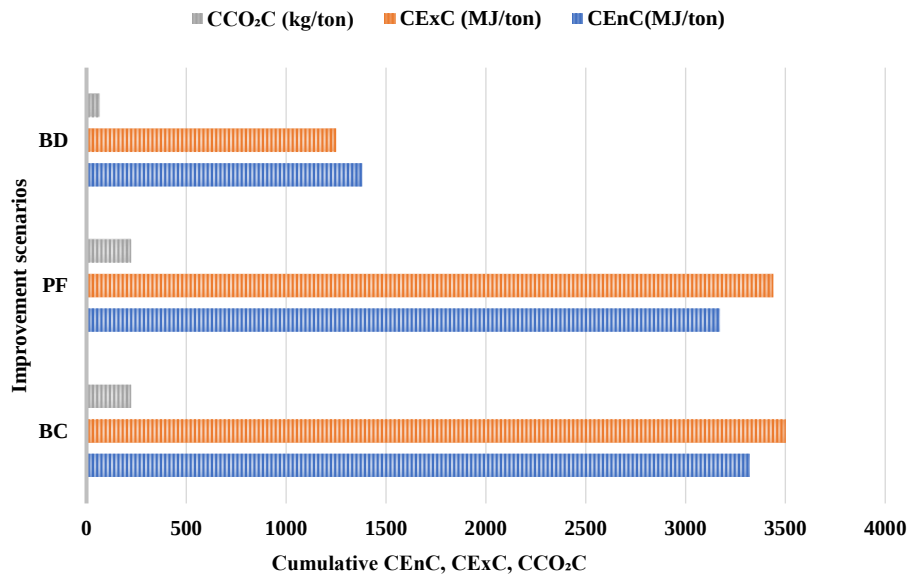


Figure 4.5. Comparison of different scenarios on 1 ton fresh retail tomato production

Considering the application of precision farming in tomato cultivation, there is a reduction of 14.7% in the CEnC value. Precision farming refers to the pursuit of improved efficiency in agricultural management. This evolving technology combines old techniques with new ones to create new tools for management positions. Integration of significant computing and electronics necessitates a more advanced systems approach for higher degrees of control. Precision farming involves monitoring and assessing an agricultural enterprise at a local and farm level, as well as understanding processes to apply inputs effectively to achieve a specific goal (Blackmore, 1994). Precision farming allows for the customization of agricultural management decisions based on specific locations and time periods. By employing site-specific sensing, sampling, and controlling techniques, farmers are able to consider a field as a heterogeneous unit. Precision farming effectively minimizes waste by strategically utilizing inputs, resulting in reduced private variable costs and environmental expenses, including those associated with agrichemical residuals. Technological advancements and the progress of big data are continuously enhancing the connectivity, accuracy, efficiency, and broad applicability of precision farming technologies. Enhancements in the technical infrastructure and the legal environment have the potential to broaden the availability of precision farming and consequently increase its overall socioeconomic advantages (Finger, Swinton, El Benni, & Walter, 2019).

4.1.2. Tomato juice

Through the entire process of tomato juice production, the CEnC, CExC, and CCO₂C values are presented in Table 4.2. When examining the individual production process (Figure 4.6) steps for CEnC, CExC, and CCO₂C, it is clear that, the packaging and transportation step within GP exhibits the greatest values for CEnC, CExC, and CCO₂C. Conversely, the lowest values are observed in the BD scenario in all categories. The factory processing stage is identified as the second most substantial contributor, whereas the cultivation step exhibits the lowest values. From Figure 4.7, the primary factors contributing to the industrial processing stage for tomato juice CEnC value are natural gas, which accounts for 97% of the energy used in the tubular sterilization machine, the aseptic filling unit, which accounts for 2%, and electricity usage, which accounts for 1%. On the other hand, as shown in Figure 4.8, the primary sources for CExC are natural gas (77%) and electricity (9%), because of the tubular sterilization machine. Additionally, only a fraction of natural gas (1%) is used for the aseptic filling unit, while the remaining equipment relies on electricity (13%).

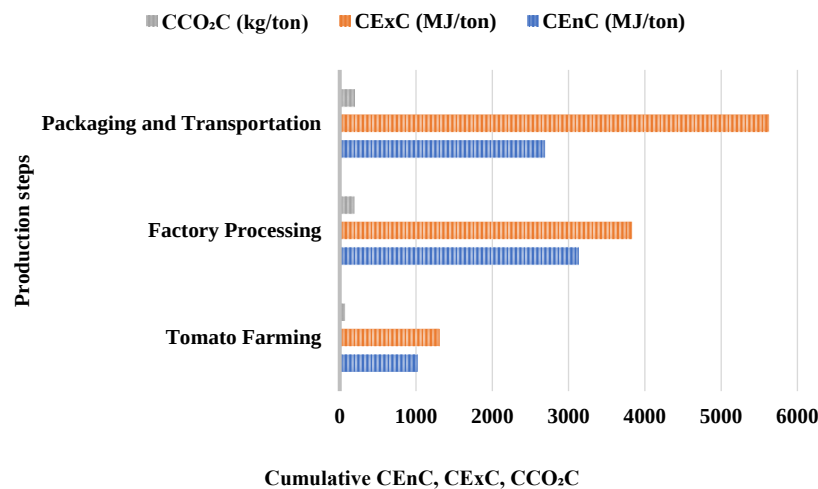


Figure 4.6. Contributions of production steps to CEnC, CExC and CCO₂C values of tomato juice production

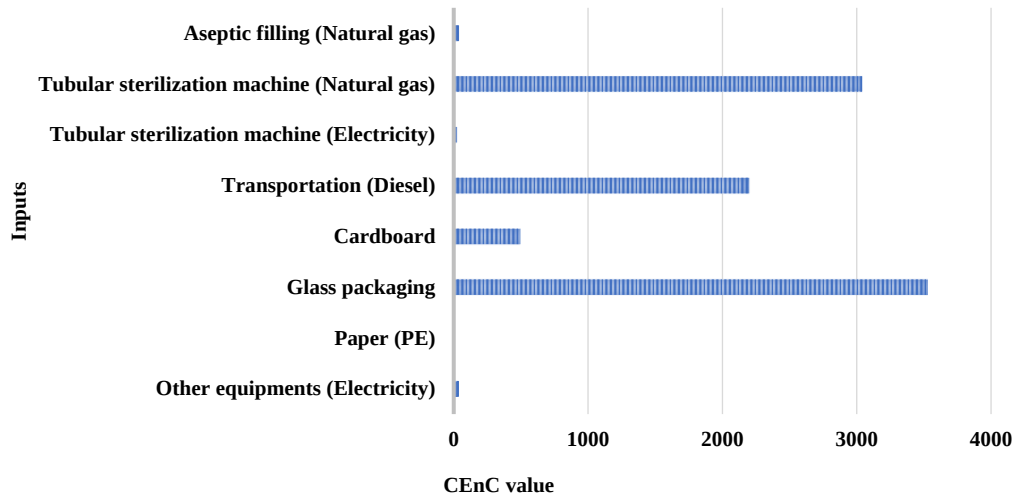


Figure 4.7. The top contributors to cumulative energy consumption (MJ/ton) of tomato juice factory processing and packaging and transportation for the base case

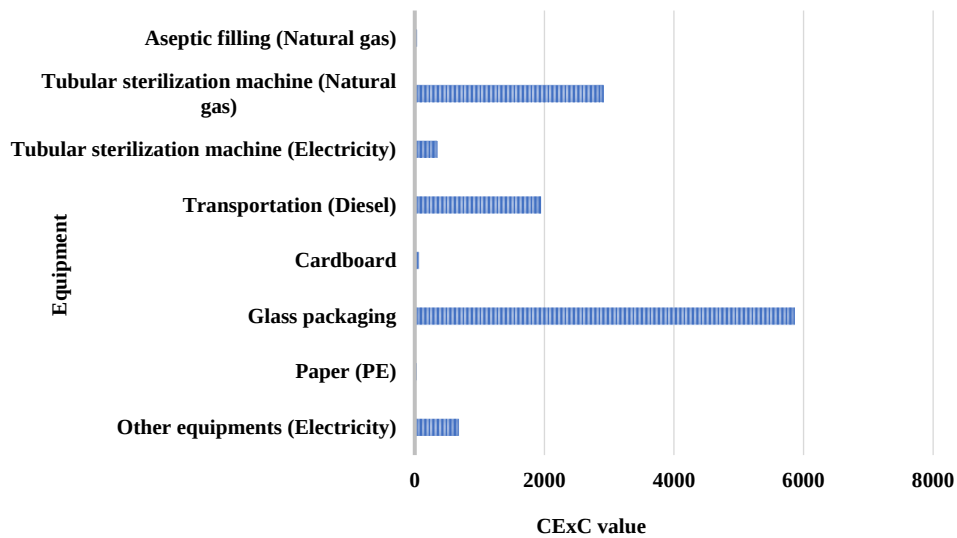


Figure 4.8. The top contributors to CExC (MJ/ton) of tomato juice factory processing and packaging and transportation for the base case

A study evaluating the relationship between water and energy in industrial tomato processing found that significant amounts of both water and energy are consumed in this process. The investigation determined that the thermal energy utilized to produce steam for the heat exchangers and evaporators used in the processing is the primary source of embedded energy

in the process water, amounting to 778000 gigajoules every season. The process water included a total of 4.4 million kilowatt-hours of electrical energy per season, with pumping accounting for almost 80% of this amount (Amón, Wong, Kazama, Maulhardt, Maulhardt, & Simmons, 2018). A different study was conducted on tomato juice, where the juice was concentrated using a microwave-vacuum heating system. The findings were then compared with those obtained from conventional and conventional-vacuum heating methods. An investigation was conducted to examine the impact of pressure and microwave power on several quality indicators, energy consumption, exergy performance, and processing kinetics of tomato juice concentration. The processing time in the microwave-vacuum approach was 2.3 to 6.3 times shorter, compared to the conventional and conventional-vacuum methods. The exergy performance achieved ranged from 7.16% to 13.29% for microwave-vacuum heating and from 2.04% to 2.99% for traditional methods. They stated that, microwave vacuum heating has the potential to decrease energy consumption by 30–71% when compared to conventional-vacuum approaches. In addition, they stated that microwave-vacuum heating is a highly effective method for concentrating tomato paste, resulting in enhanced nutritional value, improved exergy efficiency, shorter processing time, and reduced energy usage compared to traditional and conventional vacuum methods (Sofizadeh et al., 2023).

An extensive thermodynamic evaluation and exergetic performance analysis of a large-scale orange juice producing factory revealed that the total amount of exergy destroyed in the entire plant was 17.7 MW. Out of the total, the steam generation accounted for the bulk (76.2%), with the boiler and compressor contributing the most (12073.09 kW/89%) to the destruction of exergy. In the refrigeration system described, the ice-water tank had the most significant loss of available energy, with an exergy destruction of 2802.36 kW, accounting for 71% of the total exergy destruction. This issue might be mitigated by implementing thermal insulation. The mixing and pasteurization lines exhibited the least amount of exergy destruction, with a total of 1.5% (Khorasanizadeh, Nasiri, & Mahyari, 2021).

According to the novel processing studies (Sofizadeh et al., 2023; Sabanci, 2021; Alaei, Chayjan, & Zolfigol, 2022; Darvishi et al., 2015) presented in the literature, novel technologies such as microwave, ultrasound, ohmic heating, or their combinations have the potential to increase both quality and energy efficiency, resulting in lower CEnC values throughout the food supply chain. In a study conducted by Sabanci (2021), grape juice was

concentrated using the ohmic heating-assisted evaporation process, until it reached a water-to-dry matter content ratio of 2 ± 0.3 kg/kg. The concentrated grape juice was then analyzed in terms of thermodynamic laws and electrical conductivity value. It was shown that, an increase in the voltage gradient had a favorable impact on both exergy efficiency and energy efficiency. The resulting values ranged from 78% to 82%. Moreover, the increase of voltage gradient yielded a favorable impact on exergy efficiency and enhancement potential value. Notably, the exergy efficiency value varied between 68.9 and 73.1, in accordance with the principles of the 2nd law of thermodynamics. In another study conducted with the goal of improving tomato juice concentration using a novel ultrasound-thermal concentrator under vacuum conditions was carried out. The results included a reduction in the time required for concentration by 28.42% and a decrease in total energy consumption by 4.94%. Additionally, ultrasound increased the levels of lycopene by 49.20% and vitamin C by 22.10% in the concentrated tomato juice. Overall, the total energy consumption increased as a result of an increase in increasing the concentration temperature, lowering the vacuum pressure, and applying ultrasonic power. However, by shortening the length of the concentration process, the overall energy consumption of the tomato juice concentration process decreased in two different scenarios: with and without the use of ultrasound. The energy loss in ultrasonic waves and vacuum pressure was relatively low. The tomato juice's overall energy consumption during the concentration process decreased under the same conditions, as a result of the reduced concentration process time. This reduction had a greater impact on the tomato juice compared to the heat concentration provided by the outer surface of the concentration chamber in the hot water tank. The results suggest that, the tomato juice's overall energy consumption during the concentration process decreased under the same conditions, primarily because of a reduction in the duration of the concentration process (Alaei et al., 2022).

In the context of tomato production, Darvishi et al. (2015) investigated the energy and exergy analyses of liquid food in an ohmic heating process. They reported that, the energy efficiency declined from 100% to 55.53% as the moisture content decreased and the voltage gradient increased. On the other hand, the exergy efficiency increased from 3% to 83.51% as the moisture content decreased ($p < 0.05$). The energy efficiency ranged from 67.07% to 85.40%, while the exergy efficiency ranged from 27.75% to 60.34%. The specific energy consumption and average improvement potential decreased from 4.64 to 2.73 MJ/kg of water evaporation

and 14.18–2.82 kW, respectively, as the voltage gradient increased. The energy losses increased from 6.88 to 21.48 kW, while the exergy losses increased from 6.81 to 21.47 kW. They claimed that, this occurred as the voltage gradient and moisture content dropped.

As shown in Figure 4.9, the tomato juice supply chain revealed a CCO₂C value of 151.97 kg/ton for the tubular sterilization machine, which was derived from natural gas use. Additionally, the electricity consumption contributed 15.15 kg/ton to the CCO₂C value. Since the beginning of the Russia-Ukrainian conflict in 2022, natural gas has regained significance on the agenda of European nations. Nevertheless, natural gas is a fossil fuel that has significant environmental consequences (Belucio, Santiago, Fuinhas, Braun, & Antunes, 2022). Natural gas is commonly regarded as a more environmentally friendly fossil fuel that has the potential to be significant in a limited carbon allowance. Although natural gas produces less CO₂, when burned compared to other fossil fuels, it primarily consists of methane, which has a far greater climate forcing effect than CO₂ in the near term.

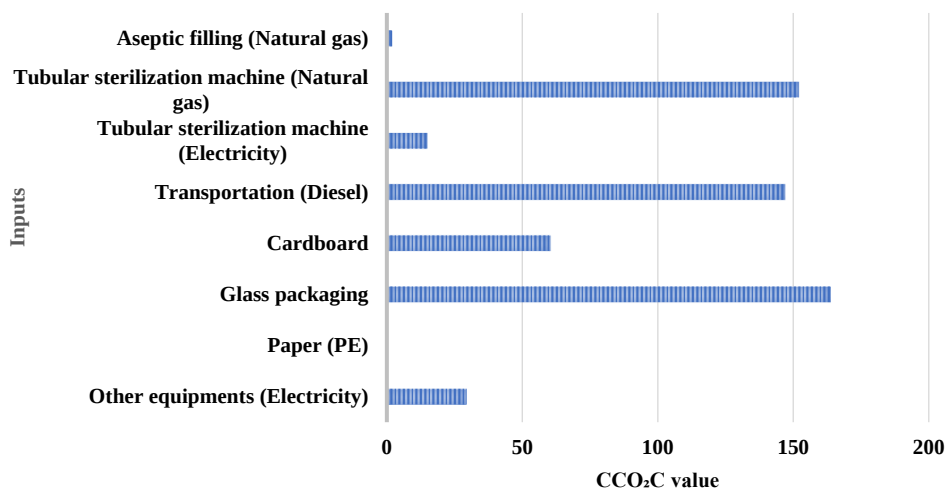


Figure 4.9. The top contributors to cumulative CO₂ consumption of tomato juice factory processing and packaging and transportation step for the base case

The calculation of methane emissions in the natural gas supply chain has been a topic of significant discussion, mostly due to ambiguities surrounding the techniques of estimation, the quality of data, and the assumptions made (Balcombe, Anderson, Speirs, Brandon, & Hawkes, 2017). Moreover, the CCO₂C value derived from the use of diesel in packaging and

transportation is 147 kg/ton, which represents a substantial portion of the total emissions. Motor vehicle CO₂ emission factors can be derived from fuel consumption data under stoichiometric conditions or obtained by direct emission measurements. Calculated emissions are based on the assumption that hydrocarbon fuels completely break down into water (H₂O) and CO₂. However, measured emissions take into account the inefficiencies in the combustion process, which means they may deviate slightly from the ideal reaction. In the case of petrol and diesel fuel, the complete combustion of one liter produces approximately 2.5 and 2.7 kilograms of CO₂, respectively (Australian Greenhouse Office, 2003). The findings suggest that, in the short term, natural gas has a minimal effect on CO₂ emissions compared to oil consumption (6.7 times lower). On the other hand, the use of renewable and hydroelectric energy has been shown to reduce CO₂ emissions in both the short and long term. The oil consumption elasticity is below unity, suggesting that efficiency improvements have been made throughout the switch to cleaner energy sources. If economies rely on non-renewable energy sources, governments should persist in prioritizing natural gas above oil. In order to reverse the trajectory of CO₂ emissions, it is imperative to utilize renewable energy sources including hydroelectric power. In light of the volatile situation resulting from the War in Eastern Europe, it is imperative for governments to prioritize expediting the shift from fossil fuels to renewable energy sources (Belucio et al., 2022).

It was found that, the highest values are obtained in the GP scenario of the packaging and transportation step, followed by the BC, PF, GP-BD, and BD, respectively (Figure 4.10). The BD scenario has resulted in a decrease in all measured metrics. Furthermore, the utilization of a combination of glass packaging and biodiesel, GP-BD, has resulted in a decrease in the values associated with glass packaging.

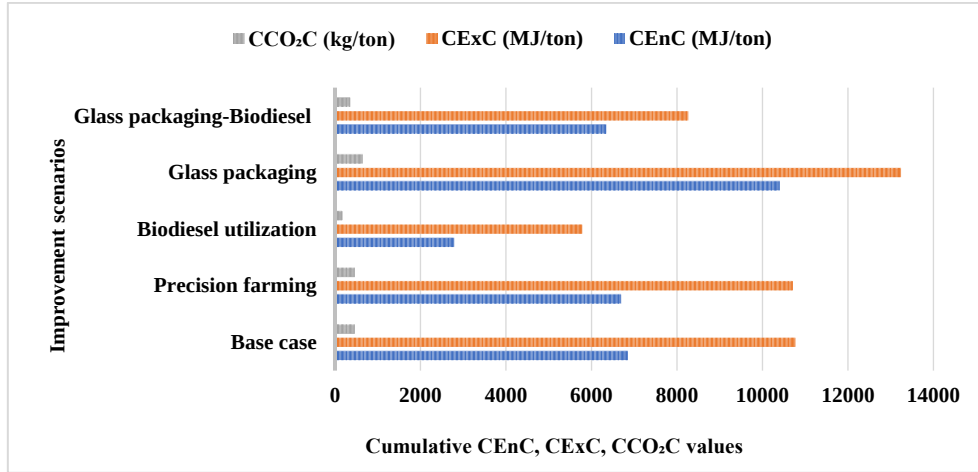


Figure 4.10. Comparison of different improvement scenarios on tomato juice production

Table 4.2. Cumulative energy, exergy and CO₂ results of tomato juice

Product	Scenario	CEnC(MJ/ton)	CExC (MJ/ton)	CCO ₂ C (kg/ton)
Tomato farming	BC	1023.54	1309.21	69.24
	PF	872.76	1246.52	68.59
	BD	632.30	857.83	41.59
	GP	1023.54	1309.21	69.24
	GP-BD	632.30	857.83	41.59
Factory processing	BC	3134.26	3834.87	191.97
	PF	3134.26	3834.87	191.97
	BD	1017.02	1108.85	63.21
	GP	3134.26	3834.87	191.97
	GP-BD	1017.02	1108.85	63.21
Packaging and transportation	BC	2689.15	5630.49	200.44
	PF	2689.15	5630.49	200.44
	BD	1142.41	3830.61	70.58
	GP	6241.04	8102.36	379.38
	GP-BD	4694.30	6302.49	249.52
Whole process	BC	6846.95	10774.56	461.65
	PF	6696.17	10711.88	461.00
	BD	2791.73	5797.29	175.38
	GP	10398.84	13246.44	640.59
	GP-BD	6343.62	8269.17	354.32

4.1.3. Tomato paste

The tomato is highly significant as a food source because of its abundant nutritional content, including high levels of vitamin C, carotenes, and several other vitamins. Processing procedures can enhance the bioavailability of bioactives found in tomatoes. Tomato paste is the predominant product derived from tomatoes. The conversion of tomatoes into tomato paste, which is cultivated during specific seasons and has a limited shelf life due to its high water content, is of great significance in this regard. Tomato paste is a preserved product that is made by extracting the liquid from the tomato once it has been separated from the skin and seeds. The evaporation process in tomato paste manufacture involves the use of several types of evaporators to remove water from heat-sensitive goods at low temperatures, employing convective heat transfer under vacuum (Gundogan, Tomar, Karaca, & Gökmen, 2024).

Based on the data presented in Figure 4.11, 4.12, and 4.13, the primary factors influencing the CEnC, CExC, and CCO₂C values in tomato paste production are diesel fuel for transportation, natural gas for the tubular sterilization machine and evaporator, steel for packaging, and paper for packaging. The values for CEnC, CExC, and CCO₂C are 14%, 10%, and 10%, correspondingly. An evaporation process entails the transfer of mass and heat. The tomato juice is regarded as a binary solution consisting of water and soluble solids, both of which are considered chemically inert (Yadav, & Jana, 2010). An evaporator is a widely used device for concentrating a solution by extracting an amount of the solvent in the form of vapor. It has diverse applications. The multiple effect evaporators are commonly employed in industrial and commercial applications, due to its superior advantages compared to the single effect system. The first and foremost benefit is the economy. The multiple effect method increases the amount of water evaporated per kilogram of steam by recycling the vapor from one stage to heat the next stage. Furthermore, the heat transmission is enhanced as a result of the increased viscosity of the concentrated products (Yadav, & Jana, 2010).

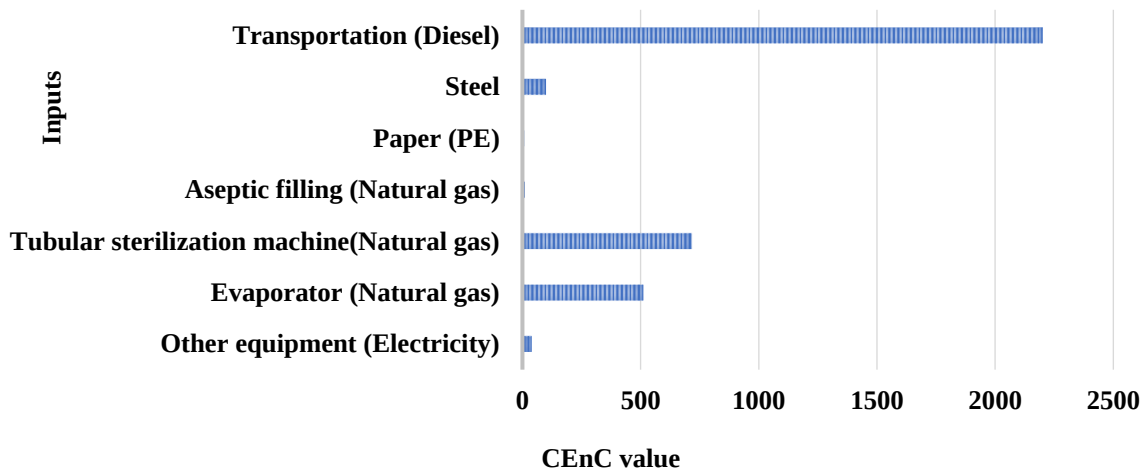


Figure 4.11. The top contributors to CEnC (MJ/ton) of tomato paste factory processing and packaging and transportation for the base case

Upon analyzing the tomato paste production process, it is clear that, the packaging and transportation step significantly impacts the assessed metrics. The packaging and transportation step in the GP-glass packaging scenario exhibits the highest values of the examined parameters, with the PF, base case, GP-BD, and BD scenarios following subsequently. In terms of overall perspective, the GP scenario exhibits the highest values, while the BD scenario demonstrates the lowest values. Glass manufacture is commonly considered a sector that requires a reasonable amount of energy. Approximately 85% of the fossil fuels consumed on site are attributed to high temperature melting furnaces (Perry, 2017). The majority of furnaces is fueled by natural gas and is utilized for the purpose of melting raw materials, such as sand and limestone. Electricity is utilized to power additional equipment and occasionally to augment the furnace, such as by an electric boost (Hammond, & McKenna, 2007). In the early 2010s, glass manufacturers released 2.2 million metric tons of CO₂ into the atmosphere. As an example, United Kingdom glass companies have made tremendous efforts to enhance energy efficiency in the past 30 years, as energy procurement is a major expense for the sector. As a result, the amount of energy used to create glass has been reduced by 50% to 1.47 MWh per ton. While the production of glass necessitates energy, numerous glass products contribute to energy and carbon savings throughout their usage (Perry, 2017). As an example, energy efficient double-glazed windows conserve a greater amount of energy in residential and commercial structures than the energy expended in the

glass manufacturing process. In addition, glass packaging is specifically engineered to minimize food waste, while continuous filament fiberglass plays a crucial role in the production of wind turbine blades. As a result, the process of manufacturing glass leads to the release of pollutants from the factories. However, glass goods might be seen as a potential option for decreasing emissions in the overall economy (Griffin, Hammond, & McKenna, 2021). Another notable environmental advantage arises from the fact that remelting cullet does not produce any CO₂ emissions during the glass-making process, unlike when fresh raw materials are utilized (WSP, 2015). The recycling of glass packaging was not included in the present study. However, it can be inferred from this argument that despite the energy-intensive and CO₂-emission-intensive production process of glass packaging, it can offer numerous benefits when recycling is taken into account.

A comprehensive analysis of energy and exergy was performed in a manufacturing plant that produces orange juice. The energy analysis results indicated that, the primary energy sources utilized in the orange juice manufacturing were electricity and steam energy. The corporation analyzed in the case study heavily relied on the utilization of electrical energy produced by its generator, which proved to be economically inefficient. The pasteurizer was determined to be the operation that used the most energy, with an energy intensity of 0.932 MJ/kg. The packaging unit followed closely behind with an energy intensity of 0.119 MJ/kg. The exergy analysis indicated that, the pasteurizer accounted for the majority of the exergy loss, exceeding 90%, while packaging contributed 6.60%. They claimed that, this was due to the utilization of steam to heat the process stream. One way to enhance the thermodynamic efficiency of the plant is through the implementation of process heat integration. Repairing any leaks in the steam pipelines is essential in order to minimize energy loss. Enhancing the electrical power supply from the national grid is crucial for achieving cost-effective production. A recommendation was made to enhance the capacity of the pasteurizer in order to mitigate the plant's inefficiency (Waheed, Jekayinfa, Ojediran, & Imeokparia, 2008).

A study was conducted to investigate the application of the response surface approach in analyzing the energy and exergy of the ohmic heating dryer for sour orange juice. A system utilizing ohmic heating was built, with three input voltage gradients of 8.33, 10.83, and 13.33 V/cm. The thermal process was analyzed to evaluate the energy efficiency, exergy efficiency, exergy loss, possible improvement over time, and achievement of the desired weight. Based

on the findings, increasing the process time leads to a decline in energy efficiency, while it results in an increase in exergy loss and exergy efficiency. The voltage gradient and weight loss % significantly impact process time, energy efficiency, exergy loss, and possibility for improvement. The energy efficiency ranged from 50.31% to 91.68% at voltage gradients of 8.33 V/cm and 13.33 V/cm. Additionally, the maximum energy efficiency of 59.46% was achieved at a voltage gradient of 13.33 V/cm and a weight loss percentage of 30%, while the minimum energy efficiency of 31.56% was observed at a voltage gradient of 8.33 V/cm and a weight loss percentage of 10% (Torshizi, Azadbakht, & Kashaninejad, 2020).

Sabancı & İcier (2020) conducted a study on enhancing the efficiency of the concentrated sour cherry juice production using a vacuum evaporator with the assistance of an ohmic heating source. Throughout this procedure, total energy consumption rose as the total soluble solid content increased but reduced as the voltage gradient increased. Compared to process-based efficiencies, system boundary-based efficiencies were lower. As the voltage gradient increased yet the total soluble solid content grew, improvement potential values increased as well. Ohmic heating helped vacuum evaporation operate better during the extraction process in terms of energy and exergy efficiency, and it also reduced the system's upgrade requirements. Up to 65% of the sour cherry juice can be evaporated thanks to an ohmic heating source built into the vacuum system. The total soluble solid content in vacuum improved the system and process performance characteristics. They inferred that, the ohmic heating approach might therefore be assisted to increase the performance of the vacuum evaporation system at voltage gradients greater than 10 V/cm.

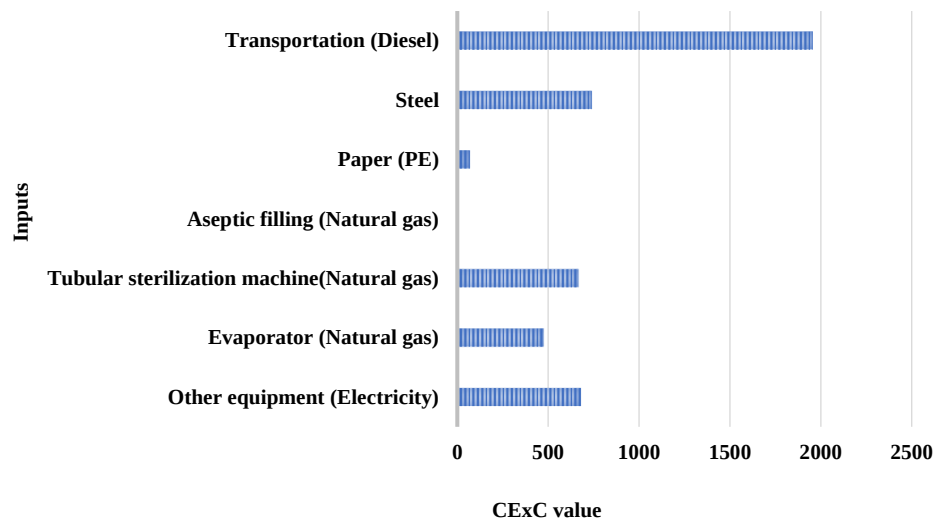


Figure 4.12. The top contributors to CExC (MJ/ton) of tomato paste factory processing and packaging and transportation for the base case

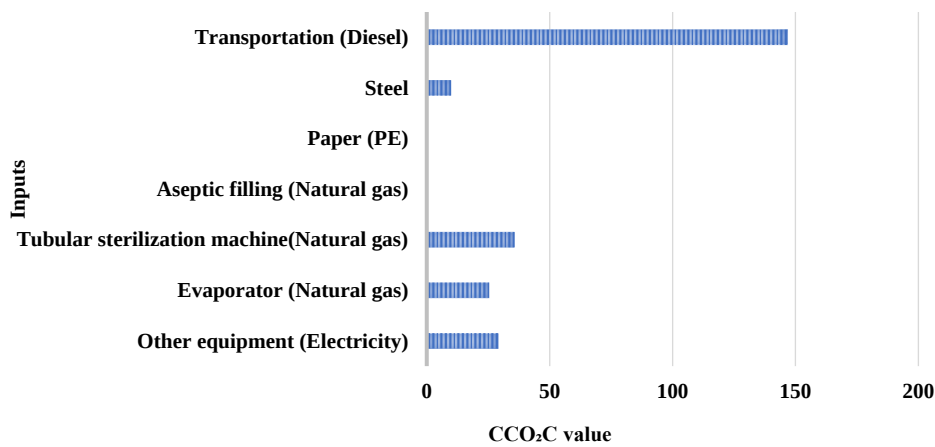


Figure 4.13. The top contributors to cumulative CO₂ (kg/ton) consumption of tomato paste factory processing and packaging and transportation for the base case

From Table 4.3, the GP scenario contributes the most to the cumulative energy, exergy consumption, and carbon dioxide emission values in the packaging and transportation step. The utilization of glass packaging combined with the use of biodiesel leads to a decrease in the value of tomato paste except CO₂ emission, as observed in the base case scenario. However, in the case of tomato juice, the cumulative values remain higher than that of the

base case. The condensed form of tomato paste compared to tomato juice results in a reduced quantity of glass required for packaging, leading to lower cumulative consumption values compared to juice. Using biodiesel fuel instead of fossil fuels like natural gas or electricity generated from fossil fuels results in a significant decrease in CEnC, CExC, and CCO₂C values, independent of packaging material used.

Table 4.3. Cumulative energy, exergy and CO₂ results of tomato paste

Product	Scenario	CEnC (MJ/ton)	CExC (MJ/ton)	CCO ₂ C (kg/ton)
Tomato farming	BC	1023.54	1309.21	69.24
	PF	872.76	1246.52	68.59
	BD	632.30	857.83	41.59
	GP	1023.54	1309.21	69.24
	GP-BD	632.30	857.83	41.59
Factory processing	BC	1287.88	1997.32	98.29
	PF	1287.88	1997.32	98.29
	BD	434.66	936.75	46.51
	GP	1287.88	1997.32	98.29
	GP-BD	434.66	936.75	46.51
Packaging and transportation	BC	2314.66	2814.95	159.49
	PF	2314.66	2814.95	159.49
	BD	767.92	1015.07	29.63
	GP	3269.57	3780.26	198.32
	GP-BD	1855.63	2581.95	68.46
Whole process	BC	4626.08	6121.47	327.02
	PF	4475.30	6058.79	326.37
	BD	1834.88	2809.65	117.73
	GP	5580.99	7086.78	365.85
	GP-BD	2922.58	4376.53	156.56

4.2. Life Cycle Assessment Results of Tomato Products

4.2.1. Retail tomato

There has been a greater emphasis on the impact of global warming and energy depletion on agricultural production systems. In recent times, there have been an increasing number of

studies that have specifically looked into the potential for acidification and eutrophication caused by fertilizer inputs in agriculture production (Wang et al., 2018). From Table 4.4, it is clear that, the AFDP exhibits the highest value among all impact categories for retail tomato production. It is followed by GWP, FWEP, and HTP, respectively. Between Figures 4.14-4.17, the main contributors to hot spot impact categories are illustrated. The top five contributors to AFDP, according to open LCA results, are the transportation (diesel) process (61.8%), diesel (25.6%), electricity (5.8%), natural gas (1.7%), and other categories (5.1%). The top five contributors for GWP, HTP, FWEP, and ODP are also the same as for AFDP, and additional factors include pesticides, steam production in chemical factories, and chemical factories for organic materials.

Pesticides are utilized extensively in agriculture to tackle the damage caused by different fungal diseases and pests, resulting in increased quantity and improved quality of crops, while preventing losses in production. The United States Department of Agriculture specifies that the maximum allowable level of anilazine residue in food items should range from 0.2 to 10 mg/kg. The tomato (*Lycopersicon esculentum* Mill) is a widely consumed fruit that is susceptible to pests and fungal diseases, resulting in leaf spot problems. Therefore, anilazine is commonly used to address these issues in tomato cultivation. Anilazine has adverse impacts on human health, specifically in relation to its HTP value. Additionally, it has a harmful influence on the environment, as indicated by its effects on FWEP and TEP. The principal path of human exposure to pesticide residues is through the consumption of food, particularly fruits and vegetables. In the meantime, continuous exposure to low levels of pesticides might trigger chronic ailments such as Parkinson's disease, diabetes, cancer, cardiovascular diseases, respiratory disorders, congenital disorders, and reproductive abnormalities. Therefore, creating innovative techniques including the ability to break down fungicide residues using advanced technologies is crucial for the food business (Manzoor, Ali, Aadil, Ali, Goksen, Li, Zeng, & Proestos, 2023).

A study on olives proposed the use of insect traps as a substitute for pesticides in the cultivation of organic olives, as an alternative to insecticides. Enhancing the effectiveness of these traps and expanding their use to additional crops has the potential to decrease the environmental consequences and energy expenditure associated with agro-chemicals. In order to make food production more environmentally friendly, it is necessary to attain the same

level of technological advancement in industries as has been achieved in farms (Kaltsas, Mamolos, Tsatsarelis, Nanos, & Kalburtji, 2007). The tomato farming and packaging-transportation step in the BC has exhibited the highest values, while the BD scenario has demonstrated the lowest values. In terms of whole process, the BD scenario is the most environmentally friendly, followed by the PF scenario and BC.

Zarei et al. (2019) conducted a study to evaluate the environmental effects of cucumber and tomato production in both open field (OF) and greenhouse (GH) conditions using the LCA approach. The results showed that, tomato production in GH had a greater environmental impact compared to tomato production in OF, mostly due to the use of natural gas in GH heating systems and the higher demand for diesel fuel. Diesel fuel and natural gas were the primary factors influencing all impact categories in terms of GHG emissions. Electricity and nitrogen-based fertilizers had the greatest impact on all impact categories in terms of open field. According to Khoshnevisan et al. (2014), GWP required producing one metric ton of cucumber and tomato in a greenhouse was 244.93 and 129.39 kg of CO₂-eq respectively. The larger GWP seen in their study can be ascribed to the increased utilization of natural gas for heat production and the inclusion of transportation factors in their analysis. In addition, a greater amount of water for irrigation and power was utilized in the area that they examined.

In line with their study, as seen in Table 4.4, GWP required to produce one metric ton of fresh tomato in the present study was 120 kg CO₂-eq. The main contributors to this result were diesel used in packaging and transportation (49.8%), diesel consumed in agricultural machinery (32.3%), and electricity (13.2%). Kaltsas et al. (2007) stated that, the rate of diesel fuel consumption per unit of farmed land is influenced by factors such as the horsepower of the tractor and the size of the plough. The farming system and location had no impact on the global warming potential and CO₂ emissions in olive farming. They reported that, organic olive groves exhibited reduced CO₂ emissions, likely attributed to distinct utilization of fossil energy in comparison to conventional plantations. Organically cultivating olives resulted in a decrease in diesel fuel emissions from machinery operations. They demonstrated that, organic olive groves typically reduce energy inputs without compromising productivity and tend to have lower CO₂ emissions resulting from the various uses of fossil energy. It can be inferred that, farming systems, such as organic farming, have the potential to decrease environmental impacts and CO₂ emissions by minimizing the usage of agricultural machinery and diesel fuel.

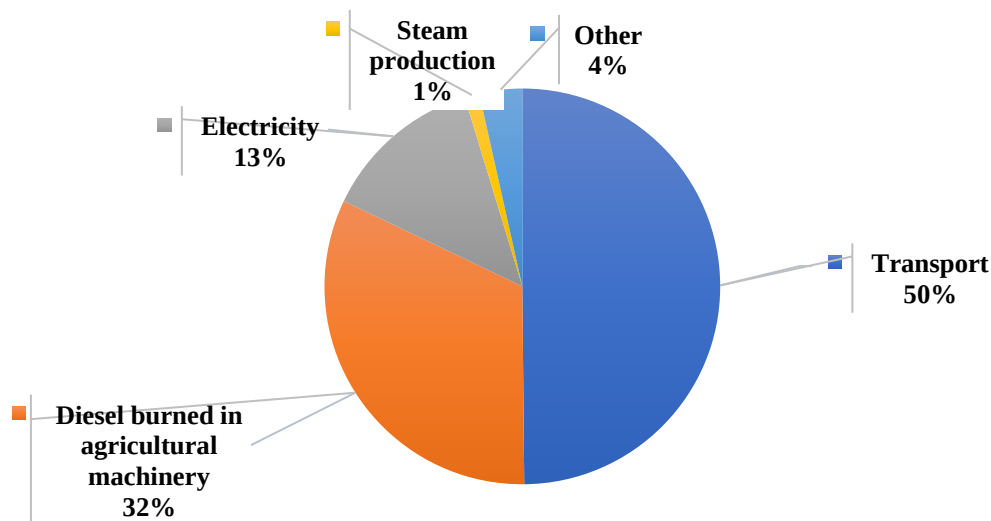


Figure 4.14. The top contributors to GWP (kg CO₂-eq) impact category in retail tomato production

Parajuli et al. (2021) examined the environmental LCA of potato and tomato supply chains from cradle to grave. The processed foodstuffs were potato chips, frozen fries, dehydrated flakes, and tomato pasta sauce. The consumption of 1 kg of fresh potatoes was found to result in higher GHG compared to ingesting the same amount of potato chips or dehydrated potato products (0.97 kg CO₂-eq/FU for fresh potatoes vs 0.85 kg CO₂-eq/FU for potato chips and 0.65 kg CO₂-eq/FU for dehydrated products). Meanwhile, frozen fries had the greatest GHG emissions among all potato products, measuring 1.21 kg CO₂-eq/FU. When comparing tomato products, the GWP100 of tomato sauce was approximately twice as high as that of fresh tomatoes. Specifically, the GWP100 values for fresh tomatoes and tomato sauce were 0.74 kg CO₂-eq/FU and 1.5 kg CO₂-eq/FU, respectively. In the present study it was found 120 kg CO₂ eq. The main differences between assessed values may be due to different cultivation practices, fertilizer usage, soil characteristics, namely region differences.

A different study employed LCA in conjunction with a field investigation to evaluate the environmental advantages resulting from optimized fertilizer and pesticide inputs. Specifically, there was a reduction of 24.7% in nitrogen, 35.6% in phosphorus pentoxide, 18.8% in potassium oxide, 17.1% in organic fertilizer, and 30.9% in pesticides, as compared to conventional farmer inputs. The results indicated that, optimized inputs in farming management led to significant reductions in various environmental impacts. Specifically, compared to traditional methods, optimized inputs resulted in a 24.7% decrease in energy

depletion, a 6.4% decrease in water depletion, a 28.8% decrease in global warming, a 23.7% decrease in acidification, a 34.2% decrease in aquatic eutrophication, a 34.8% decrease in human toxicity, a 34.8% decrease in aquatic eco-toxicity, and a 26.7% decrease in soil eco-toxicity. Among these impacts, aquatic eco-toxicity and aquatic eutrophication were found to be the most significant in cherry tomato production, primarily due to the use of chlorothalonil and phosphate fertilizer, respectively. These findings offer information on how to optimize the use of fertilizers and pesticides to reduce various environmental effects, while still ensuring a high production of cherry tomatoes and enhancing economic advantages (Guo et al., 2021). In the present study, it was aimed to reduce adverse environmental impacts resulting from excessive fertilizer usage by implementing the PF scenario.

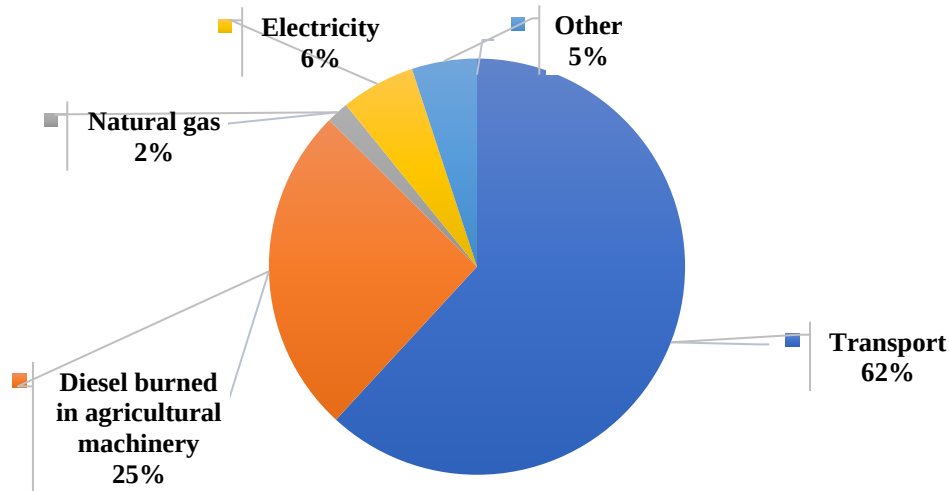


Figure 4.15. The top contributors to AFDP (MJ) impact category in retail tomato production

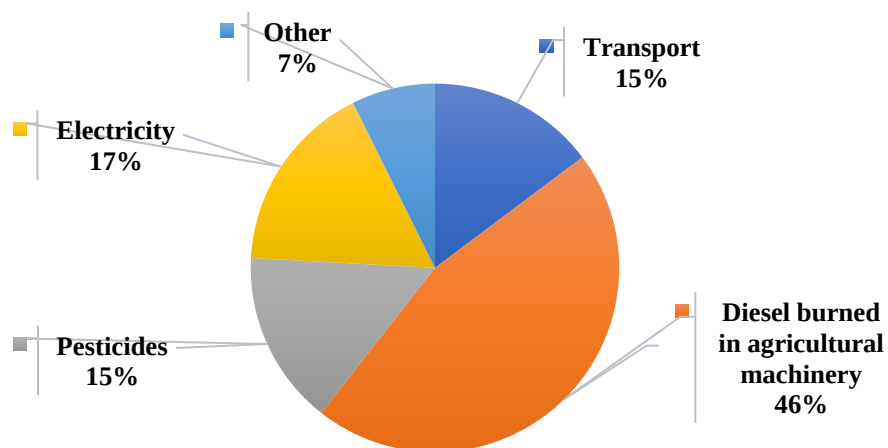


Figure 4.16. The top contributors to FWEP (kg 1.4 DB-eq) impact category in retail tomato production

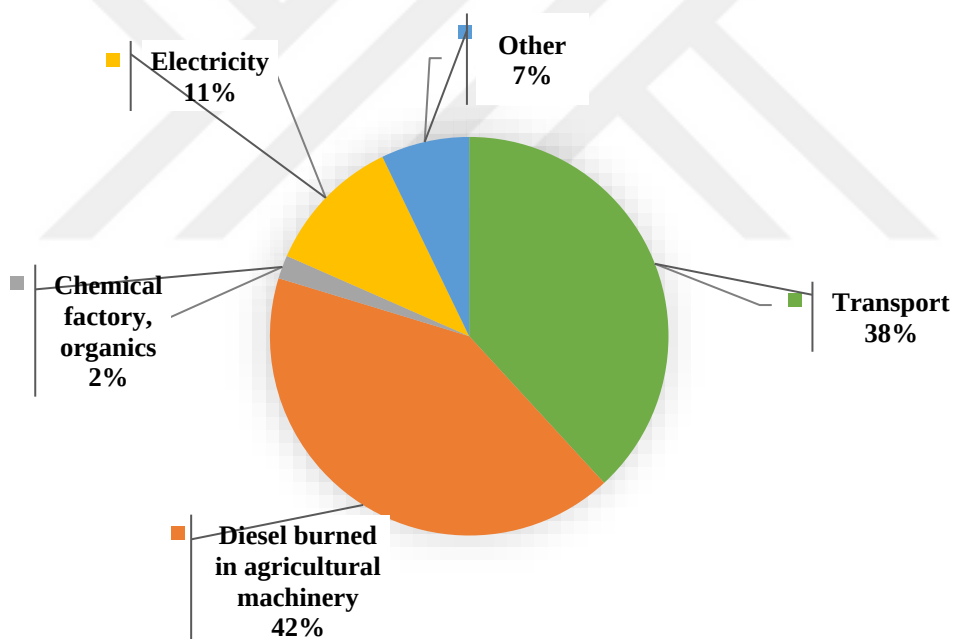


Figure 4.17. The top contributors to HTP (kg 1.4 DB-eq) impact category in retail tomato production

Table 4.4. Life cycle assessment results of retail tomato

Product	Scenario	Impact categories									
		ADP	AFDP	AP	EP	FWEP	GWP	HTP	ODP	POCP	TEP
Tomato farming	BC	5.2E-04	1.2E+03	6.6E-01	2.3E-01	5.6E+01	1.2E+02	6.0E+01	1.3E-05	3.5E-02	4.2E+00
	PF	4.9E-04	1.1E+03	6.3E-01	2.2E-01	5.5E+01	1.2E+02	5.8E+01	1.3E-05	3.4E-02	4.1E+00
	BD	5.7E-05	3.4E+02	1.8E-01	8.1E-02	2.5E+01	3.5E+01	1.7E+01	2.9E-06	7.8E-03	3.9E+00
Packaging and transportation	BC	2.5E-04	1.2E+03	2.8E-01	6.3E-02	9.1E+00	8.5E+01	2.9E+01	1.5E-05	1.4E-02	1.1E-01
	PF	2.5E-04	1.2E+03	2.8E-01	6.3E-02	9.1E+00	8.5E+01	2.9E+01	1.5E-05	1.4E-02	1.1E-01
	BD	5.7E-05	3.4E+02	1.8E-01	8.1E-02	2.5E+01	3.5E+01	1.7E+01	2.9E-06	7.8E-03	3.9E+00
Whole process	BC	7.6E-04	2.4E+03	9.4E-01	2.9E-01	6.5E+01	2.0E+02	8.9E+01	2.9E-05	4.9E-02	4.3E+00
	PF	7.4E-04	2.3E+03	9.1E-01	2.8E-01	6.4E+01	2.0E+02	8.7E+01	2.8E-05	4.8E-02	4.2E+00
	BD	5.7E-05	6.1E+02	1.9E-01	8.4E-02	2.6E+01	3.6E+01	1.8E+01	4.6E-06	1.0E-02	3.9E+00

4.2.2. Tomato juice

Tomato juice is a delicious and nourishing beverage that effectively provides significant advantages to the body. Tomatoes are rich in the distinctive antioxidant lycopene. A 100-gram serving of pure tomato juice contains 9050 micrograms of this orange-red pigment. Carotenoids, responsible for the red color in vegetables and fruits, hinder cellular oxidative processes, thereby preventing premature aging of the body. They also have a beneficial impact on eye health by preventing lens clouding and the development of cataracts. Additionally, carotenoids protect the cardiovascular system from atherosclerosis (Eliseeva, & Shelestun, 2023).

From Figure 4.18, LCA of tomato juice production reveals that, the packaging and transportation step consistently exhibits the highest values across all improvement scenarios. In a study conducted on tomato, the cultivation and packaging subsystems of tomato products are identified as hot spots, because they have a significant consumption of fossil fuels and electricity. They stated that these steps primarily affects the impact categories of global warming and energy resource consumption (Del Borghi et al., 2014). Similarly, in the present study diesel fuel emerges as a hot spot among other inputs. The top contributors to GWP impact category in tomato juice production are glass (34%), PE (25%), HDPE (22%), transport-diesel (10%), and agricultural machinery-diesel (9%). The top contributors to AFDP impact category in tomato juice production are PE (37%), glass (31%), natural gas (20%), transport-diesel (8%), and agricultural machinery-diesel (4%). Notably, the glass packaging scenario emerges as the most significant contributor to this trend. In Figures 4.19-4.22, it is evident that, glass packaging has the greatest influence on GWP, accounting for 34% of the impact. It also contributes 31% to AFDP, 25% to FWEP, and 55% to the HTP impact category in the base case. Manfredi and Vignali (2014) reported that, the analysis of the overall environmental impact, categorized by phases, revealed that packaging was the primary factor contributing to the majority of impact categories. It accounted for 41-69% of all impacts, with the exception of EP, where it contributed 20%. The cultivation phase had the greatest impact on EP, accounting for 71% of the total impact. It also contributes between 7-27% to the other impacts. The processing phase accounts for 6-20% of the total impact in all categories, except for EP, where it accounts for 2%. Transportation accounts for 14-25% of the total impact in all categories, except for EP, where it accounts for 6%.

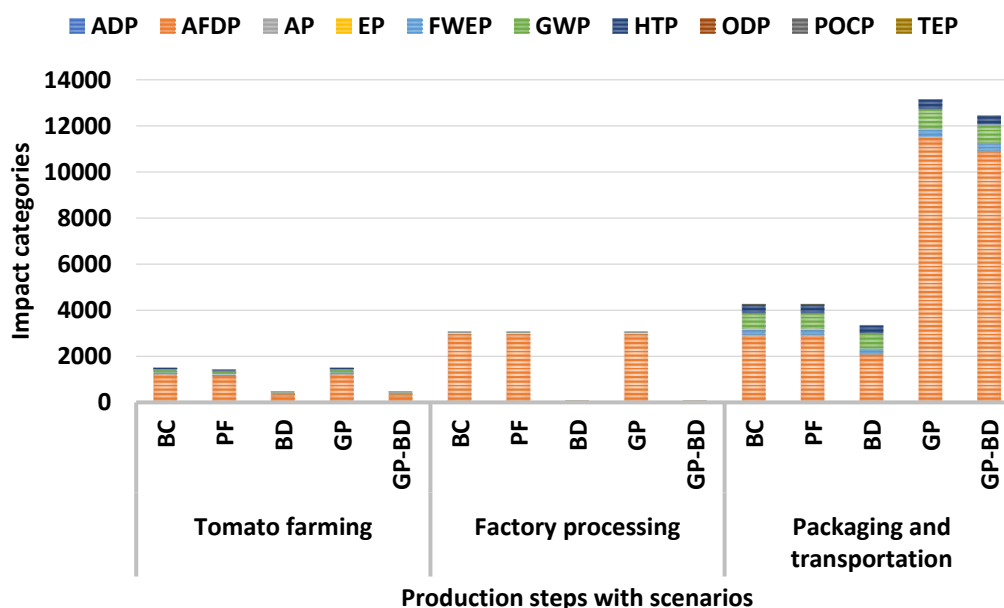


Figure 4.18. Contributions of tomato juice processing steps on impact categories with different improvement scenarios

Figure 4.18 illustrates the impact of various improvement scenarios on every step involved in tomato juice production. The BD scenario, which replaces diesel usage with biodiesel utilization, yields the most favorable environmental outcomes. However, the GP scenario which is also base case demonstrated the most significant consequences for the environment as a result of its extensive use of glass packaging. A study was undertaken in the production of virgin olive oil to investigate the effects of different packaging materials on life cycle impact assessment results. The study revealed that, the packaging had varying influences, ranging from 2% to 300%, depending on the impact category and the type of packaging material used (glass, tin, or polyethylene terephthalate). Glass, which is associated with greater perceptions of quality by customers, was determined to be the most influential material due to its weight. They offered that, the influence of glass may be significantly reduced by using eco-design methods, such as reducing weight and increasing the amount of recycled glass. Out of the 12 analyzed impact categories, glass packaging has a greater impact in 9 categories, whereas tin packaging has a higher impact in human toxicity, and PET packaging has a larger impact in terrestrial eco-toxicity. The comprehensive assessment of the environmental impact of glass packaging includes a thorough analysis of the contribution made by each step of its life cycle to each examined impact category. Olive production has the most impact in the majority of impact categories, specifically in 8 out of 12 categories. The packaging stage, furthermore,

has the highest contribution in 2 areas. The manufacture of diesel used for agricultural operations is the primary factor contributing to the majority of impact categories within the olive production stage. The manufacturing of the packaging material is the most significant factor throughout the packaging stage. This is directly related to the weight of the packaging, which tends to be rather high in restaurants, due to the emphasis on quality and design. Ultimately, during the oil production process, the most influential factor is typically the generation of power. Production is mostly driven by electricity (Navarro, Puig, Martí, Bala, & Fullana-i-Palmer, 2018). Figure 4.19, 4.20, and 4.21, and 4.22 demonstrate that, glass packaging and diesel fuel play significant roles in the packaging and transportation stages of tomato juice manufacturing in accordance with previous studies in the literature. Garofalo et al. (2017) reported in their study packaging (manufacturing and transport) was the second hot-spot of the entire supply chain, with the tin can that was the most impacting input among packaging materials. Several materials for packaging may be taken into account to reduce GHG emissions for their manufacturing, such as carton beverage or PET. However, in order to protect the integrity of tomato from accidental crushing, there are few alternatives, such as glass or tin can for the packaging of the whole-peeled fruits or similar products.

The utilization of biodiesel as a fuel, when combined with glass packaging, GP-BD scenario, effectively mitigates the environmental consequences associated with glass packaging to a considerable extent. However, it is important to note that despite this positive impact, GP-BD remains the second most influential scenario among others. Among all the scenarios examined in this study, the BD scenario stands out for its greater environmental effect values in relation to other tomato products. This is mostly due to the substantial reduction in transportation impacts resulting from the use of diesel. Transportation has a crucial role in facilitating commerce, trade, and travel. It is reported that, currently, fossil fuels are the primary sources of energy for transportation in the United States resulting in them being responsible for around 29% of the country's GHG emissions. On a global scale, the need for liquid fuels is expected to rise by 32% from 2020 to 2050 (IEO, 2021). In order to maintain a stable global climate within acceptable limits, it is necessary to shift from using fossil fuels to utilizing renewable energy sources. Sustainably generated biofuels can be crucial in reducing carbon emissions in many transportation sectors, as well as other industries such as the food industry.

Biofuels play a crucial role in converting transportation sectors with few low-carbon options, such as long-haul trucks for freight, shipping, and aviation. Previous researches have indicated blending biomass-derived diesel with petroleum diesel as a GHG mitigation strategy for road freight. There are two types of biomass-derived diesel on the market: biodiesel (BD), which is a fatty acid methyl ester, and hydrogenation-derived renewable diesel (RD), which is made from hydroprocessed esters and fatty acids. BD is created via transesterification, while commercial RD is made using catalytic hydro-processing (Xu, Ou, Li, Hawkins, & Wang, 2022). Xu et al., (2022) suggested that, using BD and RD from oilseed crops and low-value feedstocks can significantly decrease GHG emissions compared to petroleum diesel. Without land-use change emissions, BD and RD produced from oilseed crops can have well-to-wheels GHG emissions 63%-77% lower than petroleum diesel. Soybean fields produce higher yields and require less fertilizer, resulting in lower GHG emissions than canola and carinata. They also stated that, without accounting for land use change emissions, well-to-wheel emissions from soybean, canola, and carinata oils to BD pathways range from 21 to 31 g of CO₂e/MJ, with soybean BD having the lowest value. Soybean, canola, and carinata oil emit around 8-10% more to RD pathways compared to BD. In line with Xu et al., (2022) in the present study, biodiesel, which is a fatty acid methyl ester, has decreased the GHG emissions and impact category results in a significant way. Table 4.5 illustrates the life cycle assessment results of tomato juice.

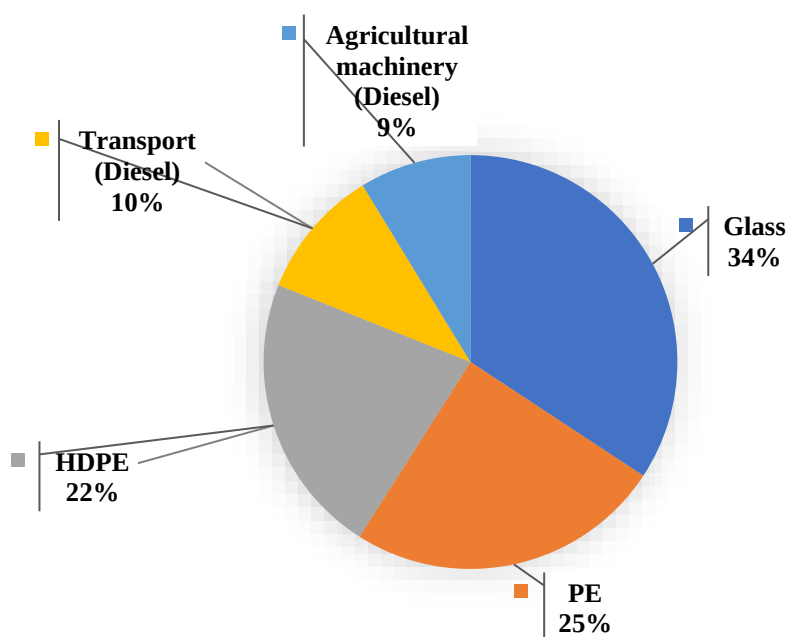


Figure 4.19. The top contributors to GWP (kg CO₂-eq) impact category in tomato juice production

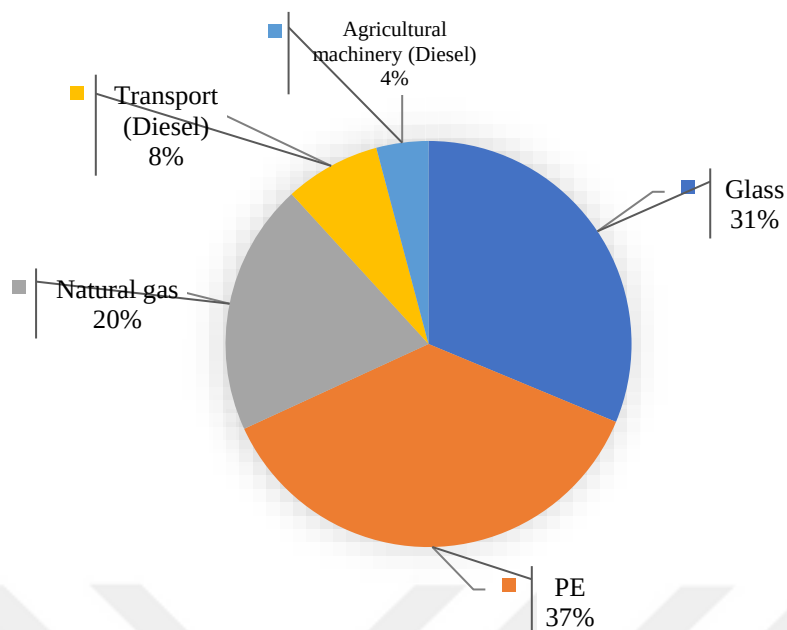


Figure 4.20. The top contributors to AFDP (MJ) impact category in tomato juice production

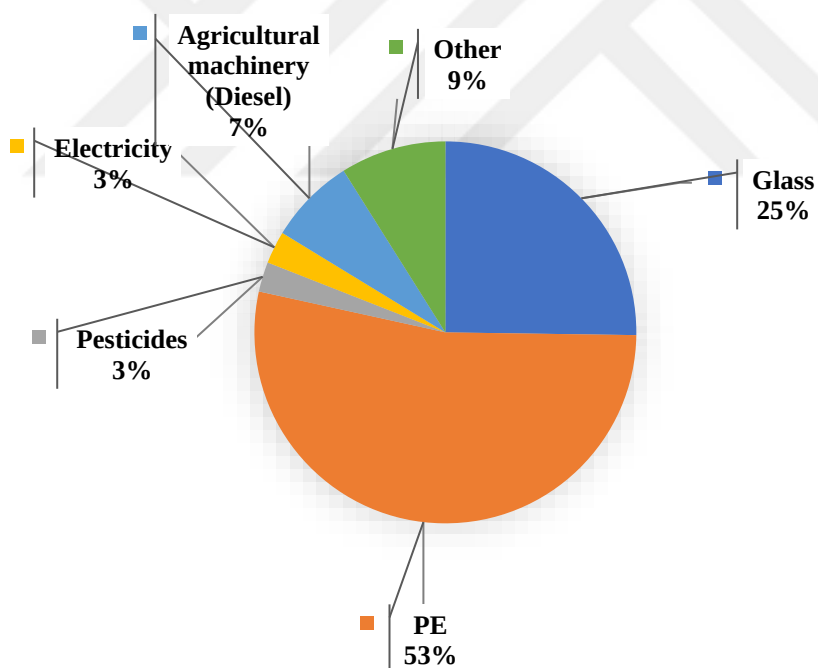


Figure 4.21. The top contributors to FWEP (kg 1.4 DB-eq) impact category in tomato juice production

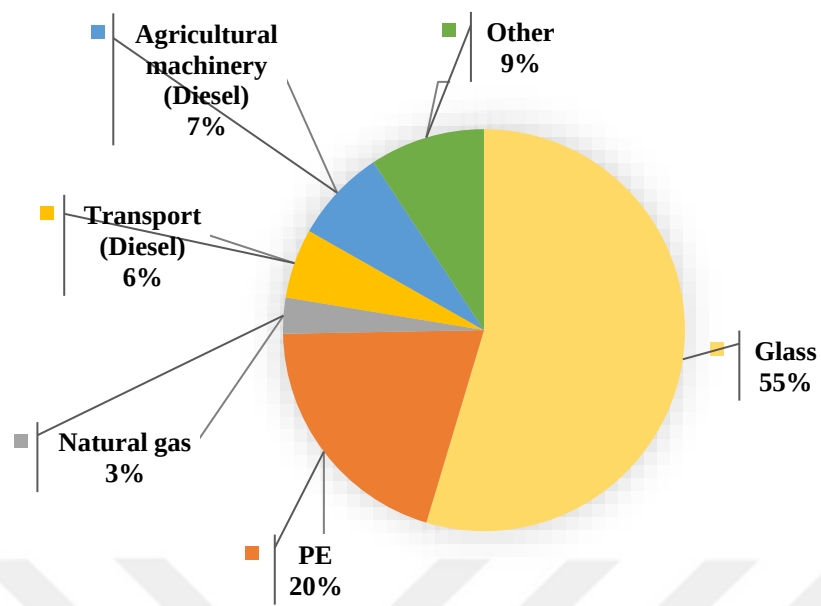


Figure 4.22. The top contributors to HTP (kg 1.4 DB-eq) impact category in tomato juice production

Table 4.5. Life cycle assessment results of tomato juice

Product	Scenario	Impact categories									
		ADP	AFDP	AP	EP	FWEP	GWP	HTP	ODP	POCP	TEP
Tomato farming	BC	5.5E-04	1.2E+03	7.1E-01	2.4E-01	6.0E+01	1.3E+02	6.4E+01	1.4E-05	3.7E-02	4.4E+00
	PF	5.2E-04	1.2E+03	6.7E-01	2.3E-01	5.9E+01	1.2E+02	6.2E+01	1.4E-05	3.6E-02	4.4E+00
	BD	6.0E-05	3.7E+02	1.9E-01	8.7E-02	2.6E+01	3.8E+01	1.8E+01	3.1E-06	8.3E-03	4.2E+00
	GP	5.5E-04	1.2E+03	7.1E-01	2.4E-01	6.0E+01	1.3E+02	6.4E+01	1.4E-05	3.7E-02	4.4E+00
	GP-BD	6.0E-05	3.7E+02	1.9E-01	8.7E-02	2.6E+01	3.8E+01	1.8E+01	3.1E-06	8.3E-03	4.2E+00
Factory processing	BC	2.1E-05	3.0E+03	1.8E-01	4.3E-02	9.8E+00	4.7E+01	1.8E+01	1.8E-05	2.1E-02	5.9E-02
	PF	2.1E-05	3.0E+03	1.8E-01	4.3E-02	9.8E+00	4.7E+01	1.8E+01	1.8E-05	2.1E-02	5.9E-02
	BD	6.1E-06	4.9E+01	4.4E-02	2.8E-02	5.0E+00	7.5E+00	3.7E+00	8.0E-07	1.6E-03	3.1E-02
	GP	2.1E-05	3.0E+03	1.8E-01	4.3E-02	9.8E+00	4.7E+01	1.8E+01	1.8E-05	2.1E-02	5.9E-02
	GP-BD	6.1E-06	4.9E+01	4.4E-02	2.8E-02	5.0E+00	7.5E+00	3.7E+00	8.0E-07	1.6E-03	3.1E-02
Packaging and transportation	BC	6.1E-04	2.9E+03	2.9E+00	1.3E+00	2.3E+02	7.1E+02	3.8E+02	4.9E-05	4.8E-01	1.2E+00
	PF	6.1E-04	2.9E+03	2.9E+00	1.3E+00	2.3E+02	7.1E+02	3.8E+02	4.9E-05	4.8E-01	1.2E+00
	BD	3.9E-04	2.1E+03	2.6E+00	1.2E+00	2.2E+02	6.4E+02	3.6E+02	3.7E-05	4.7E-01	1.1E+00
	GP	1.2E-03	1.2E+04	4.4E+00	7.1E-01	3.4E+02	8.7E+02	4.1E+02	6.3E-05	2.0E-01	7.9E-01
	GP-BD	1.0E-03	1.1E+04	4.1E+00	6.5E-01	3.4E+02	8.2E+02	3.9E+02	5.4E-05	1.9E-01	7.1E-01
Whole process	BC	1.2E-03	7.2E+03	3.7E+00	1.6E+00	3.0E+02	8.9E+02	4.6E+02	8.2E-05	5.3E-01	5.7E+00
	PF	1.2E-03	7.1E+03	3.7E+00	1.6E+00	3.0E+02	8.8E+02	4.6E+02	8.1E-05	5.3E-01	5.7E+00
	BD	4.5E-04	2.5E+03	2.9E+00	1.3E+00	2.6E+02	6.8E+02	3.8E+02	4.1E-05	4.8E-01	5.4E+00
	GP	1.7E-03	1.6E+04	5.2E+00	1.0E+00	4.1E+02	1.0E+03	4.9E+02	9.6E-05	2.6E-01	5.3E+00
	GP-BD	1.1E-03	1.2E+04	4.6E+00	8.2E-01	3.9E+02	9.2E+02	4.4E+02	6.2E-05	2.2E-01	5.0E+00

4.2.3. Tomato paste

The tomato supply chain, like other agricultural systems, is accountable for a range of environmental consequences at every stage, including cultivation, processing, distribution, and consumption. Evaluating and enhancing the effects of these impacts through a life cycle approach would allow for the improvement of sustainability and management quality concerns (Ingrao et al., 2019). An examination of the life cycle of tomato paste production in Figure 4.23 demonstrates that, tomato cultivation is the primary contributor to the entire process. It is not surprising to find such a result given that 1 kg tomato paste requires 4.583 kg raw fresh tomato. Among other impact categories, tomato paste, along with retail tomato and tomato juice, has the highest AFDP, GWP, HTP, and FWEP values.

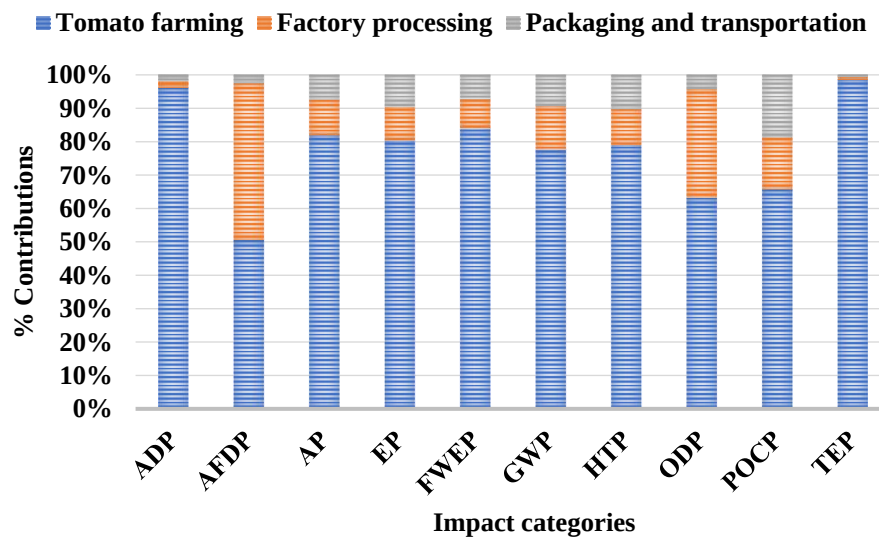


Figure 4.23. Effect of production steps on LCA impact categories in tomato paste production

Ingrao et al. (2019) reported that, the jar manufacture was the primary cause of environmental damage in the whole supply chain, with the agricultural phase being the second most significant contributor. They stated that, these were the essential components of the examined supply chain that need to be prioritized in order to identify and implement improvement solutions. The latter would be enhanced by optimizing soil management, fertilization, and irrigation, as well as by identifying alternate packaging materials. This will help reduce the overall environmental effect and harm associated with the researched supply chain. In line with results reported by Ignaro et al. (2019), in this study steel jar also was the one of the

major contributors on all impact categories. Figure 4.24 illustrates the effects of various scenarios on different production steps of tomato paste production.

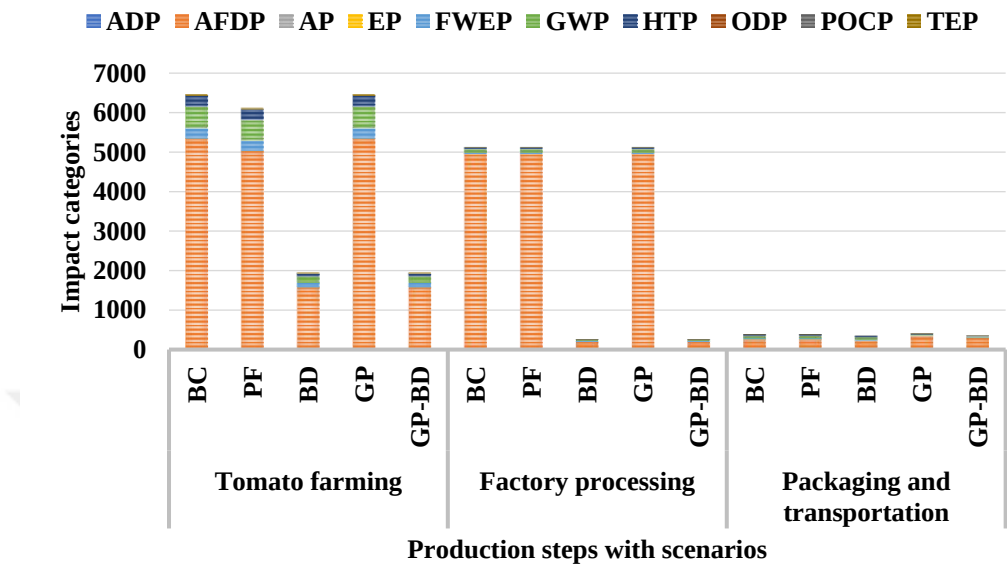


Figure 4.24. Effect of various scenarios on different production steps of tomato paste production

The steel industry is the second largest industry globally, following the oil and gas sector, and has an approximate global turnover of 900 billion USD. Steel is utilized in various industries, including building and construction, packaging, transportation, and the renewable energy sector. The output of crude steel has increased by more than two times over the past three decades, reaching a total of 1665 million metric tons in 2014. The high level of productivity in the steel production sector unavoidably results in the sector bearing significant environmental liabilities. For instance, in nations such as China, this sector is accountable for 12% of the total CO₂ emissions at the national level. On the other hand, some study results reveal that a significant number of environmental effects are connected to the energy usage and the harmfulness of the emissions produced during the whole life cycle of steel manufacturing. To minimize energy losses, one option is to enhance existing technologies, while another option is to invest in newer and more innovative steelmaking methods. For instance, increasing the amount of direct injected coal or injecting alternative fuels into the blast furnace could potentially reduce coke usage by 50% and energy consumption by 30%. Moreover, the implementation of waste energy reuse practices could be considered (Renzulli, Notarnicola, Tassielli, Arcese, & Di Capua, 2016). On the other hand the steel can is the most

commonly recycled container worldwide. The global recycling rate in recent stood at 68%. Steel recycling results in a 75% reduction in energy usage and an 80% decrease in CO₂ emissions, compared to the production of steel from new ore (Karakaya & Özilgen, 2011). But, the recycling rate was not included in current study.

The primary contributors to AFDP, GWP, FWEP, and HTP are shown throughout the Figures 4.25 to 4.28. The primary factors contributing to the manufacturing of tomato paste are the consumption of steel in packaging and transportation, the use of electricity and natural gas for evaporation and sterilizing operations, and the utilization of diesel fuel for transportation and agricultural machinery purposes. When considering the impact of scenarios on various impact categories during the entire process, it was observed that the base case and glass packaging scenario exhibit the highest values, whereas the biodiesel scenario demonstrates the lowest values. The main factors that contribute to the production of tomato paste include the use of steel for packaging and transportation, the consumption of electricity and natural gas for evaporation and sterilization processes, and the utilization of diesel fuel for transportation and agricultural machinery. When considering the impact categories of the entire process, the base case and glass packaging scenario exhibit the greatest influence, while the biodiesel scenario has the least influence. The primary factors contributing to the GWP impact category in tomato paste manufacturing are the diesel fuel used in agricultural machinery (34%), steel manufacture (32%), and electricity consumption (14%), diesel fuel used in transportation (12%), natural gas consumption (2%), and other miscellaneous factors (6%). The variables that affect AFDP, FWEP, HTP, and other impact categories are the same as those that influence GWP. Moreover, the presence of pesticides and chemicals adds to these factors.

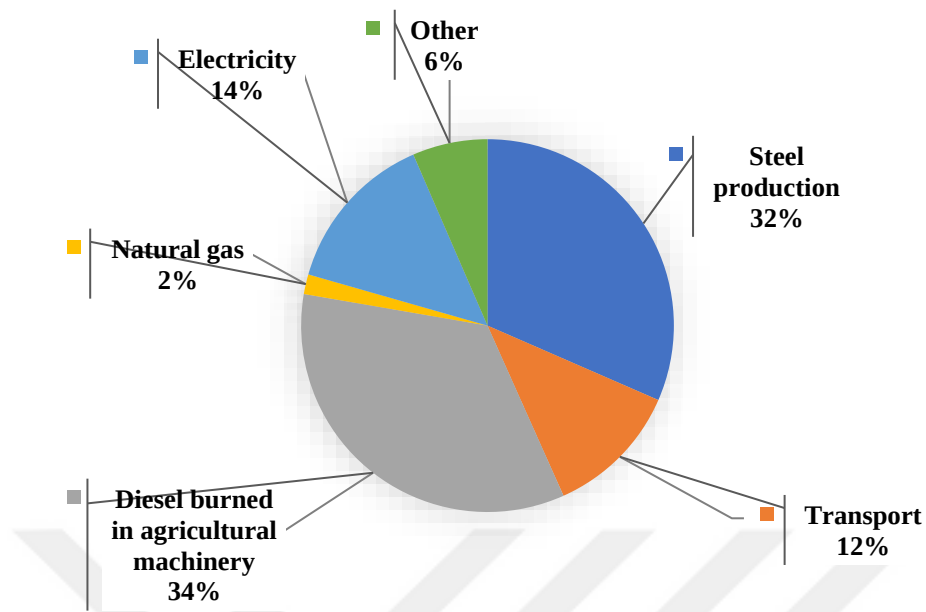


Figure 4.25. The top contributors to GWP (kg CO₂-eq) impact category in tomato paste production

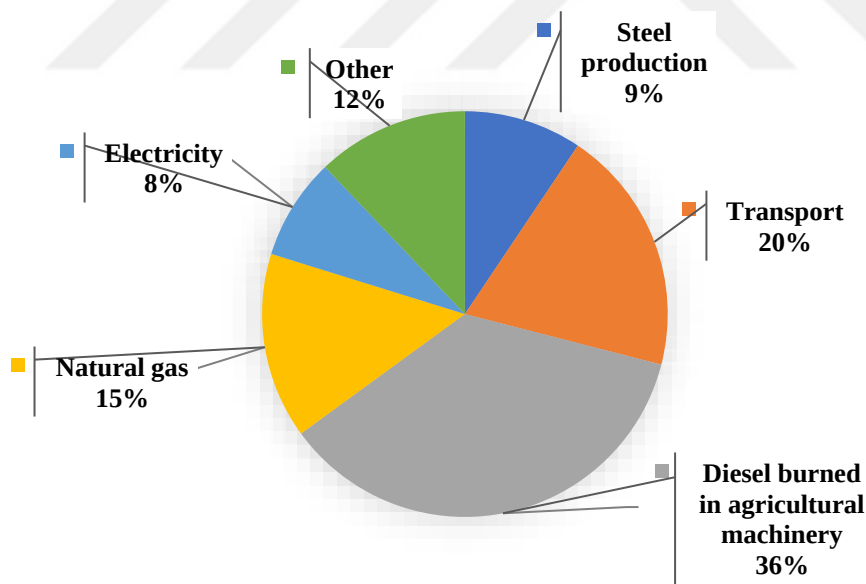


Figure 4.26. The top contributors to AFDP (MJ) impact category in tomato paste production

A study was conducted to investigate a sustainability evaluation approach for food-packaging systems. A total of four distinct ketchup products were analyzed. According to their statement, the climate change impact of all products varies between 5.66 and 9.16 kg CO₂-eq per functional unit correspondingly. The packaging accounted for 24% to 26% of the total for

PP-450-CNV, PP-550-ORG, and GL 480-ORG (the packaging material as polypropylene or glass (GL); the content of bottles of 380, 450, 480 or 550g and; if the ketchup is a product of conventional (CNV) or organic (ORG) agriculture). However, it only accounted for 12% for PP-380-ORG because of its high tomato content and low capacity to be emptied. Plastic packaging contributed between 7% and 13% to other impact categories, while glass packaging contributed between 29% and 31% to the entire outcome. Clearly, the direct environmental implications of glass packaging were more significant than those of plastic bottles (Wohner et al., 2020).

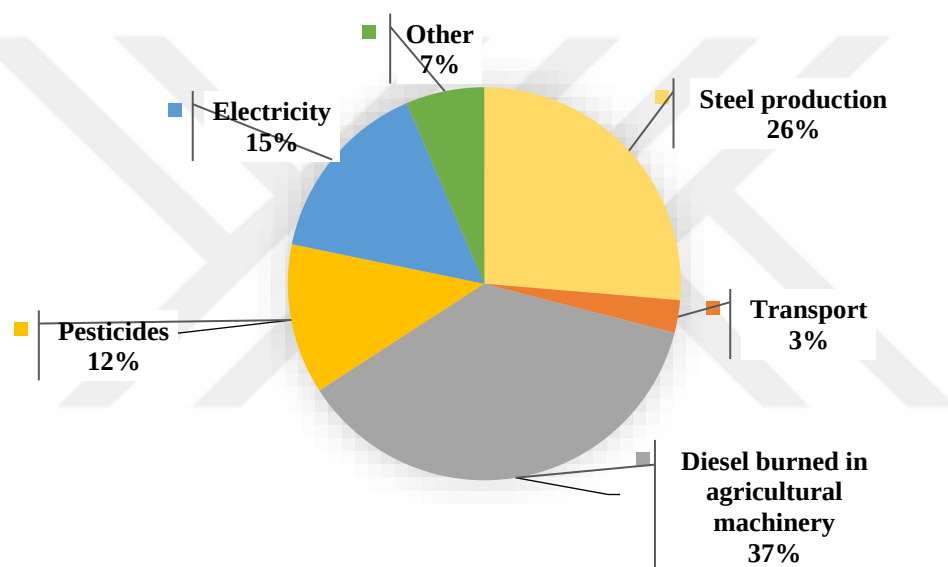


Figure 4.27. The top contributors to FWEP (kg 1.4 DB-eq) impact category in tomato paste production

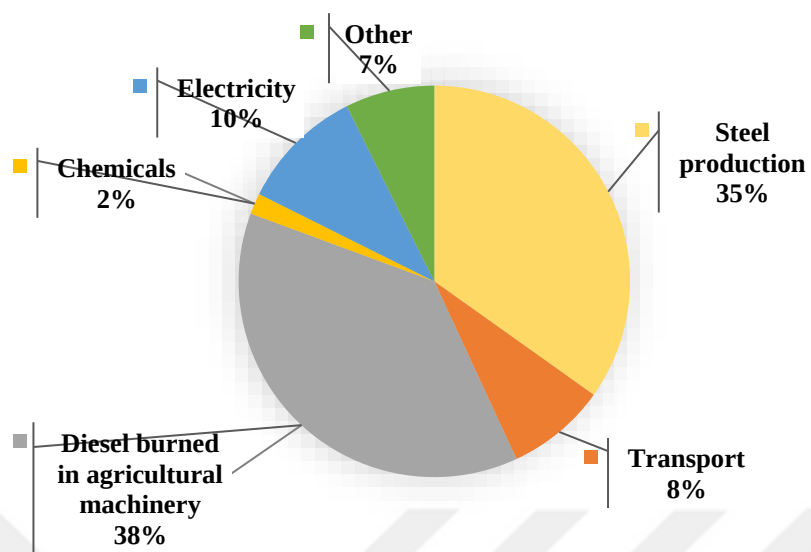


Figure 4.28. The top contributors to HTP (kg 1.4 DB-eq) impact category in tomato paste production

Table 4.6. Life cycle assessment results of tomato paste

Product	Scenario	Impact categories									
		ADP	AFDP	AP	EP	FWEP	GWP	HTP	ODP	POCP	TEP
Tomato farming	BC	2.4E-03	5.3E+03	3.0E+00	1.0E+00	2.6E+02	5.5E+02	2.8E+02	6.2E-05	1.6E-01	1.9E+01
	PF	2.2E-03	5.0E+03	2.9E+00	9.9E-01	2.5E+02	5.3E+02	2.7E+02	5.9E-05	1.5E-01	1.9E+01
	BD	2.6E-04	1.6E+03	8.2E-01	3.7E-01	1.1E+02	1.6E+02	7.6E+01	1.3E-05	3.6E-02	1.8E+01
	GP	2.4E-03	5.3E+03	3.0E+00	1.0E+00	2.6E+02	5.5E+02	2.8E+02	6.2E-05	1.6E-01	1.9E+01
	GP-BD	2.6E-04	1.6E+03	8.2E-01	3.7E-01	1.1E+02	1.6E+02	7.6E+01	1.3E-05	3.6E-02	1.8E+01
Factory processing	BC	4.8E-05	5.0E+03	4.0E-01	1.3E-01	2.7E+01	9.3E+01	3.8E+01	3.2E-05	3.8E-02	1.7E-01
	PF	4.8E-05	5.0E+03	4.0E-01	1.3E-01	2.7E+01	9.3E+01	3.8E+01	3.2E-05	3.8E-02	1.7E-01
	BD	2.4E-05	1.9E+02	1.7E-01	1.1E-01	1.9E+01	2.9E+01	1.5E+01	3.1E-06	6.3E-03	1.2E-01
	GP	4.8E-05	5.0E+03	4.0E-01	1.3E-01	2.7E+01	9.3E+01	3.8E+01	3.2E-05	3.8E-02	1.7E-01
	GP-BD	2.4E-05	1.9E+02	1.7E-01	1.1E-01	1.9E+01	2.9E+01	1.5E+01	3.1E-06	6.3E-03	1.2E-01
Packaging and transportation	BC	4.7E-05	2.6E+02	2.7E-01	1.2E-01	2.2E+01	6.6E+01	3.6E+01	4.1E-06	4.5E-02	1.1E-01
	PF	4.7E-05	2.6E+02	2.7E-01	1.2E-01	2.2E+01	6.6E+01	3.6E+01	4.1E-06	4.5E-02	1.1E-01
	BD	3.8E-05	2.3E+02	2.6E-01	1.2E-01	2.2E+01	6.3E+01	3.5E+01	3.6E-06	4.5E-02	1.1E-01
	GP	6.6E-05	3.5E+02	1.9E-01	3.3E-02	6.5E+00	2.8E+01	1.6E+01	3.2E-06	7.7E-03	4.2E-02
	GP-BD	5.4E-05	3.0E+02	1.8E-01	3.0E-02	6.1E+00	2.4E+01	1.5E+01	2.6E-06	7.1E-03	3.7E-02
Whole process	BC	2.5E-03	1.1E+04	3.7E+00	1.3E+00	3.1E+02	7.1E+02	3.5E+02	9.7E-05	2.4E-01	1.9E+01
	PF	2.3E-03	1.0E+04	3.6E+00	1.2E+00	3.0E+02	6.9E+02	3.4E+02	9.5E-05	2.4E-01	1.9E+01
	BD	3.2E-04	2.0E+03	1.3E+00	6.0E-01	1.5E+02	2.5E+02	1.3E+02	2.0E-05	8.7E-02	1.8E+01
	GP	2.5E-03	1.1E+04	3.6E+00	1.2E+00	2.9E+02	6.7E+02	3.3E+02	9.6E-05	2.1E-01	1.9E+01
	GP-BD	5.4E-04	3.2E+03	1.8E+00	6.3E-01	1.6E+02	3.0E+02	1.6E+02	2.9E-05	7.5E-02	1.8E+01

4.3. Cumulative Energy, Exergy and CO₂ Results of Sweet Red Pepper Products

4.3.1. Retail sweet red pepper

Global fertilizer usage has experienced a significant increase of over 800% since the 1950's, leading to harmful consequences for the environment. The anticipated rise in crop production, as a result of growing demands for food, feed, biofuel, and other purposes, is likely to lead to a further escalation in fertilizer usage. Past research investigated methods of increasing agricultural productivity, while also considering environmental sustainability. However, these studies have not specifically addressed the economic implications of long-term changes in fertilizer usage within the entire agricultural system (Sinha, Calvin, Kyle, Hejazi, Waldhoff, Huang, Vishwakarma, & Zhang, 2022). In 2018, the agricultural industry in the EU utilized 10.2 million tonnes of nitrogen as fertilizer, representing a growth of almost 2% compared to the previous decade. The phosphorus values are rather low, with a quantity of 1.1 million tonnes, and this has experienced a decline of approximately 1% over the past decade (Martinho, 2021). The technologies employed to generate nitrogen, phosphorus, and potash and their respective inputs differ. For instance, to generate nitrogen, there exists a necessity of natural gas as a crucial input (Agricultural, 2019).

Fertilizer usage is a hotspot in sweet red pepper farming. The fertilizer needs for cultivating pepper should be determined by considering the chemical properties of the soil, the irrigation method employed and the estimated yield. When considering the latter, it is important to consider the amounts of nutrients that are taken out of the crop. Consequently, the exact quantities retrieved are frequently unknown; suggestions are typically derived from multiple publications cited as sources for the incorporation of nutrients. Typically, the quantity of fertilizer to be used during planting is calculated by referring to published reports from certain states or regions (Ramalho do Rêgo, Monteiro do Rêgo, Finger, Pinto, dos Santos, de Araujo, & da Silva, 2016). Figure 4.29 illustrates the primary factors that contribute to the results of BC SRP farming step, specifically CEnC, CExC, and CCO₂C while Figure 4.30 presents the retail SRP farming step CEnC, CExC and CCO₂C changes within different scenarios. The primary factor contributing to all evaluated metrics is the utilization of fertilizers. Possessing the values for the CEnC, CExC, and CCO₂C were 87%, 71%, and 32% respectively. In addition to the use of fuel in agricultural machinery and transportation, the use of electricity,

chemicals, and water for irrigation also have an impact on the overall outputs. One ton of fresh SRP farming results in 39.92 kg/ton of CO₂ emissions. These emissions are derived from various sources: 32% from fertilizer, 28% from transport-diesel, 23% from agricultural machinery-diesel, 13% from power, and 3% from chemicals. Figure 4.31 demonstrates the primary factors that contribute to the whole process of producing retail fresh SRP. The highest contributors are fertilizer and diesel usage. Baran et al. (2022) stated in their study regarding the sauceboat peppers, the fuel oil contributed the largest proportion, accounting for 31.65% of the overall energy input. The subsequent energy requirements included energy for planting seedlings, energy for fertilizer, energy for irrigation, energy for human labor, energy for spraying, and energy for machines, accounting for 21.55%, 19.64%, 12.55%, 8.59%, 4.45%, and 1.87% correspondingly (Baran et al., 2022).

A more efficient use of materials (for example, nitrogen fertilizers) can have a significant impact on industrial energy use. In a previous investigation, a strategy for assessing the potential for lowering nitrogen fertilizer input was investigated. A cost-savings function was used to examine both prospective savings and economics. Eight strategies for increasing fertilizer efficiency in the Nethedafids were studied. These strategies apply to six crop categories (which account for 97% of fertilizer use). The fertilizer application rate can be lowered from 228 kg N/ha in 1988 to 128 kg N/ha in the near future. This would cut fertilizer requirement by 44% (minimum 28%, maximum 51%), from 458 ktonnes N to 258 ktonnes. As a result, energy usage will be lowered by 8 PJ. A national economic review indicates that material savings of 41% are attainable (Worrell, Meuleman, & Blok, 1995)

So et al. (2010) conducted a study and the pepper production system was classified into two categories: field cropping for red pepper and greenhouse cropping for green pepper, based on the type of pepper being cultivated. The data collected for establishing the life cycle inventory of red pepper and green pepper production systems revealed that the amount of fertilizer input for red pepper production was greater than that for the green pepper production system. The LCI analysis specifically examined the GHG emissions and found that the carbon footprint values were 4.13E+00 kg CO₂-eq per kg for red pepper and 4.70E+00 kg CO₂-eq per kg for green pepper. Notably, 90% of CO₂ emissions were attributed to fertilizer usage, while 6% were attributed to pepper production (So et al., 2010).

In another study, the production of 1 ton of bell peppers caused 1156 kg of CO₂-eq. The main factor responsible for CO₂ emissions in growing systems is the pre-cultivation stage, particularly the production of raw materials, which accounts for approximately 45% of emissions. Next one was the cultivation stage, which is responsible for approximately 38% of emissions, followed by post-cultivation activities, mainly transportation, which contributed to 17% of emissions (Wang et al., 2018). As shown in Table 4.7, in the present research it was found that the production of one ton of fresh SRP results in the emission of 39.82 kg/ton of CO₂, with CEnC and CExC values of 2742.20 MJ/ton and 1387.91 MJ/ton, respectively.

Table 4.7. Cumulative energy, exergy and CO₂ results of retail SRP

Product	Scenario	CEnC(MJ/ton)	CExC (MJ/ton)	CCO ₂ C (kg/ton)
SRP farming	BC	2742.20	1387.91	39.82
	BD	2527.71	1138.32	21.87
	PF	1554.99	897.88	33.39
	BD-PF	1340.51	648.29	15.43
Packaging and transportation	BC	2773.14	2230.54	163.65
	BD	1226.43	430.67	33.79
	PF	2773.14	2230.54	163.65
	BD-PF	1226.43	430.67	33.79
Whole process	BC	5515.33	3618.45	203.48
	BD	3754.14	1568.99	55.66
	PF	4328.13	3128.42	197.04
	BD-PF	2566.94	1078.97	49.22

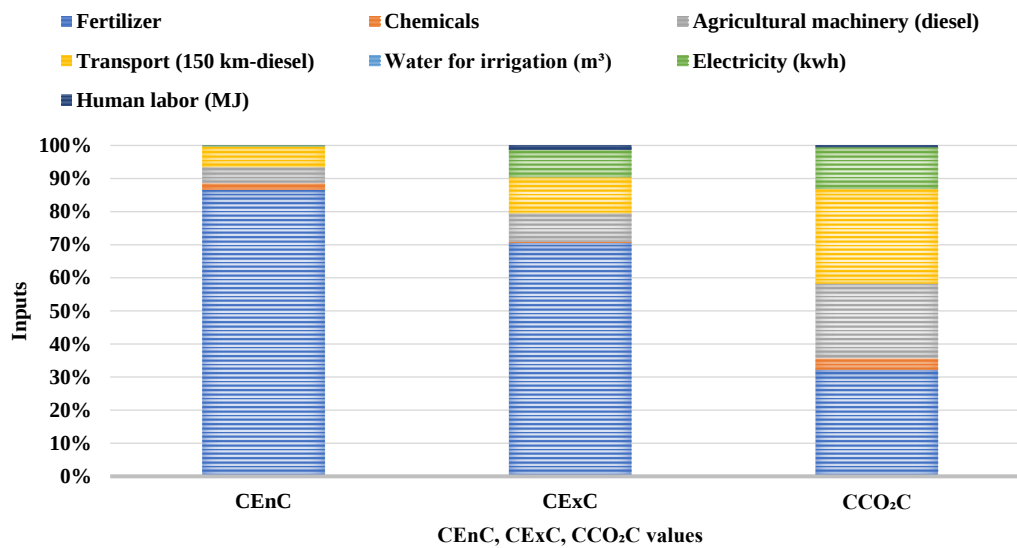


Figure 4.29. The main contributors to CEnC, CExC and CCO₂C results of BC SRP farming step

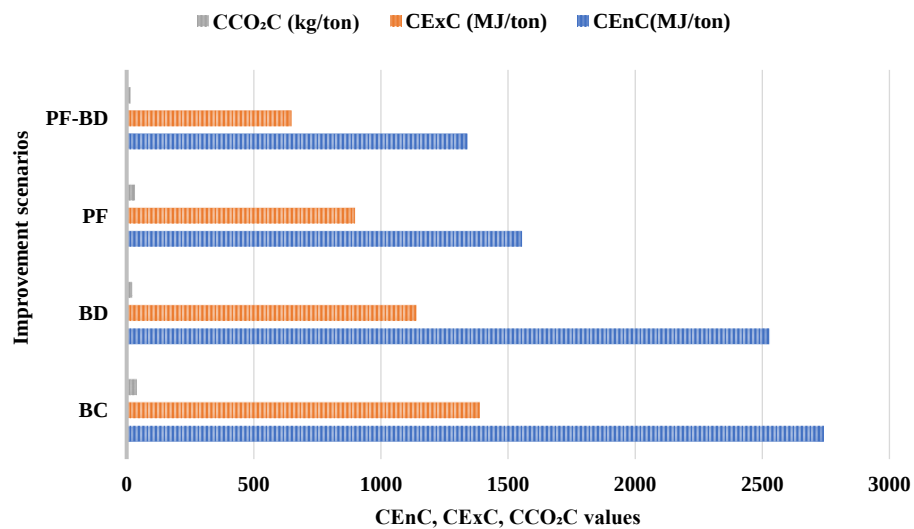


Figure 4.30. Retail SRP farming step CEnC, CExC and CCO₂C changes within different scenarios

Upon applying improvement scenarios to the farming process, it's clear in Figure 4.30 that the PF-BD scenario, which involves using precision farming for fertilizer application and substituting fossil fuels with biodiesel, is the optimal choice for cultivating fresh sweet red peppers. Within the scope of precision farming, the most beneficial outcomes have been observed, while reducing fertilizer application by 50%, compared to other scenarios. The

manufacture of nitrogenous fertilizers through industrial operations is the primary source of reactive nitrogen compounds, chemicals, and effluents that have a direct influence on the biosphere. An exergy analysis was conducted on a nitrogen fertilizer factory. The results demonstrated that, the simultaneous utilization of physical-chemical and biological methods can enhance the overall efficiency of exergy utilization and prevent the release of reactive substances into the atmosphere. This enables the recovery of lost condensate from effluent, which can then be reintegrated into the steam production network. As a result, the energy utilization and environmental performance of the process will be improved (Kiperstok, 2013).

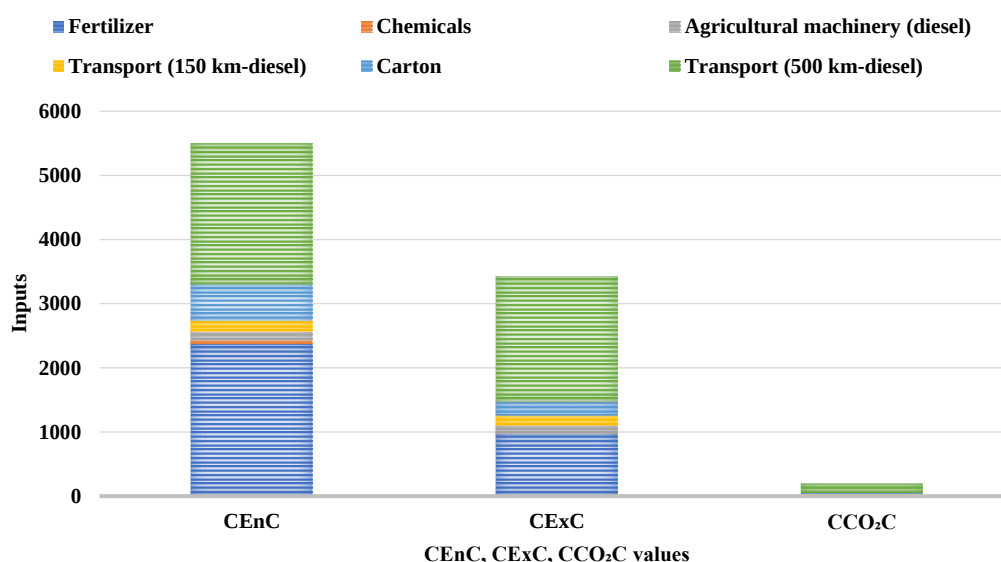


Figure 4.31. The main contributors to CEnC, CExC and CCO₂C results of BC retail SRP whole process

Figure 4.32 illustrates the influence of different scenarios on the CEnC, CExC, and CCO₂C values of retail SRP production. The BD and PF-BD scenarios exhibit the lowest values, whereas BC demonstrates highest values. Based on the research conducted and the aforementioned studies, it is clear that, the utilization of diesel has a significant impact on cumulative energy, exergy consumption, and CO₂ emissions. Therefore, it is reasonable to consider replacing diesel with a more environmentally and economically sustainable fuel alternative like biodiesel. Substituting conventional diesel fuel with alternative fuel is a viable solution to address the challenges and enable the utilization of diesel engines. Biodiesel fuels are highly favored as an alternative fuel for diesel engines due to their renewable nature,

biodegradability, and the simplicity of their production procedure. In a study conducted by Şanlı & Uludamar (2020), exergy and energy evaluations on a diesel engine using conventional diesel, hazelnut biodiesel, and canola biodiesel fuels were investigated. The investigation revealed that, the utilization of biodiesel led to a decrease in the conversion of fuel energy to output power and exergy work rate across all engine speeds.

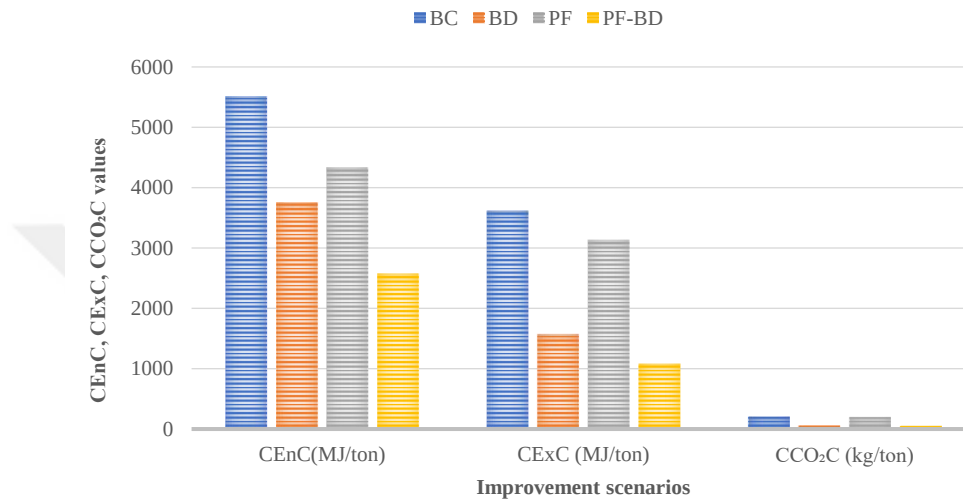


Figure 4.32. Comparison of cumulative energy, exergy and CO₂ results of retail SRP whole process within different scenarios

4.3.2. Sweet red pepper paste

Pepper paste production is a prevalent method of utilizing red peppers in Türkiye. The consumption of red pepper paste, also known as paprika paste or pepper paste, is prevalent in communities with significant Turkish populations, including Mexico, Korea, Germany, Belgium, the Netherlands, the UK, Australia, and Türkiye (Bozkurt & Erkmen, 2004; Erdoğan, 2013; Koca & Erdoğan, 2011). For many years, this product has been made using traditional techniques in households located in the southeastern regions of our country, such as Şanlıurfa, Gaziantep, and Adana. Red pepper paste has been manufactured in contemporary facilities and distributed to several areas in recent times. Furthermore, it has started to be widely utilized and has emerged as a growing industry (Okur, 2011).

The cumulative energy, exergy, and CO₂ emission results are shown in Table 4.8. According to the data presented in Table 4.8 and Figure 4.33, the primary factors that have the greatest impact on SRP cultivation are chemical fertilizer application, diesel usage, and electricity

consumption respectively. In SRP farming step, the cumulative energy consumption is mainly resulted from fertilizer usage (86.5%), followed by diesel usage (11.0%). Although there are no data about the exergetic evaluation of the pepper farming, several studies conducted on the tomato, olive and some agricultural products on farming. A study conducted on olives found that, irrigation and fertilizer application accounted for the highest proportion of energy inputs in both conventional (21% and 12% respectively) and organic (27% and 7% respectively) olive groves (Kaltsas et al., 2007).

Table 4.8. Cumulative energy, exergy and CO₂ results of SRP paste

Production step	Scenarios	CEnC (MJ/ton)	CExC (MJ/ton)	CCO ₂ C (kg/ton)
SRP farming	BC	2742.20	1387.91	39.82
	BD	2527.71	1138.32	21.87
	PET	2742.20	1387.91	39.82
	PF	1554.99	897.88	33.39
	BD-PF	1340.51	648.29	15.43
	BD-PF-PET	1340.51	648.29	15.43
Factory processing	BC	1266.29	1882.60	33.63
	BD	959.99	967.15	56.19
	PET	1266.29	1882.60	33.63
	PF	1266.29	1882.60	33.63
	BD-PF	959.99	967.15	56.19
	BD-PF-PET	959.99	967.15	56.19
Packaging and transportation	BC	3137.38	3532.49	191.03
	BD	1590.58	1732.60	61.16
	PET	3363.81	3308.70	184.47
	PF	3137.38	3532.49	191.03
	BD-PF	1590.58	1732.60	61.16
	BD-PF-PET	1817.02	1508.81	54.61
Whole process	BC	7145.86	6803.00	264.48
	BD	5384.58	4753.52	116.66
	PET	7372.30	6579.20	257.93
	PF	5958.66	6312.97	258.05
	BD-PF	4197.38	4263.49	110.23
	BD-PF-PET	4117.51	3124.26	126.24

Karakaya and Özilgen (2011) stated that, the main energy consumers in agriculture are diesel-powered trucks and chemical fertilizers. They offered that diesel oil consumption can be minimized by utilizing energy-efficient trucks and improving delivery routes. Yıldızhan and Taki (2018) claimed that, diesel fuel, irrigation, fertilizer, and chemicals were identified as the

primary inputs influencing all cumulative metrics assessed in both open field and greenhouse tomato production.

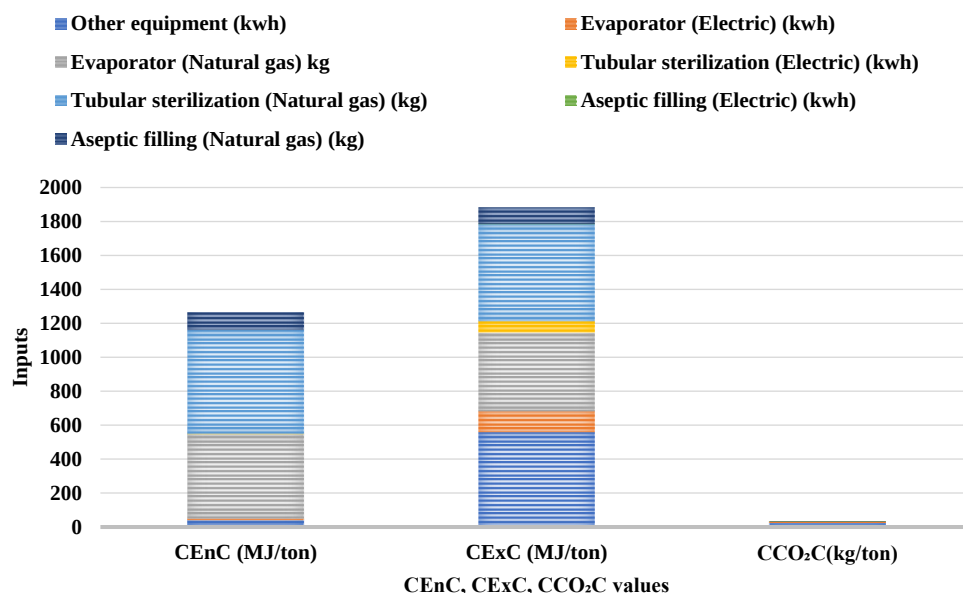


Figure 4.33. The main contributors to CEnC, CExC and CCO₂C results of BC SRP paste factory processing step

Singh et al. (1998) reported that, the energy consumption associated with fertilizer production constitutes around 40% of the overall energy usage in agricultural output within developed nations. The majority of the energy was utilized in the manufacturing process of nitrogen, phosphorous, and potassium fertilizers. Thus, in the present context, the results of the study align with previous investigations reported in the literature. On the other hand, from Figure 4.33 due to natural gas consumption in factory processing step, particularly in the tubular sterilization machine, evaporator, and aseptic filling, emerges as the primary contributor among all equipment. As seen in Figure 4.35, diesel, glass, steel, label and diesel consumption are the major contributors of packaging and transportation step. In packaging and transportation step, the largest energy, exergy and CO₂ emission values were observed in diesel consumption, glass, label, steel and cardboard usage in this study. The individual contributions of inputs to packaging and transportation step could be expressed as 70% diesel, 20% glass, and 5.2% label (low density polyethylene, LDPE). Since the product delivery trucks are regarded as making one-way trip merely, because they frequently transport additional goods on the way back, the packaged SRP paste is assumed to be transported to

500 km distance from plant to the market. When comparing the fuel economy of diesel and biodiesel, it is reported that, at 60 km/h, 1-1.5-ton capacity trucks utilize 0.1667 l/km of diesel fuel and 0.06022 l/km of biodiesel fuel (Gnansounou & Raman, 2016; Roy et al., 2008). The impacts of transition from diesel to biodiesel in factory processing, is shown in Figure 4.34. The biodiesel use in the BD scenario is shown by a drop from the calculated values of 24–48%. In terms of factory processing, the best results are obtained in BD, BD-PF and BD-PF-PET scenarios.

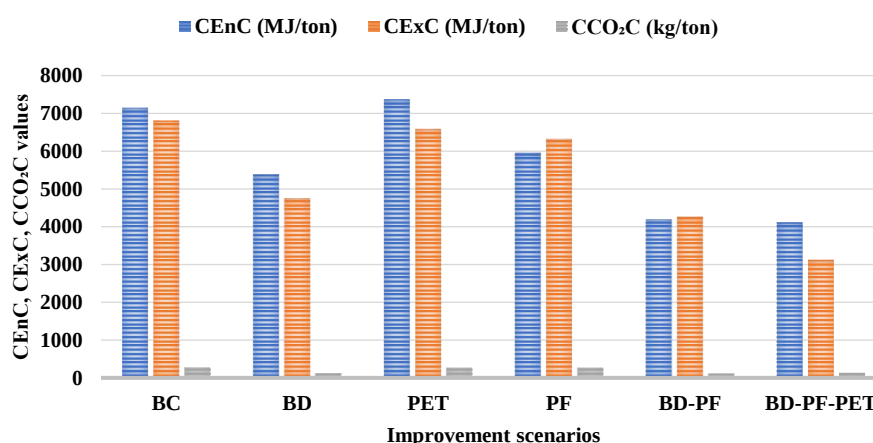


Figure 4.34. SRP paste packaging and transportation step CEnC, CExC and CCO₂C changes within different scenarios

The packaging and transportation step is identified as the primary contributor with a contribution of 44%, 52%, and 72% for CEnC, CExC, and CCO₂C values respectively, in the whole process of SRP paste production for the base case. The factory processing step contributes 17.7%, 27.6%, and 12.7% of the CEnC, CExC, and CCO₂C values, respectively. The agricultural process contributes 38.4%, 20.4%, and 15% of CEnC, CExC, and CCO₂C values, respectively. Therefore, this study's hotspots are the SRP farming and packaging-transportation processes, and the development of improvement scenarios should take these factors into account.

Glass, steel, label, and diesel are the main factors that affect packaging and transportation, as shown in Figure 4.35. Thus, because of significant effect of glass material, the system is performed by PET packaging scenario. In terms of the primary packaging material category, the CEnC, CExC, and CCO₂C values for glass packaging-BC are 652.18 MJ/kg, 1083.35 MJ/kg, and 30.28 kg/ton, whereas the CEnC, CExC, and CCO₂C values for PET packaging

are 606.38 MJ/kg, 628.08 MJ/kg, and 16.86 kg/ton, respectively (Appendix C). By comparing these values, it is possible to determine that, the primary packaging materials are not the sole factor causing changes in the process parameters calculation. When PET packaging is conducted in process design, PET labels and HDPE jar lids are applied to the packaging components. The transition from BC to PET does not result in a significant decrease in CEnC, CExC and CCO₂C values. However, when the combinations of PET packaging, biodiesel, and precision farming (PET-BD-PF) and precision farming, biodiesel, and glass are compared, the PET-BD-PF scenario yields the best results. Still, the BD-PF scenario performs better than the other scenarios as could also be seen from Figure 4.36.

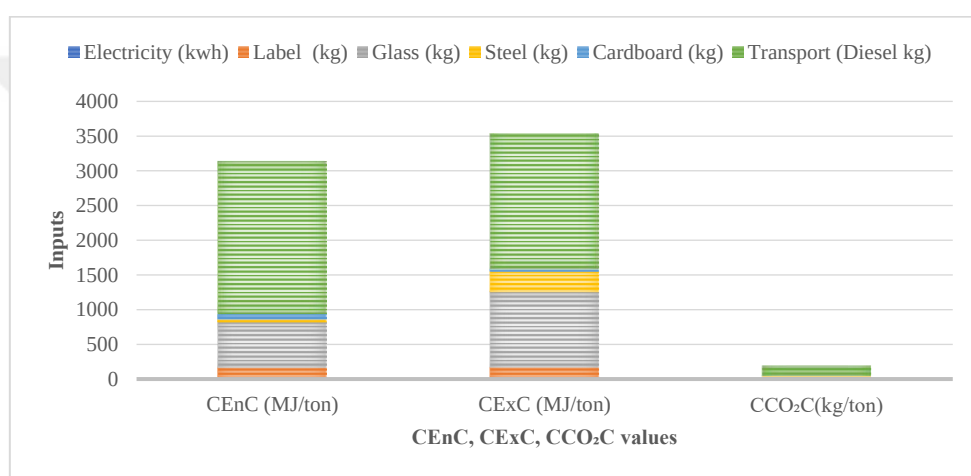


Figure 4.35. The main contributors to CEnC, CExC and CCO₂C results of BC SRP paste packaging and transportation step

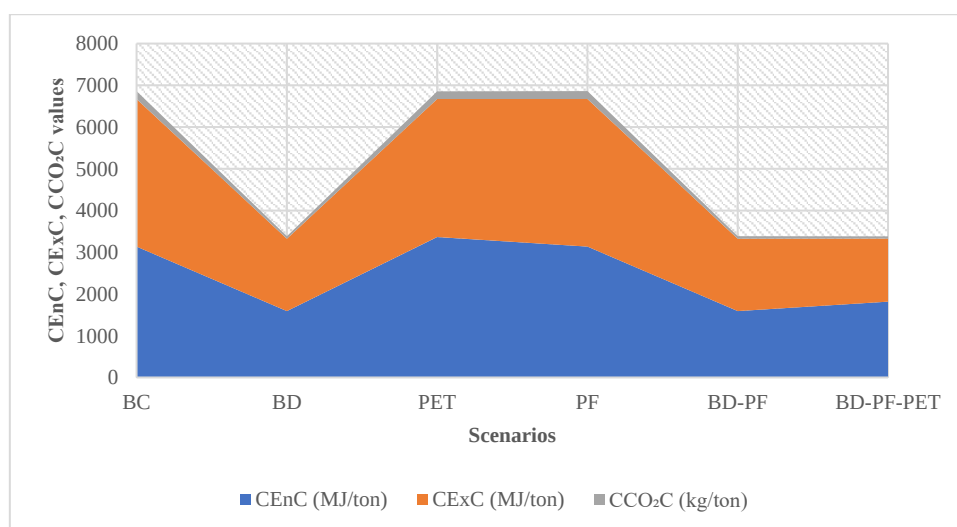


Figure 4.36. SRP paste packaging and transportation step CEnC, CExC and CCO₂C changes within different scenarios

Based on a detailed analysis of the consequences of each step on the process's established parameters, Figure 4.37 shows that the BC has the highest values for CEnC, CExC, and CCO₂C. A CEnC value reduction of 48.6%, 50%, and 30% in the factory processing, packaging-transportation step, and whole process, respectively, is observed when the BD scenario is represented to the system. On the other hand, the best results are obtained in the combination of PET packaging, biodiesel and precision farming (PET-BD-PF) scenarios are used.

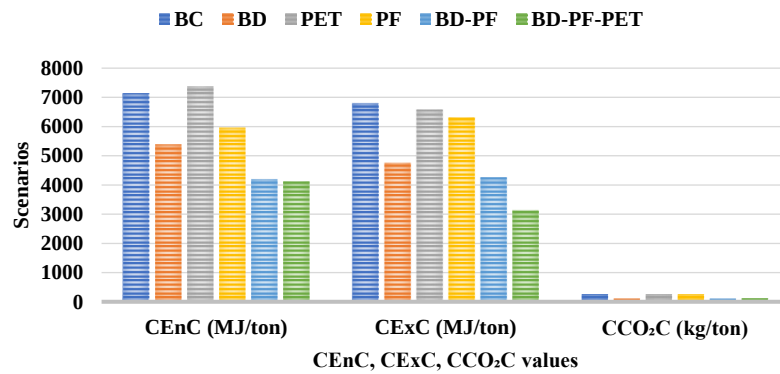


Figure 4.37. Comparison of cumulative energy, exergy and CO₂ results of SRP paste whole process within different scenarios

4.3.3. Roasted sweet red pepper

In 2021, the worldwide production of peppers reached to 36.29 million metric tons (Shahbandeh, 2023). The cultivation of red peppers, which are utilized in the process of roasting, has shown a significant growth of 45.5% from 2004 to 2018, ultimately reaching an annual production of 1.13 million tons. The cultivation of these peppers has shown a consistent upward trend over the past decade, mostly driven by the strong demand for exports (Güvenç, 2020). The consumption and production rate of roasted peppers in Türkiye holds great importance in Turkish cuisine (Gül et al., 2021).

Roasting is a highly prevalent method for processing food products. This process is intended to enhance their attractiveness to consumers. The process is highly energy-intensive, necessitating substantial quantities of electrical and thermal energy (Sheikhshoei, Dowlati, Aghbashlo, & Rosen, 2020). Within the processing steps for roasted SRP, the packaging and transportation step has emerged as the primary factor influencing the entire supply chain, as depicted in Figure 4.38 and 4.40. The primary factor in reaching at this conclusion is the

utilization of glass packaging. Within the entire supply chain, glass packaging accounts for 46.1% of the overall CEnC, 56.8% of the total CExC, and 27.4% of the total CCO₂C. 11.3% of the total CEnC, 8.1% of the total CExC, and 6.3% of the total CCO₂C originate from LDPE label packaging. 12.3%, 8.1% and 10.5% of the total CEnC, CExC and CCO₂C, respectively, originate from diesel usage for transportation. Figure 4.39 illustrates the primary factors that influence the factory processing step of the roasted SRP manufacturing. The raw materials used in the formulation of roasted SRP have the most significant impact. Vinegar, sugar, and water have significant impacts on CEnC, CExC, and CCO₂C levels.

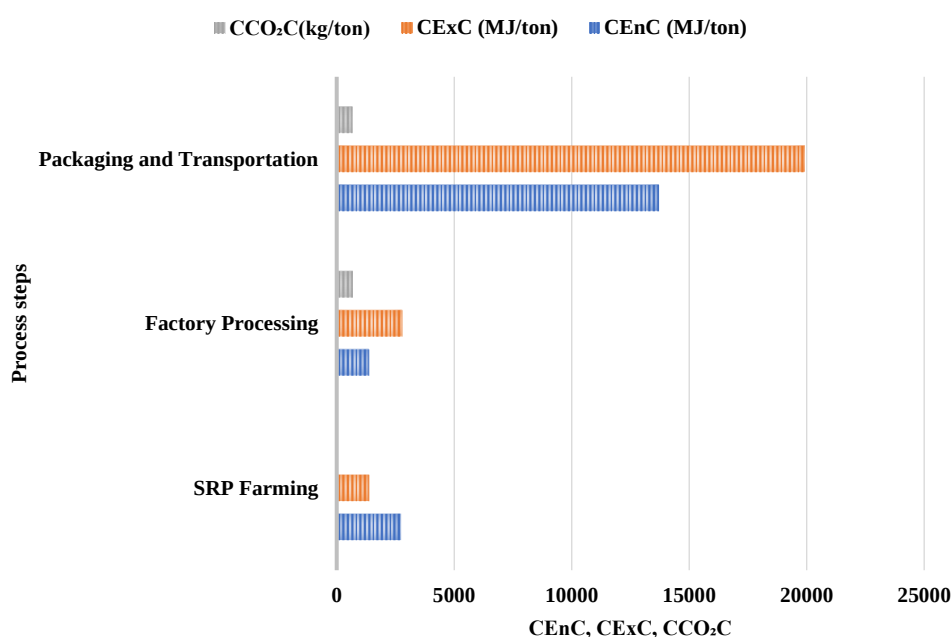


Figure 4.38. Contributions of roasted SRP processing steps on CEnC, CExC and CCO₂C

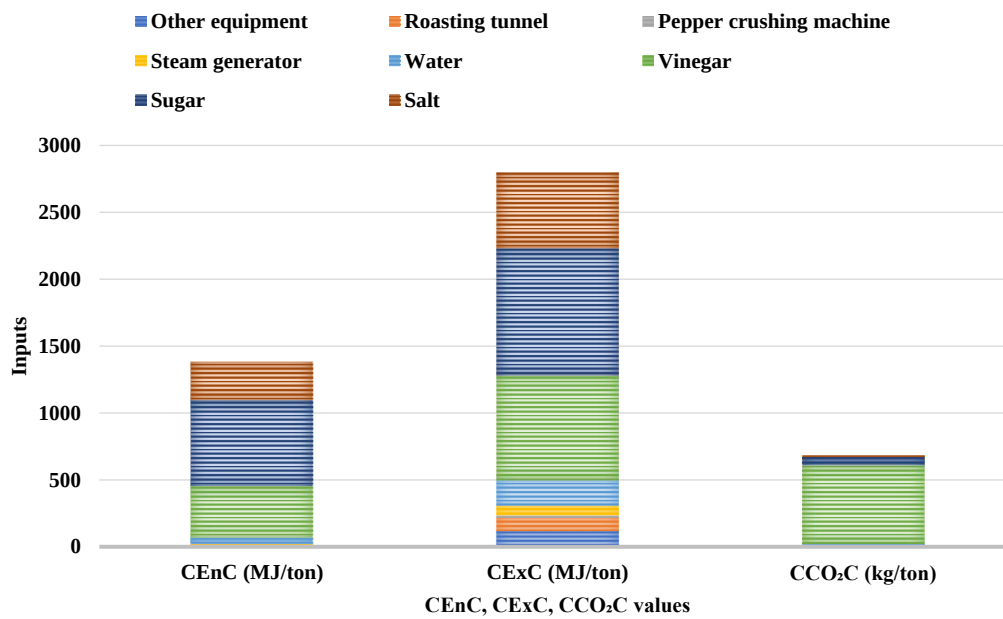


Figure 4.39. The main contributors to CEnC, CExC and CCO₂C results of BC roasted SRP factory processing step

From Table 4.9, among the SRP products, the roasted SRP production has the highest CEnC value, measuring 17846.46MJ per product produced from one ton of fresh SRP. Compared to the TPC scenario, the BD, PF and PF-BD scenarios exhibit the similar pattern. One reason is the high energy need of glass packing, while another factor is the high energy consumption during the roasting process. Applying the TPC scenario results in a significant reduction of 56.8% in the total CEnC value of roasted SRP production. In line with study results, in a study analyzing the exergy of roasted pistachios, Özilgen (2016) stated that, the energy required to create one metric ton of packaged, roasted, and in-shell pistachio nuts is 17543 megajoules per ton of edible pistachios. The high energy consumption in the manufacturing of pistachio nuts is due to the tiny proportion of the fruit that is edible (Kallsen et al., 2009), as well as the significant reduction in moisture content through evaporation during the roasting process (Kahyaoglu, 2008). While the packaging may appear similar, the quantities of the edible products contained in each pouch vary. Potato chips and pretzels are packaged in 60 g pouches, pitted dried apricots in 200 g pouches, and roasted in-shell pistachios in 200 g pouches (equivalent to 60 g of edible snack). Consequently, the energy cost of the packaging, when expressed per weight of the edible product, differs significantly.

Table 4.9. Cumulative energy, exergy and CO₂ results of roasted SRP

Product	Scenario	CEnC (MJ/ton)	CExC (MJ/ton)	CCO ₂ C (kg/ton)
SRP farming	BC (GP)	2742.20	1387.91	39.82
	BD	2527.71	1138.32	21.87
	TCP	2742.20	1387.91	39.82
	PF	1554.99	897.88	33.39
	PF-BD	1340.51	648.29	15.43
Factory processing	BC (GP)	1382.79	2797.45	685.76
	BD	1382.79	2797.45	685.76
	TCP	1382.79	2797.45	685.76
Packaging and transportation	BC (GP)	13723.47	19909.36	670.93
	BD	12176.68	18109.52	541.44
	TCP	3997.13	8177.58	254.17
Whole process	BC (GP)	17848.46	24094.72	1396.51
	BD	16260.50	21784.58	1240.93
	TCP	7710.17	12205.96	968.62
	PF	16661.26	23604.69	1390.08
	PF-BD	15073.29	21294.55	1234.50

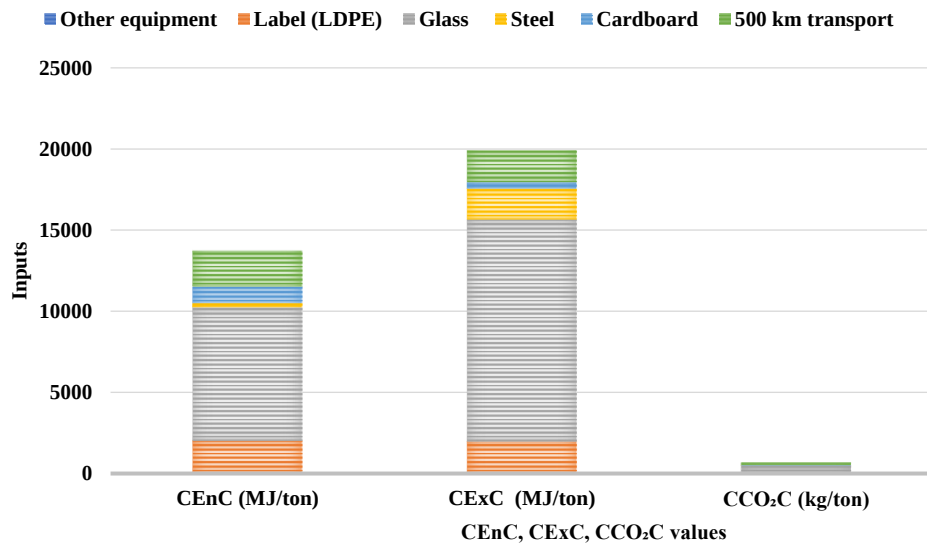


Figure 4.40. The main contributors to CEnC, CExC and CCO₂C results of BC roasted SRP packaging and transportation step

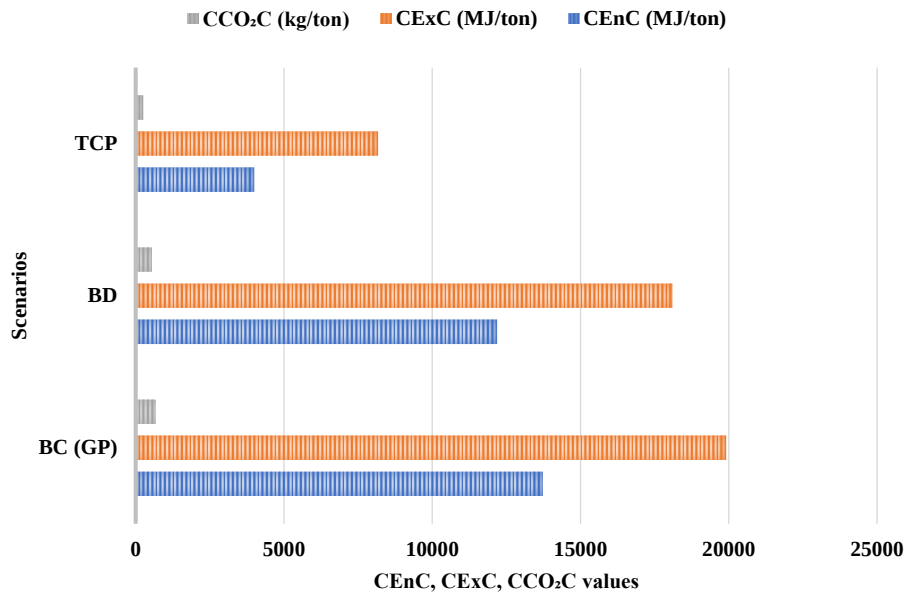


Figure 4.41. Roasted SRP packaging and transportation step CEnC, CExC and CCO₂C changes within different scenarios

As seen in Figure 4.41, in order to decrease the effects of the packaging and transportation step as well as other steps, certain scenarios are carried out because this is the hotspot of the roasted SRP supply chain. TPC, tin can packaging, has demonstrated superior results across several scenarios in roasted SRP production. In Türkiye, one among the marketing strategies for selling roasted SRP is to put it in tin cans weighing 3-5 kg. In this case, when the roasted SRP was placed in a tin can, the values of CEnC, CExC, and CCO₂C reduced by 56.8%, 49.3%, and 30.6% respectively, compared to the BC scenario. Normally, the BD scenario resulted in a notable reduction in CEnC, CExC, and CCO₂C values in the other pepper products investigated. However, this scenario did not have a significant impact on roasted SRP due to the significant influence of the glass packaging and the raw materials used in the factory process. It is also evident from Figure 4.42 that the TPC scenario yields the best overall outcomes. Given that, the TPC scenario has a packaging weight of 3 kg, it can be inferred that, one of the factors contributing to the better performance of the TPC scenario is the larger amount of food packaged using less packaging material.

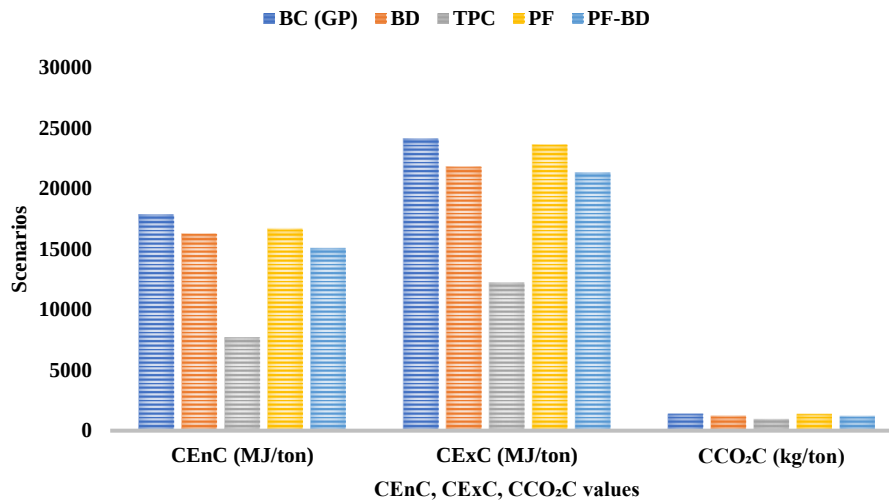


Figure 4.42. Comparison of cumulative energy, exergy and CO₂ results of roasted SRP whole process within different scenarios

4.3.4. Dried sweet red pepper

Drying is a crucial unit operation in various sectors, including food processing, chemical, pharmaceutical, textile, and paper. From ancient times to the current day, drying has been a conventional method of preserving food. The objective of drying food products is to make food resistant to microbiological, chemical, and enzymatic deterioration by reducing the water activity of the surrounding environment to a specific level. Drying is the process of removing moisture through the combined transfer of heat and mass. Throughout the drying process, various concurrent physical, chemical, mechanical, physicochemical, and microbiological phenomena occur, and each of these phenomena has an impact on the ultimate quality of the product (Yıldız & İzli, 2020). During the drying process of a wet agricultural product, two simultaneous phenomena take place: the transfer of thermal energy to the product and the migration of internal moisture towards the surface of the product, where it is subsequently evaporated. There are three primary methods of drying that rely on heat transfer: conduction, convection and radiation (Liu, Bia, Wang, Meng, Wang, Yu, Gao, & Xiao, 2019). The impacts of various dried SRP processing steps are displayed in Figure 4.43.

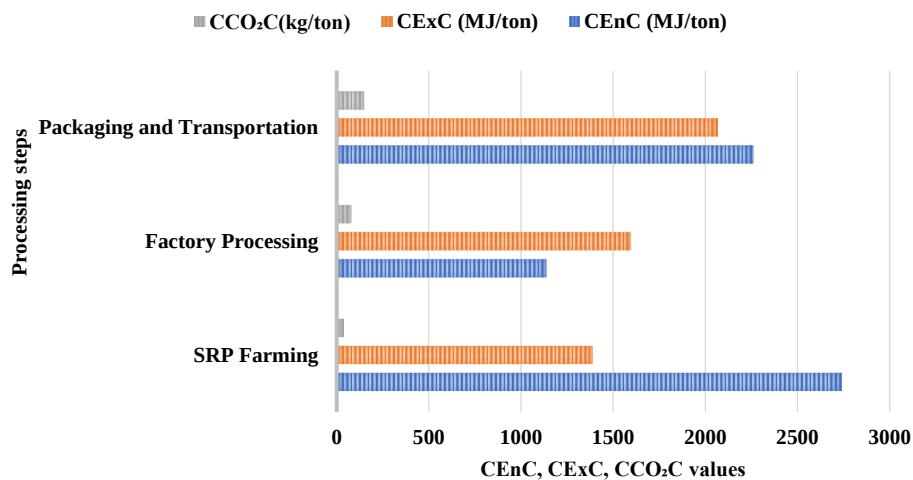


Figure 4.43. Contributions of dried SRP processing steps on CEnC, CExC and CCO₂C values

The impact of farming on dried SRP was found to be 45%, followed by factory processing at 18%, and packaging and transportation at 37% for CEnC values. The main contributory factor of SRP farming is the excessive use of chemical fertilizers rather than following to soil requirements. Supplying chemical fertilizers from energy-efficient chemical plants could reduce energy consumption resulting from the high energy production of chemical fertilizers. The utilization of chemical fertilizers in agriculture is typically not grounded on soil analysis and exceeds the real requirement by a significant margin. Introducing some microorganisms into the soil can promote nitrogen fixation, dissolve minerals that are not easily soluble, and decrease the requirement for producing and transporting significant quantities of chemical fertilizers (Aslantaş, Çakmakçı, & Şahin, 2007). Fertilizer management strategies can potentially cut energy consumption by up to 72%. As a result, the use of herbicides and pollution levels also decrease (Özilgen, 2016).

The dried SRP CExC values were impacted by the farming step 27%, factory processing 32%, packaging and transportation 41%. Akpınar, Bicer, & Yildiz (2003) stated that, the drying process of the red peppers began with an initial moisture content of approximately 87.25% (wet basis) and continued, until there were no more observable changes in their mass. At this point, the peppers reached a final moisture content of roughly 10% (wet basis), which was then considered as the equilibrium moisture content for subsequent calculations (Akpınar, Bicer, & Yildiz, 2003). According to the data in Appendix-A, the mass balance for dried SRP processing shows that 1 kg of dried SRP is produced from 10.0801 kg of fresh SRP.

Therefore, this result is expected since the SRP farming is the primary factor in the dried SRP supply chain. Figure 4.44 presents the main contributors to the CEnC, CExC and CCO₂C results of BC-Dried SRP factory processing step while Table 4.10 presents the cumulative energy, exergy and CO₂ results of dried SRP

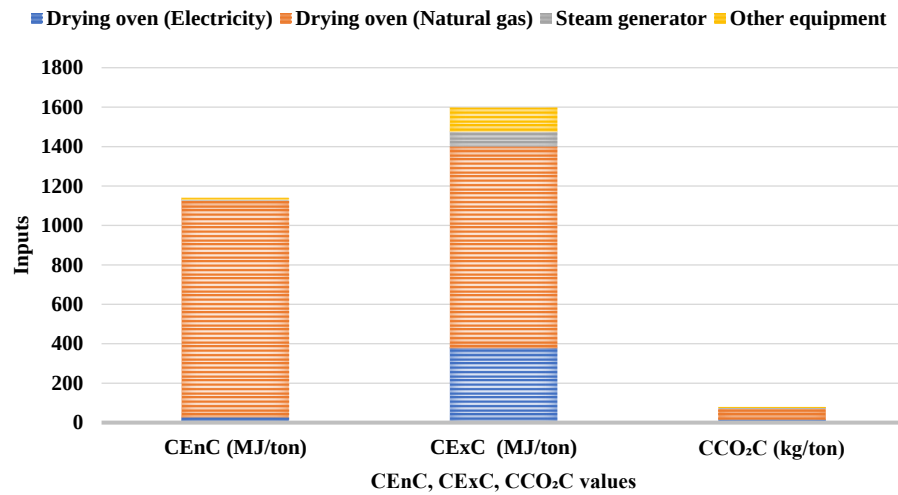


Figure 4.44. The main contributors to the CEnC, CExC and CCO₂C results of BC-Dried SRP factory processing step

Table 4.10. Cumulative energy, exergy and CO₂ results of dried SRP

Product	Scenario	CEnC (MJ/ton)	CExC (MJ/ton)	CCO ₂ C (kg/ton)
SRP farming	BC (1 kg DP)	2742.20	1387.91	39.82
	BD	2527.71	1138.32	21.87
	25KP	2742.20	1387.91	39.82
	PF	1554.99	897.88	33.39
	PF-BD	1340.51	648.29	15.43
	25KP-BD-PF	1340.51	648.29	15.43
Factory processing	BC (1 kg DP)	1138.40	1596.07	79.63
	BD	444.54	1799.06	82.76
	25KP	1138.40	1596.07	79.63
Packaging and transportation	BC (1 kg DP)	2262.99	2067.72	148.90
	BD	716.19	267.84	19.40
	25KP	2228.55	2047.96	147.37
	25KP-BD-PF	681.75	248.07	17.88
Whole process	BC (1 kg DP)	6143.58	5051.70	268.35
	BD	3688.44	3205.21	124.03
	25KP	6109.14	5031.94	266.83
	PF	4934.89	4547.33	261.34
	PF-BD	2501.24	2715.19	117.60
	25KP-BD-PF	2466.80	2695.43	116.07

The primary factors that contribute to the factory processing step are natural gas and electricity, which are utilized for the drying oven and steam generator. The drying oven accounts for almost 80% of the contribution for CEnC, CExC, and CCO₂C. Drying is a process that consumes a substantial amount of energy in industrial operations. It is reported that, in the United Kingdom, the proportion of total energy consumption attributed to drying is approximately 18% (Kumar, Arora, & Kundli, 2019). Drying is a highly energy-demanding procedure, with research indicating that it accounts for 10% to 25% of the total energy consumption in manufacturing facilities (Kudra, 2004). Additionally, there are certain

industries where the proportion of energy consumption dedicated to drying might reach up to 50% (Kumar et al., 2019). Pepper fruits can rapidly degrade after being harvested due to their high initial moisture content, which can reach up to 90% on a wet basis (Soysal, Ayhan, Eştürk, & Arıkan, 2009). Therefore, fresh fruits such as peppers are extremely prone to spoilage and are typically dehydrated to extend their storage duration and ensure year-round availability to consumers. Various drying methods, including sun drying, hot-air drying, infrared drying, and microwave drying, are used to preserve this perishable product, while maintaining its quality, including its color and important vitamins, minerals, and nutrients. While sun drying and hot air drying remain the predominant ways for producing red pepper flakes and powdered spices, these processes are time-consuming and result in quality degradation (Arslan, Soysal, & Keskin, 2020). Drying under the sun using solar radiation to preserve food has been practiced since ancient times. It is the oldest and most widespread traditional method for preserving agricultural items such as grains, fruits, vegetables, and fish, in which the products are placed directly on the ground and exposed to solar radiation. The sun radiation that falls on the surface is partially reflected and partially absorbed. The absorbed radiations and surrounding air heat the surface. A portion of this heat is used to evaporate the moisture from the surface into the surrounding air. Part of this heat is lost through long-wavelength radiations to the atmosphere and conduction to the earth. However, significant losses may occur owing to dirt, dust, insects, microorganisms, animals, and birds. As a result, advanced drying techniques can be used to dramatically minimize crop losses and improve product quality when compared to the old method of open sun drying (Sahdev, 2014). Given the objective of the study to examine industrial food processing and considering the aforementioned negative consequences of sun drying in an open area, drying sweet red peppers utilizing cabinet hot air drying in the present research was preferred. The CEnC, CExC, and CCO₂C estimations for the dried SRP supply chain are displayed in Table 4.10.

Upon analyzing the packaging and transportation stage from Figure 4.45, it's clear that transportation-packaging and the use of diesel fuel are the main factors contributing to CEnC, CExC, and CCO₂C values, accounting for over 90% of the total impact. Additional components include cardboard, PET, PE, PP, paper, and other packaging machinery. In order to minimize the effects of packaging and transportation, many improvement scenarios have been implemented, as depicted in Figure 4.46 and 4.47. For the base case, 1 kg of metallized doypack packaging is utilized to package dried SRP. In the 25KP scenario, dried SRP is

packaged using industrial packaging in a 25 kg kraft paper package. However, the most favorable result was obtained by implementing PF-BD and 25KP-PF-BD scenarios. According to the 25KP-PF-BD scenario, the CEnC, CExC, and CCO₂C values have decreased by 59.8%, 46.6%, and 56.7%, correspondingly. Similarly, in the PF-BD scenario, the values of CEnC, CExC, and CCO₂C have decreased by 59.3%, 46.3%, and 56.2%, correspondingly.

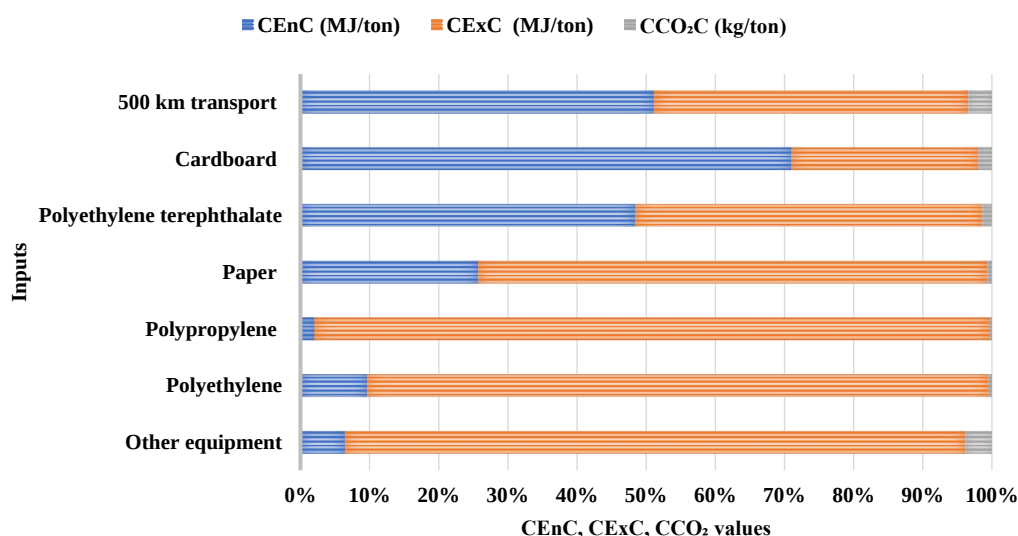


Figure 4.45. The main contributors to the CEnC, CExC and CCO₂C results of BC-Dried SRP packaging and transportation step

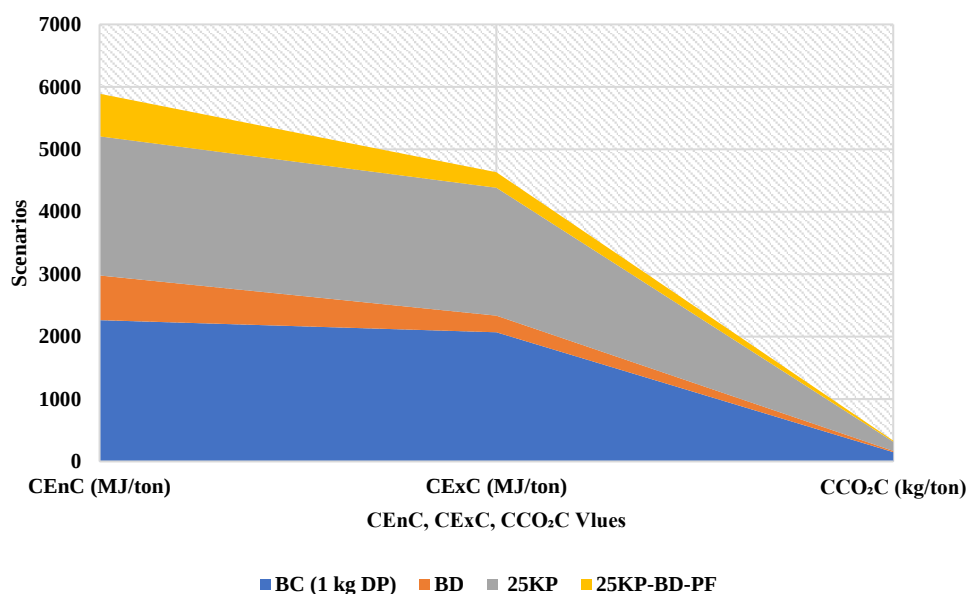


Figure 4.46. Dried SRP packaging and transportation step CEnC, CExC and CCO₂C changes within different scenarios

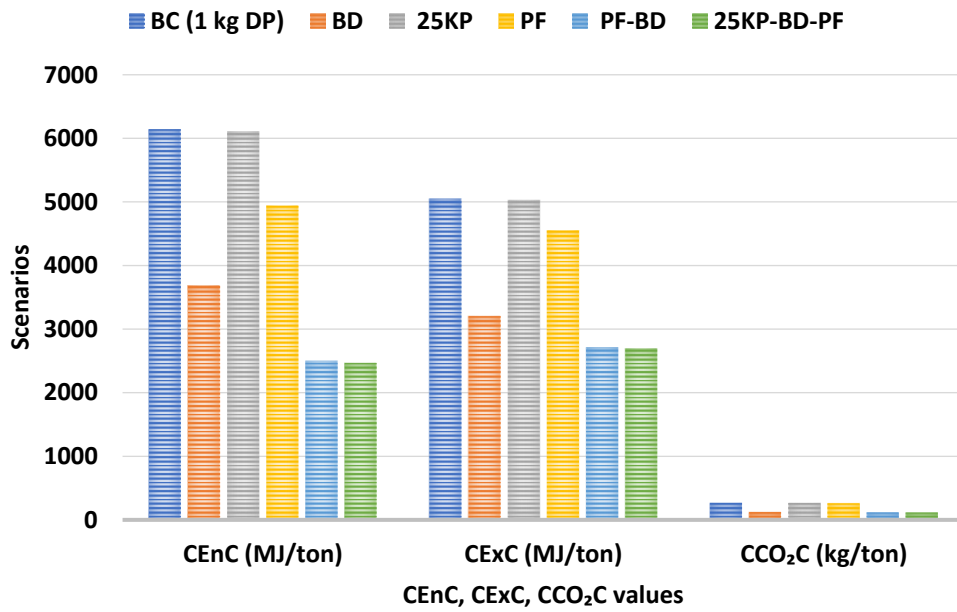


Figure 4.47. Comparison of cumulative energy, exergy and CO₂ results of dried SRP whole process within different scenarios

4.4. Life Cycle Assessment Results of Sweet Red Pepper Products

4.4.1. Retail sweet red pepper

Figures 4.48, 4.49 and 4.50 illustrate the major contributors of GWP, AFDP and HTP of the retail fresh SRP production. The primary contributors to the GWP impact category of BC-retail SRP production whole process are transport-diesel (65%), others (18%), fertilizer (9%), and steam used in fertilizer production (8%) followed by the steam, ammonia, and urea used in the fertilization process in farming, which accounts for 17%. The remaining 18% is attributed to other factors. García and García (2022) stated that, the electricity required for supplying water for irrigation was the primary factor contributing to the overall energy consumption in SRP cultivation. However infrastructure, chemical disinfection, and fertilizers also played a significant role. They also pointed out that, both the production of fertilizers, and the emissions into the atmosphere resulting from the application of nitrogenous fertilizers were important factors to consider.

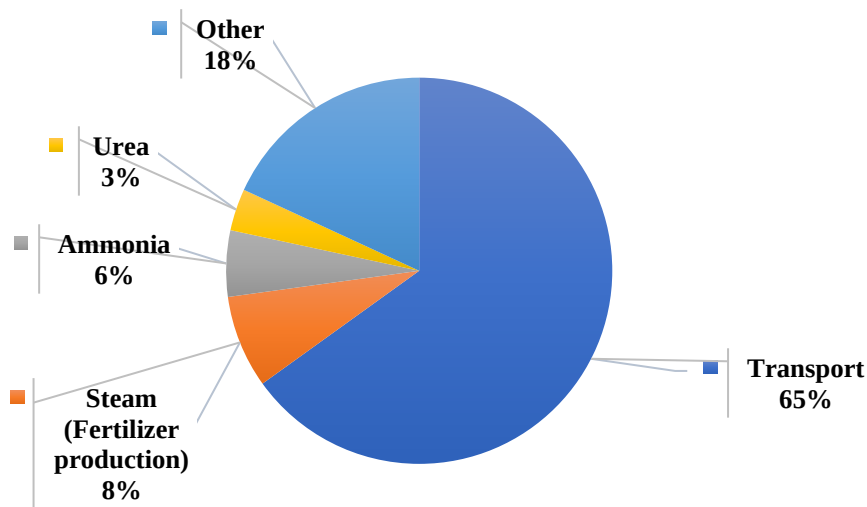


Figure 4.48. Top five contributors on GWP (kg CO₂-eq) impact category of BC-Retail SRP production whole process

Wang et al. (2018) stated that, the fertilizer was the primary factor responsible for the highest levels of global warming potential, acidification potential, and eutrophication potential. The production, transport, and application of fertilizer contributed to approximately 64.4% of the overall global warming potential. Specifically, 18.1% of this contribution was due to the production and transport of fertilizer, while 46.3% was attributed to the application of fertilizer (Wang et al., 2018). In their study, Baran et al. (2022) stated that, the total GHG emissions for the highest-quality production portion of sauceboat pepper, attributed to human labor (31.18%), were estimated to be 3703.54 kg CO₂-eq per hectare. The order of activities involved in the process included human labor, followed by the consumption of diesel fuel (25.79%), the use of machines (0.08%), seedling planting (15.90%), nitrogen fertilizer (15.88%), phosphate fertilizer (4.09%), herbicides (3.68%), fungicides (1.93%), calcium intake (0.09%), magnesium application (0.08%), and iron (0.52%). Furthermore, the GHG emissions associated with the production of sauceboat peppers were determined to be 0.096 kg CO₂-eq per kg (Baran et al., 2022). In the study, as depicted in Table 4.11, the GWP value for fresh SRP farming caused a value of 0.0954 kg CO₂-eq per kg, which aligns with the findings of Baran et al. (2022).

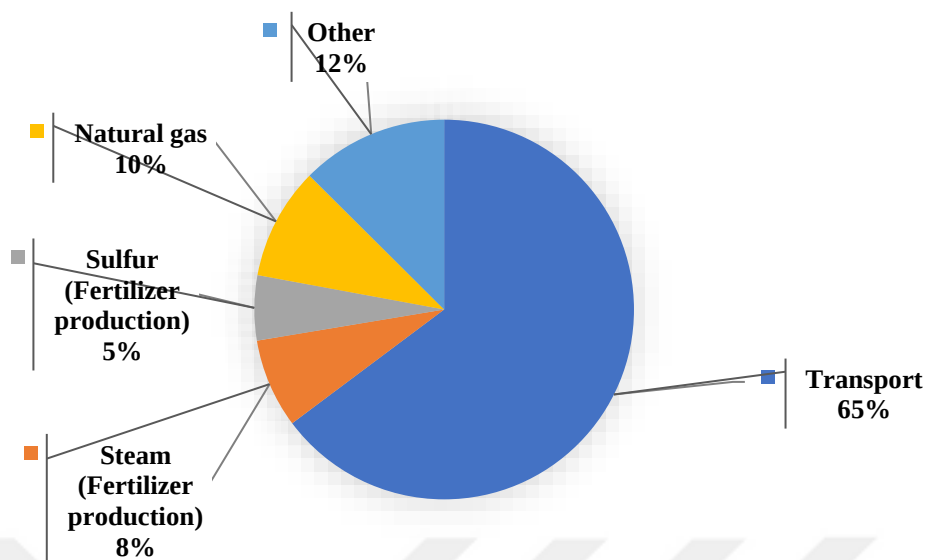


Figure 4.49. Top five contributors on AFDP (MJ) impact category of BC-Retail SRP production whole process

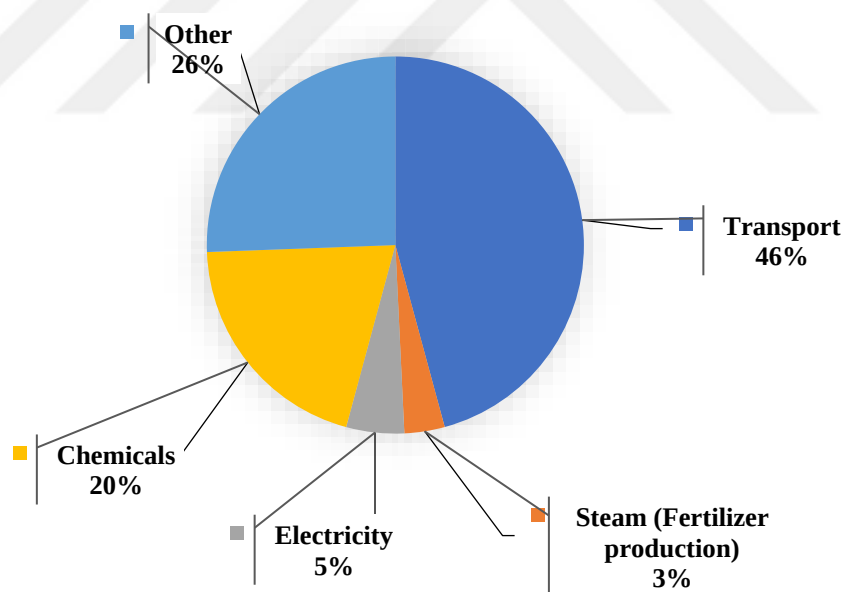


Figure 4.50. Top five contributors on HTP (1.4 DB-eq) impact category of BC-retail SRP production whole process

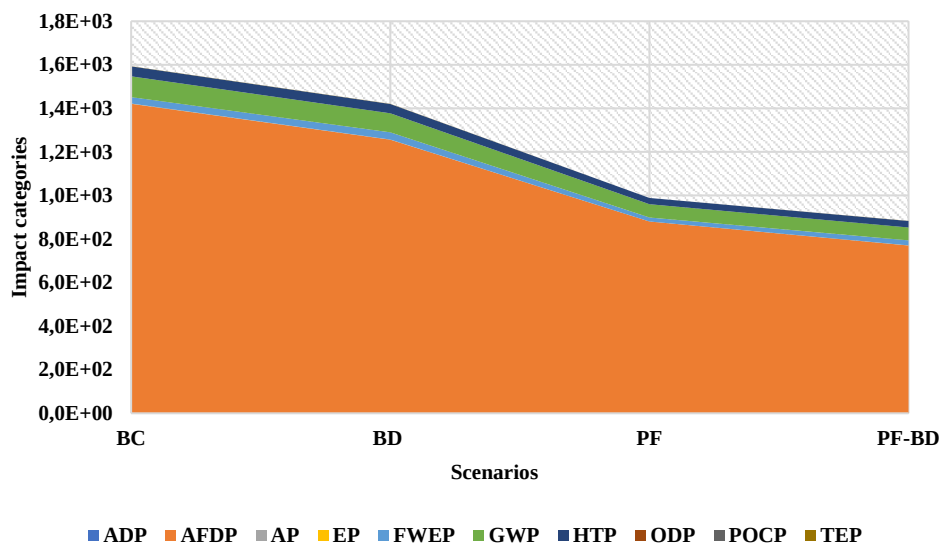


Figure 4.51. The effect of different scenarios on LCA impact categories of retail SRP-farming step

Figures 4.51, 4.52, and 4.53 depict the impact of various scenarios on the LCA impact categories of retail SRP production processes for each separate stage. Based on Figure 4.51, adopting the PF and PF-BD scenarios in the SRP farming step result in a reduction of 35.4% and 38%, respectively in the GWP impact category. Precision farming is an emerging discipline in agriculture that aims to optimize crop yield, while minimizing the use of resources such as fertilizer, pesticide, and herbicide. Precision farming is the implementation of a comprehensive management approach that utilizes information technology to gather data from various sources in order to make decisions related to agricultural output, marketing, finance, and personnel. The primary goals of precision farming are to enhance production efficiency, enhance product quality, mitigate environmental deterioration, conserve energy, and safeguard soil and groundwater. The fundamental elements of precision farming include: data, advanced technology, and effective management. The classification of precision agricultural technology consists of five main groups: computers, global positioning system, geographic information system, sensors, and application control. Precision farming offers the potential for increased crop yields and decreased input costs by optimizing agricultural management practices, resulting in reduced waste and labor requirements. Additionally, it aids in the reduction of environmental contamination (Patil Shirish, & Bhalerao, 2013). By implementing the PF-BD scenario, there is a reduction of 48.5% and 58% in the EP and AP impact categories, respectively. It can be concluded that, using biodiesel and precision

farming in SRP farming and retail SRP result in a significant reduction in almost all impact categories, indicating a more environmentally friendly practice.

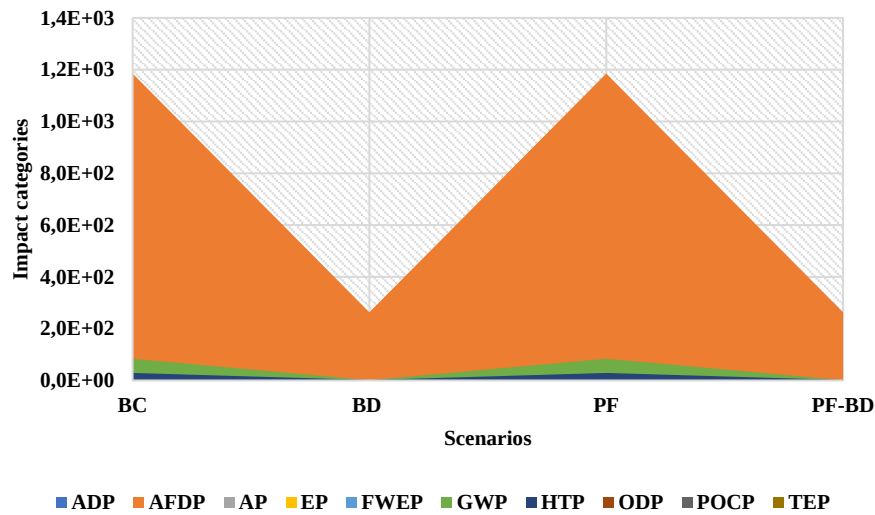


Figure 4.52. The effect of different scenarios on LCA impact categories of retail SRP-packaging and transportation step

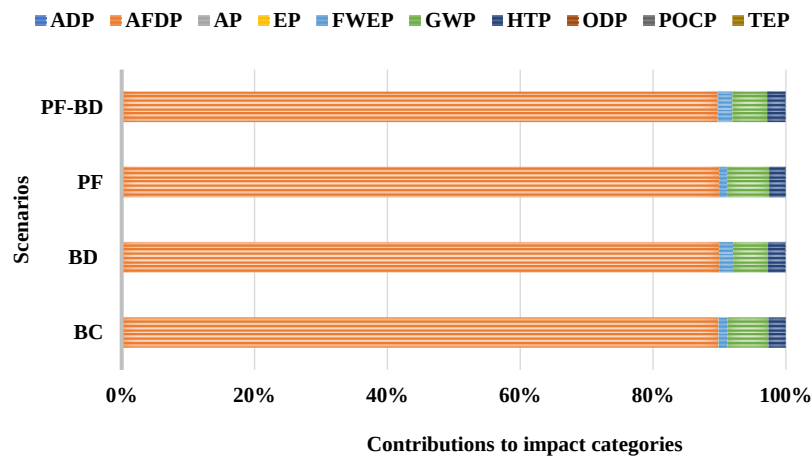


Figure 4.53. The effect of different scenarios on LCA impact categories of retail SRP- whole process

Table 4.11. Life cycle assessment results of retail SRP

Product	Scenario	Impact categories									
		ADP	AFDP	AP	EP	FWEP	GWP	HTP	ODP	POCP	TEP
SRP farming	BC	5.06E-04	1.42E+03	6.10E-01	2.38E-01	2.99E+01	9.54E+01	4.56E+01	1.36E-05	2.60E-02	5.77E-01
	BD	4.37E-04	1.26E+03	5.74E-01	2.43E-01	3.27E+01	8.78E+01	4.26E+01	1.07E-05	2.47E-02	5.69E-01
	PF	2.90E-04	8.80E+02	3.68E-01	1.38E-01	1.78E+01	6.16E+01	2.82E+01	8.89E-06	1.57E-02	3.47E-01
	PF-BD	2.89E-04	7.70E+02	3.64E-01	1.52E-01	2.31E+01	5.91E+01	2.99E+01	6.60E-06	1.58E-02	3.51E-01
Packaging and transportation	BC	2.49E-04	1.19E+03	2.74E-01	6.29E-02	9.22E+00	8.39E+01	2.90E+01	1.52E-05	1.39E-02	1.14E-01
	BD	8.05E-07	2.64E+02	6.86E-03	2.65E-03	1.58E+00	1.53E+00	1.83E+00	1.70E-06	2.39E-03	3.48E-03
	PF	2.49E-04	1.19E+03	2.74E-01	6.29E-02	9.22E+00	8.39E+01	2.90E+01	1.52E-05	1.39E-02	1.14E-01
	PF-BD	8.05E-07	2.64E+02	6.86E-03	2.65E-03	1.58E+00	1.53E+00	1.83E+00	1.70E-06	2.39E-03	3.48E-03
Whole process	BC	7.55E-04	2.61E+03	8.84E-01	3.01E-01	3.91E+01	1.79E+02	7.46E+01	2.88E-05	3.99E-02	6.91E-01
	BD	4.38E-04	1.52E+03	5.81E-01	2.46E-01	3.43E+01	8.93E+01	4.44E+01	1.24E-05	2.71E-02	5.72E-01
	PF	5.39E-04	2.07E+03	6.42E-01	2.00E-01	2.70E+01	1.46E+02	5.72E+01	2.41E-05	2.96E-02	4.61E-01
	PF-BD	2.90E-04	1.03E+03	3.71E-01	1.55E-01	2.47E+01	6.06E+01	3.17E+01	8.31E-06	1.82E-02	3.55E-01

4.4.2. Sweet red pepper paste

The environmental impacts of SRP paste resulted from processing one ton of fresh SRP have been calculated and given in Table 4.12. According to results, the agricultural and packaging-transportation steps were found as the key hotspots of this study. However, there are other investigations that have focused specifically on tomato paste. In line with this study results, a study investigating various packaging materials' impact on tomato puree production indicated that, packaging is the primary factor influencing most impact categories, accounting for 41-69% of all impacts except EP, where it contributes 20%. The cultivation phase has the greatest impact on EP, accounting for 71% of the total impact, and contributes from 7-27% to other impacts. The factory processing phase accounts for 6-20% of all effect categories, except for EP. Transportation accounts for 14-25% of all impact categories except EP, where it accounts for 6% (Manfredi & Vignali, 2014).

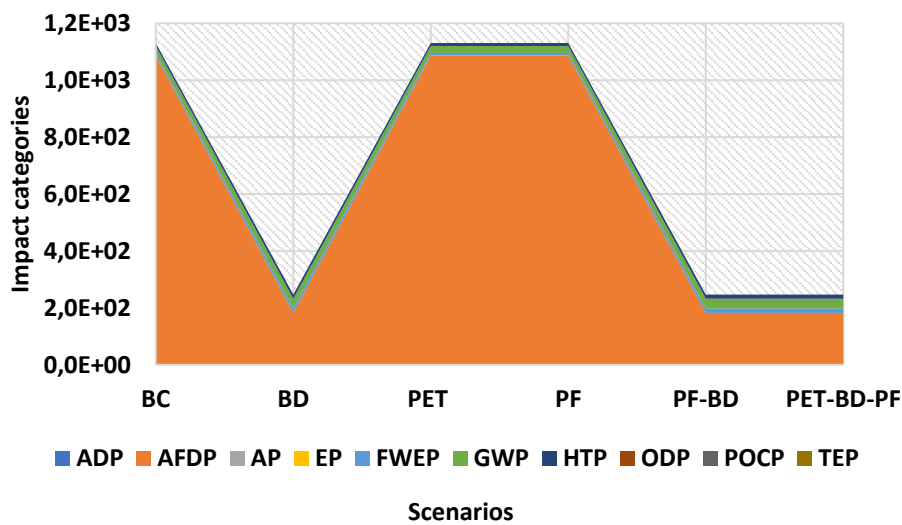


Figure 4.54. The effect of different scenarios on LCA impact categories of SRP paste-factory processing step

According to LCA results, it can be concluded that, the major impacts are caused from SRP farming step. The main effects of SRP farming are predominantly seen in specific impact categories such as AFDP, EP, AP, GWP and TEP. This is typically caused by the use of excessive amounts of fertilizer and diesel usage for transportation purposes as described in Section 4.2.1. Retail tomato and Section 4.4.1. Retail SRP. Fertilizer application in agriculture should be planned based on soil characteristics, requirements, and soil analysis. A study

comparing conventional and organic red pepper production found that in conventional agriculture, the primary environmental impacts are from irrigation (49.6%), fertilizers (40.2%), and machinery (10.2%) (Chatzisyneon et al., 2016)

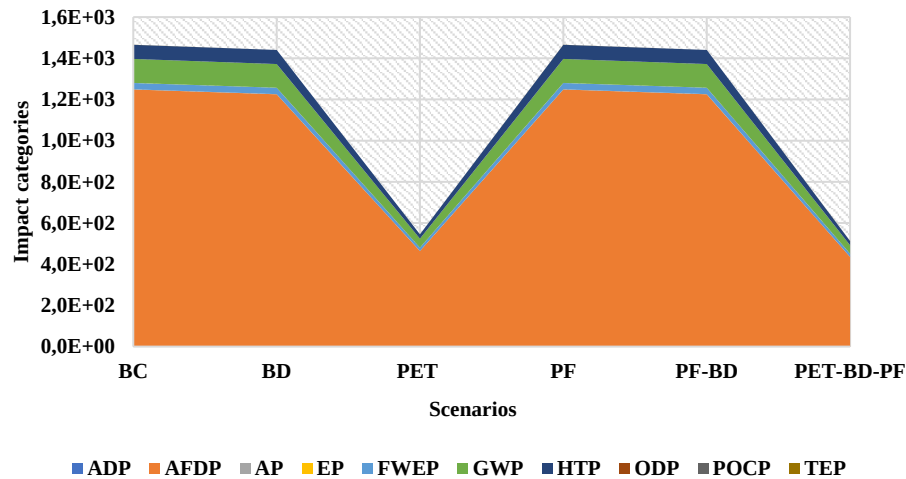


Figure 4.55. The effect of different scenarios on LCA impact categories of SRP paste-packaging and transportation step

In LCA, abiotic resource usage refers to environmental concerns associated with the use of metals, minerals, fossil and nuclear energy, atmospheric resources (e.g. argon), and flow energy resources (e.g. wind). Land and water can also be called abiotic resources (Swart et al., 2015). The issue with consuming these resources is their decreasing accessibility for future generations (Brentrup et al., 2002). The production of SRP paste has the greatest influence on the abiotic (fossil) depletion potential impact category, as illustrated in Figure 4.54, Figure 4.56, and Figure 4.57. The top five contributors to AFDP impact category can be seen from Figure 4.57. Glass contributes the most (30%), followed by the natural gas consumption, due to factory processing step-evaporator, aseptic filling machine and tubular sterilization machine transport process and due to diesel consumption in heavy duty trucks, steam and packaging film (LDPE), as well as other packaging and transportation considerations. Chatzisyneon et al. (2016) stated that, ‘Resources’ is the second most affected damage category in cultivation methods of red pepper. This damage category combines ReCiPe's endpoint impact categories: ‘metal depletion’ and ‘fossil depletion’. In traditional farming practices, the primary areas of focus for potential harm to ‘resources’ are irrigation (mostly due to the energy combination used) and fertilization. They also stated that, in the latter instance, the production of chemical fertilizers is energy-intensive and uses a lot of natural resources, which emphasizes the impact

category on "fossil depletion" According to the findings of a study conducted to examine the environmental effects of bell pepper production, 46.65 kg Sb-eq of abiotic resource depletion are needed to produce 1 ton of greenhouse bell peppers. Data analysis revealed that, the impact of abiotic resource depletion was influenced by pesticides, electricity, fertilizers and natural gas (Naderi et al., 2019).

Contemporary climate change is mostly a result of burning fossil fuels and altering land use, resulting in higher levels of greenhouse gases including CO₂, methane (CH₄), and nitrous oxide (N₂O) in the atmosphere. In the past 30 years, this has typically been accomplished by utilizing the global warming potential. The GWP is a greenhouse gas metric that compare the efficiency of various greenhouse gases in trapping infrared radiation (Neubauer, 2021).

Another significant impact category that is affected from SRP paste production is GWP, and as can be seen in Figure 4.56. The top five contributors on GWP impact category are glass (37%), steel, LDPE, fertilizer, diesel usage in packaging and transportation step, and steam production in factory processing step. This is due to the utilization of steam generated from burning a significant quantity of fuel for the purpose of evaporation, tubular sterilization and aseptic filling unit. The fuel consumption during long-distance transportation of raw materials and also the end product transportation is significant. Kiyak and Gunes (2024) studied the LCA of apricot puree concentration and, aligning with the present study conducted , they have found that, evaporation and the transport process of apricots have a notable effect on the overall GWP. They stated that, the steam generated by evaporation process and the fuel consumption during long-distance transportation of raw materials have a substantial effect on impact categories and the agricultural stage and energy consumption significantly affect the total GWP. The global warming potential of sweet red pepper farming is found as 510.74 kg/ton in this study. Wang et al. (2018) stated in their study that, the GWP value of pepper production was 368 kg/ ton and they claimed that, this value was different from published previous studies conducted in different areas of the world. They expressed that environmental factors including weather and soil conditions, in addition to fertilizer input, can greatly affect the productivity and environmental effects of agricultural systems. The discrepancies in environmental effect values per metric ton of pepper output between their study and the literature search are likely due to the lower nitrogen fertilizer production efficiency (PFP-N) values for pepper production in southwest China. The PFP-N values for horticultural crops

cultivated in open fields and greenhouses in various regions worldwide were around 7.6-8.2 times higher than the value found for pepper in their study. Therefore, the boundaries of the present study's system, inputs, and agricultural methods may differ as a result of various farming techniques and besides, results may vary with other similar studies. So et al. (2010) found that, fertilizer production contributed around 52% to the GWP of red pepper production and 48% to the GWP of green pepper production.

The HTP is a computed index that considers the potential harm of a chemical released into the environment, considering the compound's inherent toxicity and potential dose. This is utilized to quantify emissions recorded in a LCA or in the toxics release inventory and to combine emissions based on a reference chemical. Emissions can be assessed based on benzene equivalence for carcinogens and toluene equivalents for noncarcinogens. The potential dose is determined by a generic fate and exposure model that analyzes the distribution of a chemical in a simulated environment and considers several exposure pathways such as inhalation, ingestion of food, fish, and meat, and skin contact with water and soil (Hertwich et al., 2001). From Figure 4.58, the top five contributors of HTP impact category in SRP paste production are glass (45%), fertilizer, steel production in packaging and transportation step, diesel due to transport processes and electricity. Figure 4.54 shows that, BC produces the highest impact category results.

Plastic packaging materials are more prevalent in the modern world. Plastic is a significant category of chemicals in the petrochemical industry. It is derived from petroleum-based goods or by-products and natural gas through chemical transformations. Plastic packaging comes in several forms. The primary categories of these species include PET, Polyvinylchloride (PVC), Polypropylene (PP), Polystyrene (PS), and Polyethylene (PE). Plastic packages consist of many layers, including aluminum and metallized layers. They have a high potential for development and are well-suited for packaging dry products (Kulcu, 2018). The majority of the studies indicated that, the PET bottle had a lower environmental impact over its whole life cycle compared to the glass container. In their study, Kouloumpis et al. (2020) emphasized that, in order to have similar effects on the environment, glass bottles should be 40% lighter compared to PET bottles. The environmental advantages of PET bottles are further enhanced by using recycled PET bottles, as demonstrated by several life cycle assessment studies that evaluated the environmental performance of recycled PET bottles compared to glass bottles

for water and milk (Ferrara, & De Feo, 2023). In consistent with prior LCA studies, it was stated in another study that, the glass system had much greater impacts than the recycled PET system across all impact categories (Stefanini, Borghesi, Ronzano, & Vignali, 2021).

The impact category values for BD, PF, PF-BD, PET, and PET-BD-PF scenarios decreased. PF-BD and PET-BD-PF scenarios provide the best AFDP and HTP results among all scenarios performed. With a 40% reduction in GWP value the PET-PF-BD scenario which comprise of PET packaging, biodiesel, and precision farming combination yielded the best results for each impact category analyzed in this study. This is due to the 50% reduction in fertilizer usage through precision farming and the substitution of fossil fuel diesel with biodiesel. In a study conducted by Saleh (2016), the comparative LCA analysis shows that, in the Palestinian context, the 2000 ml PET beverage bottles had the lowest environmental impact. Following the PET bottles, the 330 ml aluminum beverage cans ranked second, while the 300 ml glass bottles were shown to have the highest environmental impact. Furthermore, the sensitivity analysis results indicated that, the environmental impacts can be substantially mitigated by raising the recycling rates of the three packing materials under investigation. A study conducted an LCA on the packaging materials utilized for juice, beer, and water in the Spanish market. The complete life cycles of packaging materials, starting from production and ending with disposal was examined. The analysis demonstrated that, recycling is the most environmentally sustainable method of disposing of packaging. Furthermore, it was discovered that, aseptic carton and plastic packaging exhibit the least amount of environmental consequences (Pasqualino, Meneses, & Castells, 2011). In line with mentioned packaging studies, Figure 4.55 clearly demonstrates that the PET packing scenario yields the most favorable results in terms of impact categories. The combination of PET-PF-BD results in the least adverse environmental impacts.

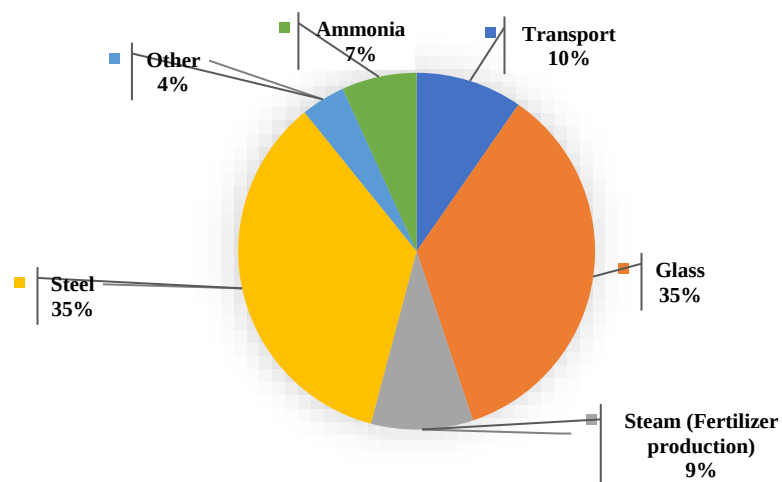


Figure 4.56. Top five contributors on GWP (kg CO₂-eq) impact category of BC-SRP paste production whole process

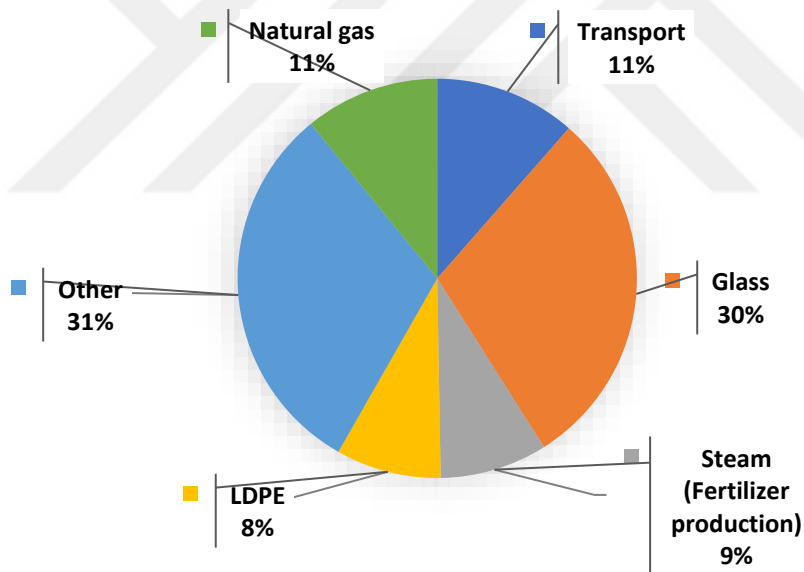


Figure 4.57. Top five contributors on AFDP (MJ) impact category of BC-SRP paste production whole process

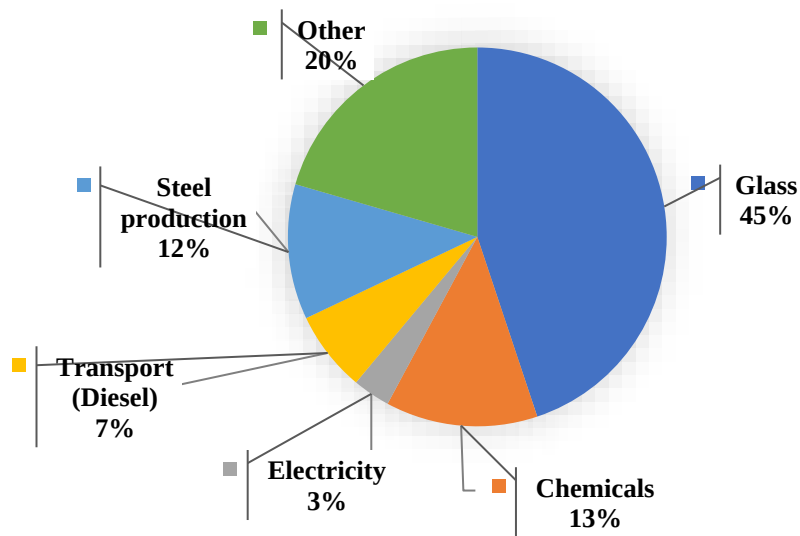


Figure 4.58. Top five contributors on HTP (kg 1.4 DB-eq) impact category of BC-SRP paste production whole process

Table 4.12. Life cycle assessment results of SRP paste

		Impact categories									
Production step	Scenario	ADP	AFDP	AP	EP	FWEP	GWP	HTP	ODP	POCP	TEP
SRP farming	BC	2.71E-03	7.61E+03	3.27E+00	1.27E+00	1.60E+02	5.11E+02	2.44E+02	7.26E-05	1.39E-01	3.09E+00
	BD	2.34E-03	6.73E+03	3.07E+00	1.30E+00	1.75E+02	4.70E+02	2.28E+02	5.75E-05	1.32E-01	3.05E+00
	PET	2.71E-03	7.61E+03	3.27E+00	1.27E+00	1.60E+02	5.11E+02	2.44E+02	7.26E-05	1.39E-01	3.09E+00
	PF)	1.55E-03	4.71E+03	1.97E+00	7.37E-01	9.53E+01	3.30E+02	1.51E+02	4.76E-05	8.40E-02	1.86E+00
	PF-BD	1.55E-03	4.13E+03	1.95E+00	8.16E-01	1.24E+02	3.17E+02	1.60E+02	3.54E-05	8.47E-02	1.88E+00
	PET-BD-PF	1.55E-03	4.13E+03	1.95E+00	8.16E-01	1.24E+02	3.17E+02	1.60E+02	3.54E-05	8.47E-02	1.88E+00
Factory processing	BC	2.27E-05	1.09E+03	1.11E-01	4.21E-02	8.93E+00	2.43E+01	1.07E+01	7.23E-06	9.55E-03	8.44E-02
	BD	2.27E-05	1.82E+02	1.59E-01	7.64E-02	1.55E+01	3.44E+01	1.41E+01	1.84E-06	6.65E-03	1.15E-01
	PET	2.27E-05	1.09E+03	1.11E-01	4.21E-02	8.93E+00	2.43E+01	1.07E+01	7.23E-06	9.55E-03	8.44E-02
	PF)	2.27E-05	1.09E+03	1.11E-01	4.21E-02	8.93E+00	2.43E+01	1.07E+01	7.23E-06	9.55E-03	8.44E-02
	PF-BD	2.27E-05	1.82E+02	1.59E-01	7.64E-02	1.55E+01	3.44E+01	1.41E+01	1.84E-06	6.65E-03	1.15E-01
	PET-BD-PF	2.27E-05	1.82E+02	1.59E-01	7.64E-02	1.55E+01	3.44E+01	1.41E+01	1.84E-06	6.65E-03	1.15E-01

Table 4.12. Life cycle assessment results of SRP paste (continue)

		Impact categories									
Production step	Scenario	ADP	AFDP	AP	EP	FWEP	GWP	HTP	ODP	POCP	TEP
Packaging and transportation	BC	2.21E-04	1.25E+03	7.52E-01	1.57E-01	3.05E+01	1.17E+02	6.86E+01	1.09E-05	4.41E-02	1.79E-01
	BD	2.13E-04	1.23E+03	7.46E-01	1.57E-01	3.07E+01	1.15E+02	6.81E+01	1.05E-05	4.39E-02	1.78E-01
	PET	6.62E-05	4.64E+02	1.64E-01	5.97E-02	1.62E+01	4.36E+01	2.07E+01	2.41E-06	1.84E-02	5.84E-02
	PF	2.21E-04	1.25E+03	7.52E-01	1.57E-01	3.05E+01	1.17E+02	6.86E+01	1.09E-05	4.41E-02	1.79E-01
	PF-BD	2.13E-04	1.23E+03	7.46E-01	1.57E-01	3.07E+01	1.15E+02	6.81E+01	1.05E-05	4.39E-02	1.78E-01
	PET-BD-PF	5.86E-05	4.35E+02	1.53E-01	5.70E-02	1.59E+01	4.10E+01	1.98E+01	1.98E-06	1.80E-02	5.46E-02
Whole process	BC	2.95E-03	9.95E+03	4.13E+00	1.47E+00	2.00E+02	6.52E+02	3.24E+02	9.07E-05	1.93E-01	3.35E+00
	BD	2.58E-03	8.14E+03	3.98E+00	1.53E+00	2.22E+02	6.20E+02	3.10E+02	6.99E-05	1.83E-01	3.34E+00
	PET	2.80E-03	9.16E+03	3.54E+00	1.38E+00	1.85E+02	5.79E+02	2.76E+02	8.22E-05	1.67E-01	3.23E+00
	PF	1.80E-03	7.05E+03	2.83E+00	9.36E-01	1.35E+02	4.71E+02	2.30E+02	6.57E-05	1.38E-01	2.12E+00
	PF-BD	1.79E-03	5.53E+03	2.85E+00	1.05E+00	1.70E+02	4.66E+02	2.42E+02	4.77E-05	1.35E-01	2.17E+00
	PET-BD-PF	1.63E-03	4.74E+03	2.26E+00	9.49E-01	1.55E+02	3.92E+02	1.94E+02	3.92E-05	1.09E-01	2.05E+00

4.4.3. Roasted sweet red pepper

Roasting is a complicated procedure that encompasses numerous chemical events, such as Maillard or non-enzymatic browning reactions between reducing sugars and amino acids, heat degradation of lipids, and decomposition of sugars, along with their interactions (Schenker et al., 2002). Gül et al. (2021) reported about roasted capia pepper that roasted capia peppers were determined to possess roughly twice the environmental effect of pickled cucumbers, primarily as a result of the extra roasting process that uses a substantial quantity of natural gas. Regarding the contributions of various stages, the growing of vegetables and the production of packaging materials (such as glass jars and steel lids) were identified as the primary sources of environmental consequences. LCA results of roasted SRP are presented in Table 4.14. Upon analyzing the primary factors influencing the roasted SRP supply chain GWP impact, Figure 4.59 reveals that, glass contributes to 72% of the total, while LDPE, other factors, and transport account for 6%, 17%, and 5% correspondingly. Specifically, the production of roasted SRP from 1 ton fresh SRP releases 2250 kg CO₂-eq per ton fresh SRP. Similarly, the AFDP and HTP impact categories exhibit the same patterns as the GWP.

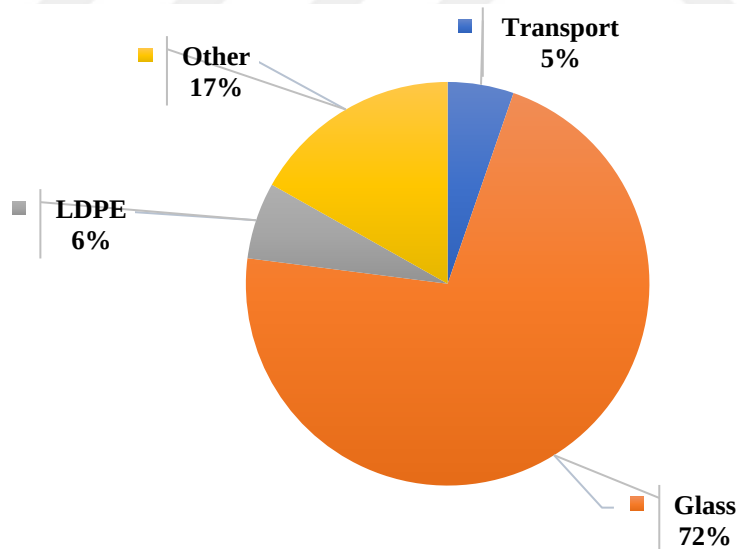


Figure 4.59. Top contributors on GWP (kg CO₂-eq) impact category of BC-roasted SRP production whole process

The glass packaging impact accounts for 64.5% of AFDP values and 73% of HTP values as seen in Figure 4.60 and Figure 4.61. In a study conducted by Banar & Cokaygil (2008), the environmental characteristics of glass bottles and cartons for beverages were compared using SimaPro LCA software. The assessment took into account the environmental impact categories of acidification/eutrophication, climate change, fossil fuels, and eco-toxicity. The investigation revealed that glass bottles have a greater negative impact on the environment when compared to cartons. Ghosh, Socci, Cashman, & Sauer, (2012), conducted an LCA study on the packaging materials used for carbonated soft drinks by PepsiCo-USA. The study shown that augmenting the recycling rates of lightweight PET bottles is highly efficacious in mitigating their corresponding environmental consequences. In addition to beverages, Manfredi and Vignali (2014) performed an LCA on glass jars specifically utilized for packaging tomato puree. The study revealed that packaging is the primary step in the life cycle that has a detrimental influence on the environment, mostly due to its high energy consumption. Furthermore, the study indicated that use lightweight main packaging for tomato puree is the most ecologically sound choice for promoting greater sustainability.

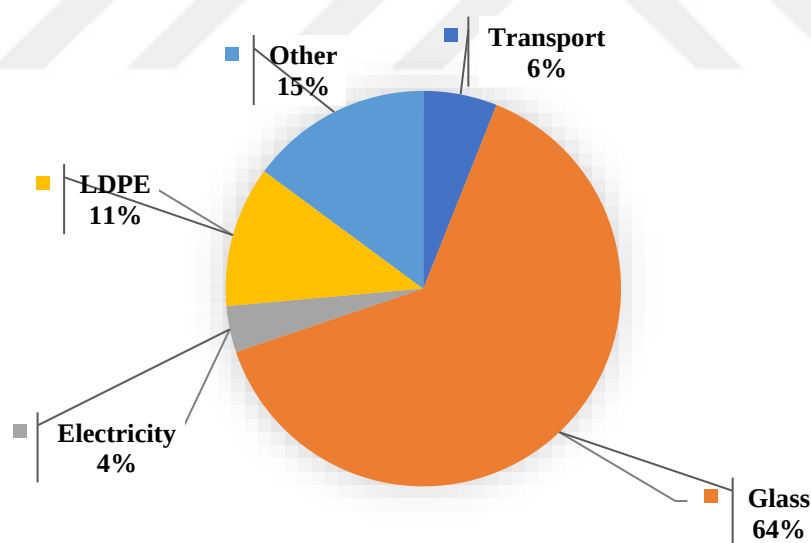


Figure 4.60. Top contributors on AFDP (MJ) impact category of BC-roasted SRP production whole process

Due to the glass packaging being a significant highlight in the packaging and transportation process, a new packaging option has been employed as a new approach. The effects of tin can packaging on roasted sweet red peppers are illustrated in Figure 4.62 and Figure 4.63. TPC has clearly reduced the values of all impact categories. By employing the TPC scenario in the production of roasted SRP, there is a significant decrease of 42.4% in AP value, 52.8% in AFDP value, 37.2% in ODP, 36.5% in GWP value, and 37.6% in HTP value. However, when examining the impact of several scenarios on the entire process of roasted SRP, it is evident from Figure 4.63 that TPC yields the most favorable results, followed by PF-BD. The literature findings confirm that the TPC scenario conducted in this study is an effective method for minimizing the environmental consequences of roasted SRP, mostly due to the extensive utilization of glass packaging.

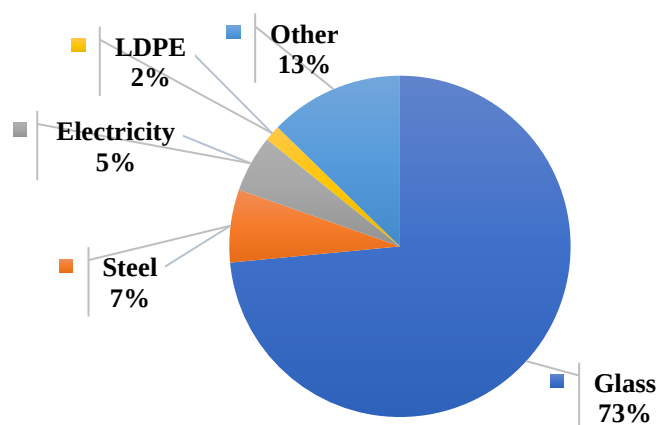


Figure 4.61. Top contributors on HTP (kg 1.4 DB-eq) impact category of BC-roasted SRP production whole process

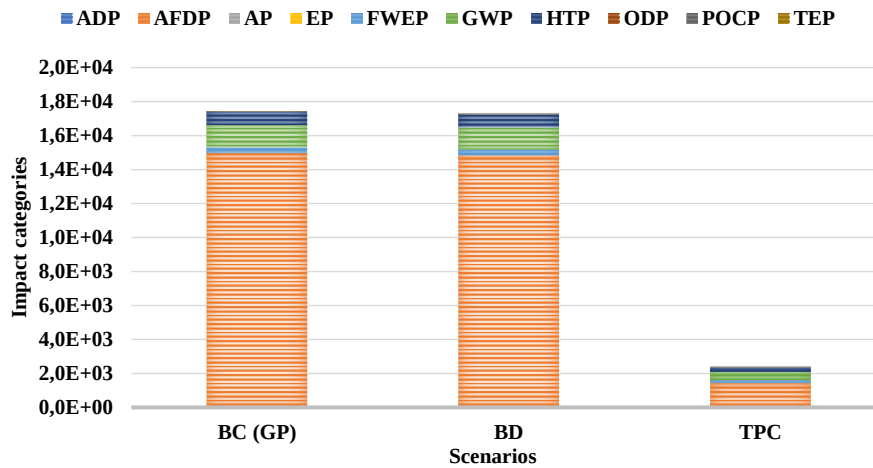


Figure 4.62. The effect of different scenarios on LCA impact categories of roasted SRP-packaging and transportation step

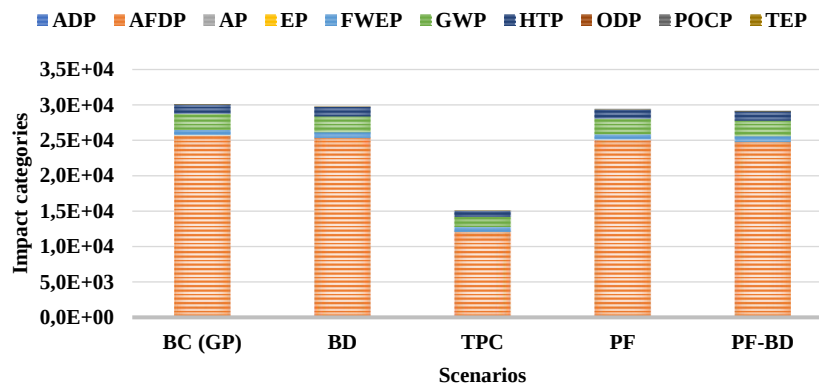


Figure 4.63. The effect of different scenarios on LCA impact categories of roasted SRP-whole process

In a different study, the findings indicated that, the glass system consistently exhibited the worst environmental performance across all impact categories considered (both at the midpoint and endpoint levels of the ReCiPe 2016 H method). This can be primarily attributed to the substantial weight of the glass, which has a significant impact on the production and distribution phases of the system. The manufacturing of glass bottles had the greatest influence on the overall life cycle assessment of these packaging solutions across all impact categories. In addition, when compared to recycled PET systems, glass packaging necessitated a greater quantity of secondary-tertiary packing and resulted in a poorer level of efficiency in palletizing. Hence, the recycled PET system proved to be the most

environmentally friendly option for all three virgin olive oil distribution markets under examination. Ultimately, throughout the end-of-life stage, the glass system exhibited superior environmental advantages in comparison to the recycled PET system, mostly due to its higher rate of recycling and efficiency. The logistics of the distribution phase demonstrated that shipping was a more sustainable mode of transportation than trucking, even when accounting for longer distances traveled (Ferrara, & De Feo, 2023). A study conducted in Michigan State University, located in the United States, examined the environmental characteristics of PET, PS, and poly lactic acid (PLA) containers in a packaging school. The utilized methodologies included ISO Standards 14040, 14044, and 14049, together with American Society for Testing and Materials Standard 7075. This study examined the many stages involved in corn harvesting, including corn-cracking. The study collected data from Europe, North America, and the Middle East. The functional unit consisted of 1000 containers with a 1-pound capacity. The assessed environmental impacts included global warming, aquatic ecotoxicity, aquatic eutrophication, ozone depletion, aquatic acidification, respiratory organics and inorganics, nonrenewable energy consumption, and land occupation. The study's findings indicate that PLA, a biodegradable material, has a smaller environmental impact compared to petroleum-based materials such as PS, PP, and PET. Among all the options, PET had the highest impact value in terms of respiratory inorganics, nonrenewable energy, and global-warming categories, except for respiratory organics and aquatic acidification (Madival, Auras, Singh, & Narayan, 2009).

Table 4.13. Life cycle assessment results of roasted SRP

Product	Scenario	ADP	AFDP	AP	Impact categories						
					EP	FWEP	GWP	HTP	ODP	POCP	TEP
SRP farming	BC (GP)	5.74E-04	1.61E+03	6.91E-01	2.69E-01	3.39E+01	1.08E+02	5.17E+01	1.54E-05	2.94E-02	6.54E-01
	BD	4.96E-04	1.42E+03	6.50E-01	2.75E-01	3.71E+01	9.95E+01	4.83E+01	1.22E-05	2.80E-02	6.45E-01
	TPC	5.74E-04	1.61E+03	6.91E-01	2.69E-01	3.39E+01	1.08E+02	5.17E+01	1.54E-05	2.94E-02	6.54E-01
	PF	3.29E-04	9.97E+02	4.17E-01	1.56E-01	2.02E+01	6.98E+01	3.19E+01	1.01E-05	1.78E-02	3.93E-01
	PF-BD	3.28E-04	8.73E+02	4.12E-01	1.73E-01	2.62E+01	6.70E+01	3.38E+01	7.48E-06	1.79E-02	3.98E-01
Factory processing	BC (GP)	3.69E-03	9.06E+03	6.57E+00	1.96E+00	4.31E+02	8.38E+02	5.13E+02	1.18E-04	2.21E-01	1.09E+01
	BD	3.69E-03	9.06E+03	6.57E+00	1.96E+00	4.31E+02	8.38E+02	5.13E+02	1.18E-04	2.21E-01	1.09E+01
	TPC	3.69E-03	9.06E+03	6.57E+00	1.96E+00	4.31E+02	8.38E+02	5.13E+02	1.18E-04	2.21E-01	1.09E+01
Packaging and transportation	BC (GP)	2.64E-03	1.50E+04	8.80E+00	1.68E+00	3.30E+02	1.31E+03	7.77E+02	1.25E-04	4.45E-01	1.97E+00
	BD	2.60E-03	1.48E+04	8.75E+00	1.67E+00	3.29E+02	1.29E+03	7.73E+02	1.23E-04	4.43E-01	1.96E+00
	TPC	3.24E-04	1.43E+03	1.99E+00	9.33E-01	1.70E+02	4.84E+02	2.72E+02	2.91E-05	3.50E-01	8.57E-01
Whole process	BC (GP)	6.90E-03	2.56E+04	1.61E+01	3.91E+00	7.95E+02	2.25E+03	1.34E+03	2.59E-04	6.96E-01	1.36E+01
	BD	6.79E-03	2.53E+04	1.60E+01	3.91E+00	7.97E+02	2.23E+03	1.33E+03	2.54E-04	6.93E-01	1.35E+01
	TPC	4.59E-03	1.21E+04	9.26E+00	3.17E+00	6.35E+02	1.43E+03	8.37E+02	1.63E-04	6.00E-01	1.25E+01
	PF	6.65E-03	2.50E+04	1.58E+01	3.80E+00	7.81E+02	2.21E+03	1.32E+03	2.54E-04	6.84E-01	1.33E+01
	PF-BD	6.62E-03	2.48E+04	1.57E+01	3.80E+00	7.87E+02	2.20E+03	1.32E+03	2.49E-04	6.82E-01	1.33E+01

4.4.4. Dried sweet red pepper

Red peppers are mainly consumed in a dried form, with more than half of them in form of the volume consumed in Korea being in the form of red pepper powder (Kim, Park, & Cho, 2022). Red pepper seeds have been crushed and used in the production of red pepper powder in the past, but recently only 10 to 15% of red pepper seeds are added for the production of high-quality red pepper powder with the remainder being wasted (Kim, Lee, & Cho, 2019). Based on the data presented in Figures 4.64, 4.65, and 4.66, it can be observed that, the primary factors contributing to GWP, AFDP, and HTP are the utilization of diesel for transportation purposes, the use of steam in fertilizer manufacturing, and the use of ammonia, sulphur, chemicals, natural gas, and electricity. In terms of the GWP impact category, steam used for fertilizer and ammonia production represents 16% and 12% respectively, as shown in Figure 4.64. Optimizing the appropriate application of fertilizer in crop production is crucial for promoting sustainable agriculture and minimizing its environmental consequences. There are fertilizers that can cause significant decreases in N_2O emissions. The manufacture of fertilizers has significant impacts on climate change, fossil fuel depletion, and acidification. However, resource depletion is the primary concern during both the production and transportation processes. Regarding the most significant aspect in the eutrophication impact category is the application of fertilizer. When aiming for a fertilizer strategy that involves applying low levels of phosphorus, the most sustainable choice is to use either a bulk blend or a single nutrient fertilizer containing calcium ammonium nitrate. On the other hand, when aiming for a fertilizer strategy with a balanced nutrient formula, sustainable options include using a bulk blend or single nutrient fertilizer with calcium ammonium nitrate, or using a standard complex fertilizer. Calculations of the scenario involving reduced N_2O emissions during the production process indicate that, this reduction technique is not applicable to urea-based fertilizers. Consequently, it can be concluded that products containing urea require alternative emission reduction techniques in order to align with the environmental advancements of other nitrogen fertilizers. By implementing an optimum fertilization approach, it is possible to achieve a reduction in the environmental burden of up to 15%. Given the significant impact of nitrogen application rates on LCA outcomes, it is crucial to use the appropriate quantities of nitrogen and to implement the most effective technique for N fertilizer production. Additionally, it is crucial to include a thorough evaluation of the specific

type of fertilizer product in every LCA conducted for food and agricultural goods, since this significantly influences the outcomes of the LCA (Hasler, Bröring, Omta, & Ols, 2015).

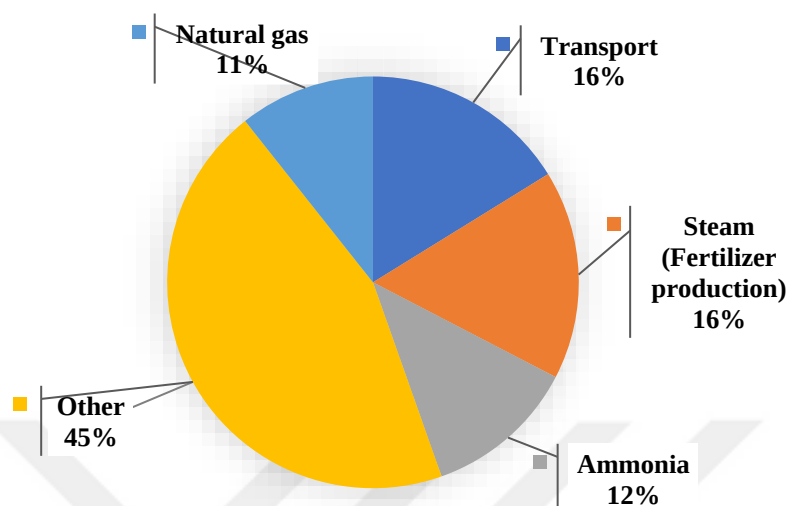


Figure 4.64. Top contributors on GWP (kg CO₂-eq) impact category of BC-dried SRP production whole process

The top contributors to the AFDP (Figure 4.65) impact category of BC-dried SRP production whole process are natural gas (51%), others (20%), transport-diesel (12%), steam for fertilizer production (10%) and sulfur for fertilizer production (7%). Due to the substantial energy needs of the drying operation, natural gas and electricity use are significant contributors to the drying process. Natural gas is frequently seen as a transitional fuel that could replace coal until the widespread adoption of dependable renewable energy sources. The effectiveness of natural gas as an interim fuel relies on assumptions regarding stabilizing goals, emissions, and technical advancements (Abrahams, Samaras, Griffin, & Matthews, 2015). The extraction of natural gas results in the production of GHGs, which play a crucial role in the overall emissions throughout the lifetime. These GHGs, particularly methane, make up a substantial portion of the human-caused methane emissions. The timing and volume of these emissions are important, as methane has a short-term global warming impact that is up to 120 times greater than that of CO₂. CH₄ emissions are the second greatest source of GHGs that contribute to global warming. They account for roughly 18% of GHG radiative forcing, excluding indirect effects, while CO₂ accounts for 64% (Crow, Balcombe, Brandon, & Hawkes, 2019). CH₄ is a potent GHG that has a shorter lifespan compared to CO₂. The radiative forcing of this substance is approximately 120 times higher than that of CO₂.

However, its climatic impact decreases quickly because to an average perturbation life of only 12.4 years. When comparing, it is important to note that the atmospheric lifetime of CO₂ is complicated. After 37 years, 50% of CO₂ disappears, but 22% stays in the atmosphere indefinitely. The GWP is commonly employed to assess the climate effects of various GHGs in relation to CO₂, based on a standard time frame of 100 years. Nevertheless, the perceived influence of methane is influenced by varying timeframes, and there is a growing utilization of diverse timeframes and measurements (Ocko, Hamburg, Jacob, Keith, Keohane, Oppenheimer, Roy-Mayhew, Schrag, & Pacala, 2017). An effective strategy for lowering cumulative greenhouse gas emissions by 30-60% is to implement a carbon price of at least 400 USD/tonne CO₂. This indicates that it is possible to achieve decarbonization of the upstream component of the natural gas supply chain by employing carbon prices that are similar to those required for decarbonizing the entire energy system. Remarkably, when carbon prices are high, the selection of emission measure does not exert a substantial influence on the total amount of emissions (Crow, Balcombe, Brandon, & Hawkes, 2019). Furthermore, the primary factor contributing to the production of fresh SRP is the utilization of fertilizer. This is because the farming stage is the most significant phase in the processing process, resulting in a ratio of 10.08 kg of fresh SRP for every 1 kg of dried SRP.

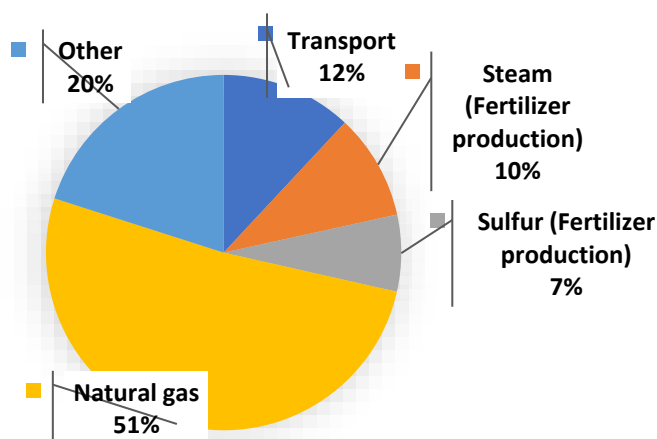


Figure 4.65. Top contributors on AFDP (MJ) impact category of BC-dried SRP production whole process

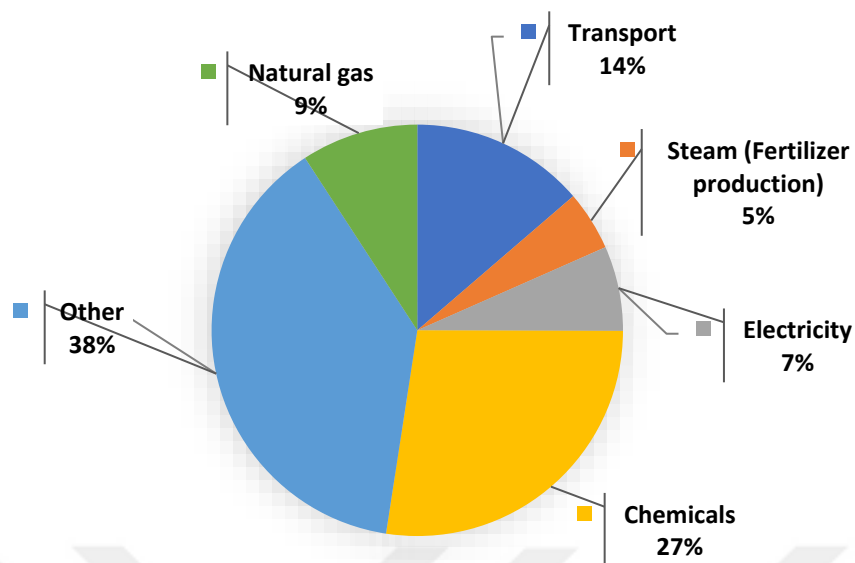


Figure 4.66. Top contributors on HTP (kg 1.4 DB-eq) impact category of BC-dried SRP production whole process

In the dry SRP supply chain, scenarios for 1 kg metallized doypack (BC), 25 kg kraft bulk (25KP), and BD are implemented as seen in Figure 4.67 and Figure 4.68. The 25KP-BD scenario has reduced the AFDP, ODP, GWP, and HTP by 49.2%, 46.7%, 22.9%, and 19.4%, respectively, across all scenarios. Table 4.14 demonstrate that adopting the PF scenario reduced the GWP value by 75%, EP value by 34.3%, AP value 30.4%, ODP 20.4%, and AFDP 19.5% in dried SRP production. Therefore, when the impact of various scenarios on the entire supply chain process of dried SRP was analyzed, it becomes evident that, the 25KP-PF-BD and PF-BD scenarios yield the most favorable results. Bertoluci, Leroy, & Olsson, (2014) utilized LCA to assess the environmental consequences of three different olive packaging options: doypacks, glass jars, and steel cans. One notable finding is that the environmental impact of different types of packaging can vary significantly between countries. This variation is mostly attributed to differences in household waste collection rates and waste treatment technologies, such as recycling or incineration. Nevertheless, the glass jar was shown to be the least favorable packaging option among all the countries examined. On the other hand, doypacks were found to have the least detrimental environmental effects, although being composed of a non-renewable and non-recyclable multilayer material.

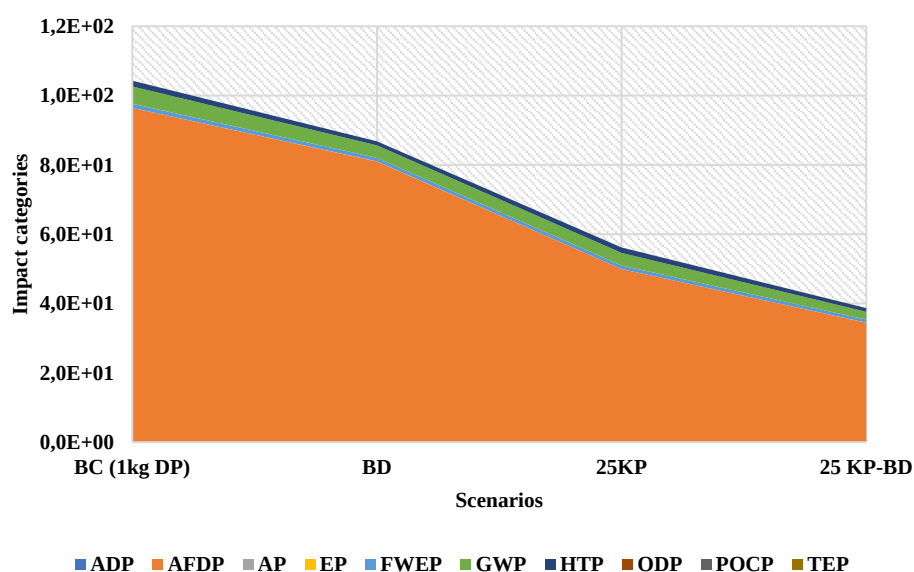


Figure 4.67. The effect of different scenarios on LCA impact categories of dried SRP-packaging and transportation step

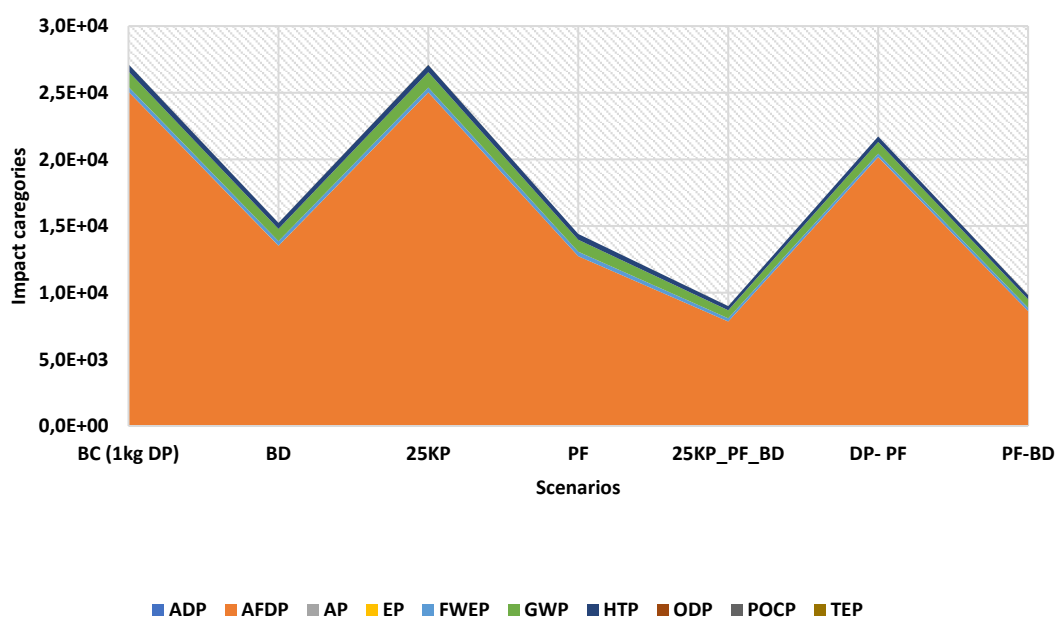


Figure 4.68. The effect of different scenarios on LCA impact categories of dried SRP-whole process

Table 4.14. Life cycle assessment results of dried SRP

Product	Scenario	Impact categories									
		ADP	AFDP	AP	EP	FWEP	GWP	HTP	ODP	POCP	TEP
SRP farming	BC (1kg DP)	5.10E-03	1.43E+04	6.15E+00	2.40E+00	3.01E+02	9.61E+02	4.60E+02	1.37E-04	2.62E-01	5.81E+00
	BD	4.41E-03	1.27E+04	5.79E+00	2.45E+00	3.30E+02	8.85E+02	4.29E+02	1.08E-04	2.49E-01	5.74E+00
	25KP	5.10E-03	1.43E+04	6.15E+00	2.40E+00	3.01E+02	9.61E+02	4.60E+02	1.37E-04	2.62E-01	5.81E+00
	PF	2.92E-03	8.87E+03	3.71E+00	1.39E+00	1.79E+02	6.21E+02	2.84E+02	8.96E-05	1.58E-01	3.50E+00
	PF-BD	2.92E-03	7.77E+03	3.67E+00	1.54E+00	2.33E+02	5.96E+02	3.01E+02	6.65E-05	1.59E-01	3.54E+00
Factory processing	BC (1kg DP)	9.15E-05	1.06E+04	8.12E-01	2.56E-01	5.31E+01	1.92E+02	7.68E+01	6.76E-05	8.03E-02	3.06E-01
	BD	1.65E-05	3.57E+01	3.12E-02	1.67E-02	3.86E+00	5.50E+00	3.39E+00	5.69E-07	1.81E-03	6.42E-02
	25KP	9.15E-05	1.06E+04	8.12E-01	2.56E-01	5.31E+01	1.92E+02	7.68E+01	6.76E-05	8.03E-02	3.06E-01
Packaging and transportation	BC (1kg DP)	9.63E-06	9.64E+01	2.09E-02	6.15E-03	1.18E+00	4.99E+00	1.66E+00	4.27E-07	1.09E-03	8.74E-03
	BD	5.60E-06	8.10E+01	1.48E-02	4.69E-03	1.04E+00	3.59E+00	1.16E+00	1.99E-07	8.89E-04	6.72E-03
	25KP	7.39E-06	4.99E+01	1.99E-02	8.37E-03	1.02E+00	3.64E+00	1.54E+00	4.96E-07	9.86E-04	3.25E-02
	25 KP-BD	3.37E-06	3.45E+01	1.38E-02	6.91E-03	8.85E-01	2.24E+00	1.04E+00	2.68E-07	7.88E-04	3.05E-02
Whole process	BC (1kg DP)	5.20E-03	2.51E+04	6.98E+00	2.66E+00	3.56E+02	1.16E+03	5.38E+02	2.05E-04	3.43E-01	6.13E+00
	BD	4.48E-03	1.35E+04	5.97E+00	2.51E+00	3.44E+02	9.27E+02	4.45E+02	1.11E-04	2.60E-01	5.87E+00
	25KP	5.20E-03	2.50E+04	6.98E+00	2.66E+00	3.56E+02	1.16E+03	5.38E+02	2.05E-04	3.43E-01	6.15E+00
	PF	4.43E-03	1.27E+04	5.83E+00	2.47E+00	3.35E+02	8.93E+02	4.34E+02	1.09E-04	2.52E-01	5.83E+00
	25KP_PF_BD	2.94E-03	7.84E+03	3.71E+00	1.56E+00	2.38E+02	6.04E+02	3.05E+02	6.74E-05	1.62E-01	3.64E+00
	DP- PF	3.71E-03	2.02E+04	4.86E+00	1.75E+00	2.59E+02	8.69E+02	4.10E+02	1.63E-04	2.54E-01	3.94E+00
	PF-BD	2.99E-03	8.62E+03	3.85E+00	1.60E+00	2.47E+02	6.38E+02	3.16E+02	6.91E-05	1.70E-01	3.67E+00



5. CONCLUSION AND RECOMMENDATIONS

The detailed analysis of the food processing industry, specifically focusing on the energy, exergy and life cycle impact assessment of tomato and sweet red pepper products production, provided crucial insights into the sector's environmental and energy dynamics. The study revealed significant environmental burdens associated with various stages of tomato and SRP production, including farming, factory processing, and packaging-transportation. Packaging materials, particularly glass and steel were identified as primary contributors to cumulative values, energy, exergy, CO₂ consumption values. The combination of precision farming, biodiesel, and PET packaging was found to be the most effective in reducing environmental impacts across all metrics of SRP products.

The packaging and transport stage has emerged as the most important contributor when taking into account the various stages of products. For all product groups, using biodiesel alone (the BD scenario) yields the best results; using biodiesel combined with precision farming (the PF scenario) yields even better results. BD scenario resulted in a great decrease in energy and exergy consumption, as well as a reduction in CO₂ carbon emissions. The AFDP exhibits the highest value among all impact categories for products. It is followed by GWP, FWEP, and HTP, respectively. The top five contributors to AFDP, according to open LCA results, are the transportation process, diesel, electricity, natural gas, and other categories. The top five contributors for GWP, HTP, FWEP, and ODP are also the same as for AFDP, and additional factors include pesticides, steam production in chemical factories, and chemical factories for organic materials. Ignoring the recycling of glass, glass packaging has the highest values for CEnC CExC, CCO₂C, and LCA impacts among all product groups. However, it can be inferred that despite the energy-intensive and CO₂-emission-intensive production process of glass packaging, it can offer numerous benefits when recycling is taken into account. The tomato farming and packaging-transportation stage in the BC has exhibited the highest values, GWP required to produce one metric ton of fresh tomato in the present study was found as 120 kg CO₂-eq. Fertilizer and diesel use are major factors in sweet red pepper farming, One ton of fresh SRP farming results in 39.92 kg/ton of CO₂ emissions. The energy consumption in SRP farming is mainly due to fertilizer usage (86.5%), followed by diesel usage (11.0%). Diesel fuel used in agricultural machinery, steel manufacture, electricity consumption, diesel fuel used in transportation, natural gas consumption, and other factors contribute to the GWP

impact category. The base case and glass packaging scenario have the highest impact on the entire process. The PF-BD scenario, which uses precision farming and biodiesel, is the optimal choice for cultivating fresh sweet red peppers.

Expanding the use of biodiesel in transportation and factory processing is recommended. Raising consumer awareness about the environmental impacts of different packaging materials and farming practices can drive demand for sustainably produced products. Educated consumers are more likely to support brands that prioritize environmental sustainability. Governments and regulatory bodies should incentivize the adoption of sustainable practices through subsidies, tax breaks, and stringent environmental regulations. Such support can accelerate the transition to greener production methods across the food industry. These findings have important implications for industry stakeholders aiming to reduce their environmental footprint and enhance energy efficiency. This study contributes to the broader field of sustainable food technology by demonstrating the practical application of exergy and life cycle analyses in identifying and mitigating inefficiencies in food production processes. Future research should focus on the implementation of the proposed improvements and their long-term effects on production efficiency and environmental impact. Future research should expand these methods to a broader range of products and explore innovative technologies to further enhance process sustainability.

REFERENCES

- Abrahams, L. S., Samaras, C., Griffin, W. M., & Matthews, H. S. (2015). Life cycle greenhouse gas emissions from US liquefied natural gas exports: implications for end uses. *Environmental science & technology*, 49(5), 3237-3245. <https://doi.org/10.1021/es505617p>
- Agricultural, E. U. (2019). Fertilizers in the EU. Prices, Trade and Use. *Agricultural Markets Briefs*, (15). https://agriculture.ec.europa.eu/cap-my-country/performance-agricultural-policy/studies-and-reports/analytical-briefs/market-analyses-and-briefs_en. [Access date: 21.07.2024].
- Akpınar, E. K. (2011). Drying of Parsley Leaves in a Solar Dryer and under Open Sun: Modeling, Energy and Exergy Aspects. *Journal of Food Process Engineering*, 34(1), 27-48. <https://doi.org/10.1111/j.1745-4530.2008.00335.x>
- Akpınar, E. K., Bicer, Y., & Yildiz, C. (2003). Thin layer drying of red pepper. *Journal of Food Engineering*, 59(1), 99-104. [https://doi.org/10.1016/S0260-8774\(02\)00425-9](https://doi.org/10.1016/S0260-8774(02)00425-9)
- Alaei, B., Chayjan, R. A., & Zolfigol, M. A. (2022). Improving tomato juice concentration process through a novel ultrasound-thermal concentrator under vacuum condition: A bioactive compound investigation and optimization. *Innovative Food Science & Emerging Technologies*, 77, 102983. <https://doi.org/10.1016/j.ifset.2022.102983>
- Alda, L. M., Gogoasa, I., Bordean, D.-M., Gergen, I., Alda, S., Moldovan, C., & Nita, L. (2009). Lycopene content of tomatoes and tomato products. *Journal of Agroalimentary Processes and Technologies*, 15(4), 540-542.
- Amón, R., Wong, T., Kazama, D., Maulhardt, M., Maulhardt, T., & Simmons, C. W. (2018). Assessment of the industrial tomato processing water energy nexus: A case study at a processing facility. *Journal of Industrial Ecology*, 22(4), 904-915. <https://doi.org/10.1111/jiec.12600>
- Andersen, S. O., & Sarma, K. M. (2012). Protecting the ozone layer: the United Nations history: Routledge. London. <https://doi.org/10.4324/9781849772266>,
- Angell, J., & Korshover, J. (1973). Quasi-biennial and long-term fluctuations in total ozone. *Monthly Weather Review*, 101(5), 426-443. [https://doi.org/10.1175/1520-0493\(1973\)101%3C0426:QALFIT%3E2.3.CO;2](https://doi.org/10.1175/1520-0493(1973)101%3C0426:QALFIT%3E2.3.CO;2)
- Anwar, F., Chaudhry, F. N., Nazeer, S., Zaman, N., & Azam, S. (2015). Causes of ozone layer depletion and its effects on human. *Atmospheric and Climate Sciences*, 6(1), 129-134. <http://dx.doi.org/10.4236/acs.2016.61011>
- Aras, C. D. (2022). The effect of cutting style, drying temperature, storage period, and temperature on the physical, chemical, and physicochemical properties of red Kapya peppers (Master's Thesis). Iğdır University, Graduate School (In Turkish).

Arslan, A., Soysal, Y., & Keskin, M. (2020). Mathematical modeling, moisture diffusion and color quality in intermittent microwave drying of organic and conventional sweet red peppers. *AgriEngineering*, 2(3), 393-407. <https://doi.org/10.3390/agriengineering2030027>

Aslantaş, R., Çakmakçı, R., & Şahin, F. (2007). Effect of plant growth promoting rhizobacteria on young apple tree growth and fruit yield under orchard conditions. *Scientia horticulturae*, 111(4), 371-377. <https://doi.org/10.1016/j.scienta.2006.12.016>

Australian Greenhouse Office, 2003. Australian Methodology for the Estimation of Greenhouse Gas Emissions and Sinks 2003. Energy (transport). Australian Greenhouse Office, Canberra.

Bacenetti, J., Duca, D., Negri, M., Fusi, A., & Fiala, M. (2015). Mitigation strategies in the agro-food sector: The anaerobic digestion of tomato puree by-products. An Italian case study. *Science of Total Environment*, 526, 88-97. <https://doi.org/10.1016/j.scitotenv.2015.04.069>

Balasuriya, B. T. G., Ghose, A., Gheewala, S. H., & Prapasongsa, T. (2022). Assessment of eutrophication potential from fertiliser application in agricultural systems in Thailand. *Science of the Total Environment*, 833, 154993. <https://doi.org/10.1016/j.scitotenv.2022.154993>

Balcombe, P., Anderson, K., Speirs, J., Brandon, N., & Hawkes, A. (2017). The natural gas supply chain: the importance of methane and carbon dioxide emissions. *ACS Sustainable Chemistry & Engineering*, 5(1), 3-20.

Banar, M., & Cokaygil, Z. (2008). A comparative life cycle analysis of two different juice packages. *Environmental Engineering Science*, 25(4), 549-556. <https://doi.org/10.1089/ees.2007.0079>

Baran, M. F., Eliçin, A. K., Bellitürk, K., & Çelik, A. (2022). Energy balance and greenhouse gas (GHG) emissions of Sauceboat Pepper (*Capsicum annuum* L.) production in Türkiye. *International Journal of Agriculture Environment and Food Sciences*, 6(4), 605-613. <https://doi.org/10.31015/jaefs.2022.4.14>

Bartocci, P., Fantozzi, P., & Fantozzi, F. (2017). Environmental impact of Sagrantino and Grechetto grapes cultivation for wine and vinegar production in central Italy. *Journal of Cleaner Production*, 140, 569-580. <https://doi.org/10.1016/j.jclepro.2016.04.090>

Baysal, T., Güreş, H., & Yurdagel, Ü. (1990). Biber salçası yapımında palper öncesi farklı haşlama yöntem ve sürelerinin palper verimi ve sıra kalitesine etkileri. *Gıda*, 15(2) 73-78.

Bebka. (2021). Preliminary Feasibility Report of the Fruit and Vegetable Drying Facility in Bilecik Province. Ministry of Industry and Technology, Bursa Eskişehir Bilecik Development Agency, Türkiye. <https://www.kalkinmakutuphanesi.gov.tr/dokuman/bilecik-ili-meyve-sebze-kurutma-tesisi-on-fizibilite-raporu/2349>. [Access date: 22.03.2023].

Belucio, M., Santiago, R., Fuinhas, J. A., Braun, L., & Antunes, J. (2022). The impact of natural gas, oil, and renewables consumption on carbon dioxide emissions: european evidence. *Energies*, 15(14), 5263. <https://doi.org/10.3390/en15145263>

Berthiaume, R., & Bouchard, C. (1999). Exergy analysis of the environmental impact of paving material manufacture. *Transactions of the Canadian Society for Mechanical Engineering*, 23(1B), 187-196. <https://doi.org/10.1139/tcsme-1999-0013>

Berthiaume, R., Bouchard, C., & Rosen, M. A. (2001). Exergetic evaluation of the renewability of a biofuel. *Exergy, An International Journal*, 1(4), 256-268. [https://doi.org/10.1016/S1164-0235\(01\)00029-2](https://doi.org/10.1016/S1164-0235(01)00029-2)

Bertoluci, G., Leroy, Y., & Olsson, A. (2014). Exploring the environmental impacts of olive packaging solutions for the European food market. *Journal of Cleaner Production*, 64, 234-243. . <https://doi.org/10.1016/j.jclepro.2013.09.029>

Blackmore, S. (1994). Precision farming: an introduction. *Outlook on agriculture*, 23(4), 275-280. <https://doi.org/10.1177/003072709402300407>

Borysovska, O., & Bovsunovsky, V. (2022). Recycling of multilayer polymer packaging doypack. *Environment Protection Technologies* No. 70. - p. 171-181. <https://doi.org/10.33271/crpnmu/70.171>

Bosona, T., & Gebresenbet, G. (2018). Life cycle analysis of organic tomato production and supply in Sweden. *Journal of Cleaner Production*, 196, 635-643. <https://doi.org/10.1016/j.jclepro.2018.06.087>

Bouwman, L., (1999). Global assessment of acidification and eutrophication of natural ecosystems: United Nations Environmental Programme (UNEP), UNEP/Earthprint, Nairobi, Kenya.

Bozkurt, H., & Erkmen, O. (2004). Effects of production techniques on the quality of hot pepper paste. *Journal of Food Engineering*, 64(2), 173-178. doi:10.1016/j.jfoodeng.2003.09.028. <https://doi.org/10.1016/j.jfoodeng.2003.09.028>

Bozkurt, S. B. (2019). Effects of organic fertilizers used in the cultivation of Kapsa pepper (*Capsicum annuum* L. cv. Kapsa) on plant growth and fruit quality (Master's Thesis). Bursa Uludag University, Türkiye.

Brentup, F., Küsters, J., Lammel, J., & Kuhlmann, H. (2002). Impact assessment of abiotic resource consumption conceptual considerations. *The International Journal of Life Cycle Assessment*, 7, 301-307. <https://doi.org/10.1007/BF02978892>

Bulle, C., Margni, M., Patouillard, L., Boulay, A. M., Bourgault, G., De Bruille, V., & Joliet, O. (2019). IMPACT World+: a globally regionalized life cycle impact assessment method. *The International Journal of Life Cycle Assessment*, 24, 1653-1674. <https://doi.org/10.1007/s11367-019-01583-0>

Büğülü, A. (2023). Personal communication; interview. Sweet Red Pepper Paste Production Steps and Specifications. Production Manager (Food Science and Technology Expertise), Olgu Gıda Sanayi ve Ticaret Limited Şirketi, Adana.

Carraretto, C., Macor, A., Mirandola, A., Stoppato, A., & Tonon, S. (2004). Biodiesel as alternative fuel: Experimental analysis and energetic evaluations. *Energy*, 29(12-15), 2195-2211. <https://doi.org/10.1016/j.energy.2004.03.042>

Castro, M., Roman, C., Echegaray, M., Mazza, G., & Rodriguez, R. (2018). Exergy Analyses of Onion Drying by Convection: Influence of Dryer Parameters on Performance. *Entropy (Basel)*, 20(5), 310. <https://doi.org/10.3390/e20050310>

Cavalett, O., & Ortega, E. (2010). Integrated environmental assessment of biodiesel production from soybean in Brazil. *Journal of Cleaner Production*, 18(1), 55-70. <https://doi.org/10.1016/j.jclepro.2009.09.008>

Cengel, A. Y., & Boles, M. Ah. (2006). *Thermodynamics an Engineering Approach Fifth Edition in SI Units* Mc Graw Hill Book Company: Singapore.

Cetin, B., & Vardar, A. (2008). An economic analysis of energy requirements and input costs for tomato production in Türkiye. *Renewable Energy*, 33(3), 428-433. <https://doi.org/10.1016/j.renene.2007.03.008>

Chatzisyneon, E., Foteinis, S., & Borthwick, A. G. (2017). Life cycle assessment of the environmental performance of conventional and organic methods of open field pepper cultivation system. *The International Journal of Life Cycle Assessment*, 22, 896-908. <https://doi.org/10.1007/s11367-016-1204-8>

Chemat, F., Rombaut, N., Meullemiestre, A., Turk, M., Perino, S., Fabiano-Tixier, A. S., & Abert-Vian, M. (2017). Review of Green Food Processing techniques. Preservation, transformation, and extraction. *Innovative Food Science & Emerging Technologies*, 41, 357-377. <https://doi.org/10.1016/j.ifset.2017.04.016>

Chen, G., & Chen, B. (2009). Extended-exergy analysis of the Chinese society. *Energy*, 34(9), 1127-1144. <https://doi.org/10.1016/j.energy.2009.04.023>

Chen, J. C., Shi, J., Xue, S. J., & Ma, Y. (2009). Comparison of lycopene stability in water- and oil-based food model systems under thermal- and light-irradiation treatments. *LWT-Food Science and Technology*, 42(3), 740-747. <https://doi.org/10.1016/j.lwt.2008.10.002>

Chow, S.; Hackett, B.; Ganji, A. R. (2005). Opportunities for Energy Efficiency and Demand Response in Corrugated Cardboard Manufacturing Facilities. *Energy Systems Laboratory* (<http://esl.tamu.edu>); Texas A&M University (<http://www.tamu.edu>). Available electronically from <https://hdl.handle.net/1969.1/5585>.

Clairand, J. M., Briceño-León, M., Escrivá-Escrivá, G., & Pantaleo, A. M. (2020). Review of Energy Efficiency Technologies in the Food Industry: Trends, Barriers, and Opportunities. *IEEE Access*, 8, 48015-48029. <https://doi.org/10.1109/Access.2020.2979077>

- Clavreul, J., Butnar, I., Rubio, V., & King, H. (2017). Intra-and inter-year variability of agricultural carbon footprints—A case study on field-grown tomatoes. *Journal of Cleaner Production*, 158, 156-164. <https://doi.org/10.1016/j.jclepro.2017.05.004>
- Coronado, C. R., de Carvalho Jr, J. A., & Silveira, J. L. (2009). Biodiesel CO₂ emissions: A comparison with the main fuels in the Brazilian market. *Fuel Processing Technology*, 90(2), 204-211. <https://doi.org/10.1016/j.fuproc.2008.09.006>
- Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., & Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, 2(3), 198-209. <https://doi.org/10.1038/s43016-021-00225-9>
- Crow, D. J., Balcombe, P., Brandon, N., & Hawkes, A. D. (2019). Assessing the impact of future greenhouse gas emissions from natural gas production. *Science of the Total Environment*, 668, 1242-1258. <https://doi.org/10.1016/j.scitotenv.2019.03.048>
- Çiftci, H. N., Gündoğdu, M. A., & Kaynaş, K. (2023). Farklı Rakımlarda Yetiştirilmiş Yenice Kırmızı Biberinin Kalite Değişimleri. *International Journal of Innovative Approaches in Science Research* 2023, Vol. 7 (2), 47-61. <https://doi.org/10.29329/ijiasr.2023.578.1>
- Dahlgren, L., Strippel, H., & Oliveira, F. (2015). Life cycle assessment: Comparative study of virgin fibre based packaging products with competing plastic materials. IVL Swedish Environmental Research Institute: Stockholm, Sweden.
- Darvishi, H., Hosainpour, A., Nargesi, F., & Fadavi, A. (2015). Exergy and energy analyses of liquid food in an Ohmic heating process: A case study of tomato production. *Innovative Food Science & Emerging Technologies*, 31, 73-82. <https://doi.org/10.1016/j.ifset.2015.06.012>
- Davis, K. F., Downs, S., & Gephart, J. A. (2021). Towards food supply chain resilience to environmental shocks. *Nat Food*, 2(1), 54-65. doi:10.1038/s43016-020-00196-3
- DCC, Directorate of Climate Change (2024). The 2024-2030 Climate Change Mitigation and Adaptation Strategy and Action Plans. Republic of Türkiye Ministry of Environment, Urbanization and Climate Change. <https://iklim.gov.tr/en/the-2024-2030-climate-change-mitigation-and-adaptation-strategy-and-action-plans-are-published-news-4245>. Access date: 13.08.2024
- De Beer, J., Worrell, E., & Blok, K. (1998). Long-term energy-efficiency improvements in the paper and board industry. *Energy*, 23(1), 21-42. [https://doi.org/10.1016/S0360-5442\(97\)00065-0](https://doi.org/10.1016/S0360-5442(97)00065-0)
- de Jesus Pereira, B., Cecílio Filho, A. B., & La Scala Jr, N. (2021). Greenhouse gas emissions and carbon footprint of cucumber, tomato and lettuce production using two cropping systems. *Journal of Cleaner Production*, 282, 124517. <https://doi.org/10.1016/j.jclepro.2020.124517>
- Dechamps, P. (2023). The IEA World Energy Outlook 2022—a brief analysis and implications. *European Energy & Climate Journal*, 11(3), 100-103.

Degerli, B., Nazir, S., Sorgüven, E., Hitzmann, B., & Özilgen, M. (2015). Assessment of the energy and exergy efficiencies of farm to fork grain cultivation and bread making processes in Türkiye and Germany. *Energy*, 93, 421-434. <https://doi.org/10.1016/j.energy.2015.08.095>

Del Borghi, A., Gallo, M., Strazza, C., & Del Borghi, M. (2014). An evaluation of environmental sustainability in the food industry through Life Cycle Assessment: the case study of tomato products supply chain. *Journal of Cleaner Production*, 78, 121-130. <https://doi.org/10.1016/j.jclepro.2014.04.083>

Del Borghi, A., Moreschi, L., & Gallo, M. (2020). Life cycle assessment in the food industry. In the interaction of food industry and environment (pp. 63-118). Academic Press. <https://doi.org/10.1016/B978-0-12-816449-5.00003-5>

Del Borghi, A., Strazza, C., Magrassi, F., Taramasso, A., & Gallo, M. (2018). Life Cycle Assessment for eco-design of product-package systems in the food industry—The case of legumes. *Sustainable Production and Consumption*, 13, 24-36. <https://doi.org/10.1016/j.spc.2017.11.001>

Demirtas, M. (2021). Evaluation of energy use and carbon dioxide emissions from the consumption of fossil fuels and agricultural chemicals for paste tomato cultivation in the Bursa region of Türkiye. *Environmental Science and Pollution Research*, 28(21), 27132-27146. <https://doi.org/10.1007/s11356-021-12593-7>

Dewulf, J., & Van Langenhove, H. (2004). Thermodynamic optimization of the life cycle of plastics by exergy analysis. *International Journal of Energy Research*, 28(11), 969-976. <https://doi.org/10.1002/er.1007>

Dewulf, J., Van Langenhove, H., Muys, B., Bruers, S., Bakshi, B. R., Grubb, G. F., Sciubba, E. (2008). Exergy: its potential and limitations in environmental science and technology. *Environmental Science & Technology* 42(7), 2221-2232. <https://doi.org/10.1021/es071719a>

Dincer, I., & Rosen, M. A. (1999). Energy, environment and sustainable development. *Applied Energy*, 64(1-4), 427-440. [https://doi.org/10.1016/S0306-2619\(99\)00111-7](https://doi.org/10.1016/S0306-2619(99)00111-7)

Ding, J., Li, Y., Liu, J., Qi, G., Liu, Q., & Dong, L. (2023). Life cycle assessment of environmental impacts of cold and hot break tomato paste packaged in steel drums and exported from Xinjiang, China. *Environmental Impact Assessment Review*, 98, 106939. <https://doi.org/10.1016/j.eiar.2022.106939>

Doğaka. (2017). Meyve-Sebze İşleme ve Depolama Tesisleri Ön Fizibilitesi. Karacadağ Kalkınma Ajansı Retrieved from https://www.dogaka.gov.tr/assets/upload/dosyalar/wwwdogakagovtr_859_dj5r93it_meyve-sebze-isleme-ve-depolama-tesis-on-fizibilitesi.pdf

Doğan, S. K. (2008). Life cycle assessment of pet bottle. (Master's Thesis). Graduate School of Natural and Applied Sciences of Dokuz Eylül University, İzmir.

Doğantan, S. Z., Tunçer, İ., & Başçetinçelik, A. (1987, September). Use Of Solar Energy For Red Pepper. In Third Technical Meeting of the FAO-CNRE on Solar Drying (pp. 9-11).

Eliseeva, T., & Shelestun, A. (2023). Tomato Juice 10 Scientifically Proven Health Benefits. *Journal of Healthy Nutrition and Dietetics*, 2(24), 25-30.

Engindeniz, S. (2006). Economic analysis of pesticide use on processing tomato growing: A case study for Türkiye. *Crop Protection*, 25(6), 534-541. <https://doi.org/10.1016/j.cropro.2005.08.009>.

Erdoğan, B. (2013). Changes in antioxidant properties during the production of red pepper paste (Master's Thesis). Ondokuz Mayıs University, Samsun, Türkiye.

Esengun, K., Erdal, G., Gunduz, O., & Erdal, H. (2007). An economic analysis and energy use in stake-tomato production in Tokat province of Türkiye. *Renewable Energy*, 32(11), 1873-1881. <https://doi.org/10.1016/j.renene.2006.07.005>

Espadas-Aldana, G., Vialle, C., Belaud, J. P., Vaca-Garcia, C., & Sablayrolles, C. (2019). Analysis and trends for Life Cycle Assessment of olive oil production. *Sustainable Production and Consumption*, 19, 216-230. <https://doi.org/10.1016/j.spc.2019.04.003>

Esposito, B., Sessa, M. R., Sica, D., & Malandrino, O. (2020). Towards circular economy in the agri-food sector. A systematic literature review. *Sustainability*, 12(18), 7401. <https://doi.org/10.3390/su12187401>

Fan, Y., Luo, Z., Hao, X., Li, S., & Kang, S. (2022). Potential pathways to reduce environmental impact in a greenhouse tomato production: Life cycle assessment for different irrigation and fertilization treatments. *Scientia Horticulturae*, 305, 111411. <https://doi.org/10.1016/j.scienta.2022.111411>

FAO, (2022). FAOSTAT: Production: Crops and livestock products. In: FAO. Rome. Cited December 2022. <https://www.fao.org/faostat/en/#data/QCL> Access date: 13.02.2024

FAO, (2021). Sustainable Food and Agriculture, Food and Agriculture Organization of the United Nations <https://www.fao.org/sustainability/en/> [Accessed 06.12.2023].

Ferrara, C., & De Feo, G. (2023). Comparative life cycle assessment of two different packaging systems for extra-virgin olive oil: glass bottle vs. 100% recycled polyethylene terephthalate (PET) bottle. *Sustainability*, 15(4), 3665. <https://doi.org/10.3390/su15043665>

Finger, R., Swinton, S. M., El Benni, N., & Walter, A. (2019). Precision farming at the nexus of agricultural production and the environment. *Annual Review of Resource Economics*, 11, 313-335. <https://doi.org/10.1146/annurev-resource-100518-093929>

Frangopoulos, C. A. (2009). Exergy, Energy System Analysis and Optimization-Volume III: Artificial Intelligence and Expert Systems in Energy Systems Analysis Sustainability Considerations in the Modeling of Energy Systems (Vol. 3): EOLSS Publications.

Frusciante, L., Carli, P., Ercolano, M. R., Pernice, R., Di Matteo, A., Fogliano, V., & Pellegrini, N. (2007). Antioxidant nutritional quality of tomato. *Molecular nutrition & food research*. 51(5), 609-617. <https://doi.org/10.1002/mnfr.200600158>

García García, J., & García García, B. (2022). Sustainability Assessment of Greenhouse Pepper Production Scenarios in Southeastern Spain. *Agronomy*, 12(6), 1254. <https://doi.org/10.3390/agronomy12061254>

Garofalo, P., D'Andrea, L., Tomaiuolo, M., Venezia, A., & Castrignanò, A. (2017). Environmental sustainability of agri-food supply chains in Italy: The case of the whole-peeled tomato production under life cycle assessment methodology. *Journal of Food Engineering*, 200, 1-12. <https://doi.org/10.1016/j.jfoodeng.2016.12.007>

Ghnimi, S., Nikkhah, A., Dewulf, J., & Van Haute, S. (2021). Life cycle assessment and energy comparison of aseptic ohmic heating and appertization of chopped tomatoes with juice. *Scientific Reports*, 11(1), 13041. <https://doi.org/10.1038/s41598-021-92211-1>

Ghosh, T., Socci, E., Cashman, S., & Sauer, B. (2012, June). Life Cycle Assessment of PepsiCo USA's Beverage Packaging. In PepsiCo presentation at IAPRI World Packaging Conference (pp. 303-311).

Gielen, D., & Tam, C. (2006). Proposal for energy and CO₂ emission indicators in the petrochemical sector. Paper presented at the IEA Workshop: feedstock substitutes, energy efficient technology and CO₂ reduction for petrochemical products in collaboration with CEFIC IEA, Paris.

Gnansounou, E., & Raman, J. K. (2016). Life cycle assessment of algae biodiesel and its co-products. *Applied Energy*, 161, 300-308. <https://doi.org/10.1016/j.apenergy.2015.10.043>

Gorjian, S., Fakhræi, O., Gorjian, A., Sharafkhani, A., & Aziznejad, A. (2022). Sustainable food and agriculture: Employment of renewable energy technologies. *Current Robotics Reports*, 3(3), 153-163. <https://doi.org/10.1007/s43154-022-00080-x>

Gould, W. A. (1974). Tomato production, processing and quality evaluation (pp. viii+-445). Avi Publishing Co., Inc. Westport, Connecticut, USA.

Gök, S. B., Göçmen, E., & İstanbulluoğlu, A. (2021). Farklı Sulama Uygulamalarının Kapyra Biberinin (*Capsicum annuum* cv. kapija) Bazı Kalite Özellikleri Üzerine Etkisi Paper presented at the Ankara V. International Scientific Research Congress, October 10-12, 2021, Ankara-TÜRKİYE <https://en.ankarakongresi.org/>

Griffin, P. W., Hammond, G. P., & McKenna, R. C. (2021). Industrial energy use and decarbonisation in the glass sector: A UK perspective. *Advances in Applied Energy*, 3, 100037. <https://doi.org/10.1016/j.adapen.2021.100037>

Groen, E. A., Heijungs, R., Bokkers, E. A., & de Boer, I. J. (2014, October). Sensitivity analysis in life cycle assessment. In Proceedings of the 9th international conference on life cycle assessment in the agri-food sector (pp. 8-10). Vashon, WA, USA: ACLCA.

Groth, C., Wegmann, C., & Meyerding, S. G. (2023). Perception of product sustainability: The case of processed tomatoes—A qualitative study in Germany. *Journal of Retailing and Consumer Services*, 71, 103214. <https://doi.org/10.1016/j.jretconser.2022.103214>

Guinée, J. B. (2002). Handbook on life cycle assessment: operational guide to the ISO standards (Vol. 7): Springer Science & Business Media, Kluwer Academic Publishers, New York, U.S.A.

Guo, X. X., Zhao, D., Zhuang, M. H., Wang, C., & Zhang, F. S. (2021). Fertilizer and pesticide reduction in cherry tomato production to achieve multiple environmental benefits in Guangxi, China. *Science of Total Environment*, 793, 148527. doi:10.1016/j.scitotenv.2021.148527

Gül, H., Üçtuğ, F., & Güngörmüşler, M. (2021). Environmental life cycle assessment of industrially produced pickled and roasted vegetables. *International Journal of Environmental Science and Technology*, 1-18. <https://doi.org/10.1007/s13762-021-03740-1>

Gundogan, R., Tomar, G. S., Karaca, A. C., & Gökmen, V. (2024). Evaporation in the tomato paste industry. In *Evaporation Technology in Food Processing* (pp. 247-265). Woodhead Publishing. <https://doi.org/10.1016/B978-0-12-818764-7.00010-4>

Güvenç, İ. (2020). Pepper Production, Foreign Trade and Competitiveness in Türkiye. *Kahramanmaraş Sütçü İmam University Journal of Agriculture and Nature*, 23(2), 441-445. DOI:10.18016/ksutarimdoga.vi.595512. (In Turkish)

Hadžiahmetović, H., Blažević, R., & Peco, E. (2021). Solution Proposal for Utilization of the Waste Heat in Refrigeration Systems. *TEM Journal*, 10(1).

Halpin, M. (2013). Advancing Standards in Energy Efficiency. *IEEE Industry Applications Magazine*, 19(4), 78-79. doi:10.1109/Mias.2013.2255426

Hammond GP, McKenna RC. Energy and exergy analyses of the UK glass sector. In: *Proceedings of the 4th European congress on economics and management of energy in industry (ECEMEI)*; 2007. p. 11.

Hasler, K., Bröring, S., Omta, S. W. F., & Olf, H. W. (2015). Life cycle assessment (LCA) of different fertilizer product types. *European Journal of Agronomy*, 69, 41-51. <https://doi.org/10.1016/j.eja.2015.06.001>

Hatirli, S. A., Ozkan, B., & Fert, C. (2006). Energy inputs and crop yield relationship in greenhouse tomato production. *Renewable Energy*, 31(4), 427-438. <https://doi.org/10.1016/j.renene.2005.04.007>

WSP/Parsons Brickherhoff [PB] and DNV.GL Industrial decarbonisation & energy efficiency roadmaps to 2050: glass. A report prepared for the Department of Energy and Climate Change [DECC] and the Department for Business, Innovation and Skills [BIS]. London, UK: DECC;2015

He, X., Qiao, Y., Liu, Y., Dendler, L., Yin, C., & Martin, F. (2016). Environmental impact assessment of organic and conventional tomato production in urban greenhouses of Beijing city, China. *Journal of Cleaner Production*, 134, 251-258. <https://doi.org/10.1016/j.jclepro.2015.12.004>

Heidari, M. D., Huijbregts, M. A., Mobli, H., Omid, M., Rafiee, S., & van Zelm, R. (2017). Regionalised life cycle assessment of pasta production in Iran: Damage to terrestrial ecosystems. *Journal of Cleaner Production*, 159, 141-146. <https://doi.org/10.1016/j.jclepro.2017.05.073>

Hekimoğlu, B., Altindeğer, M., (2018). Samsun Province Capia Pepper Sector Report. Samsun Governorship Provincial Directorate of Agriculture and Forestry, Strategy Development Unit https://samsun.tarimorman.gov.tr/Belgeler/Yayinlar/Tarimsal_strateji/Samsun_ili_Kapya_Biber_Sektor_Raporu.pdf. (In Turkish), [Access date: 12.12.2023].

Heldman, D., & Hartel, R. (1998). *Principles of food Processing*. Gaithersburg, Maryland: Aspen Publishers, Inc.

Helsel, Z. R. (1992). Energy and alternatives for fertilizer and pesticide use. Energy in farm production, 6, 177-201. Editor: Fluck, R.C. Elsevier Science Publishers, Netherlands.

Hertwich, E. G., Mateles, S. F., Pease, W. S., & McKone, T. E. (2001). Human toxicity potentials for life-cycle assessment and toxics release inventory risk screening. *Environmental Toxicology and Chemistry: An International Journal*, 20(4), 928-939. <https://doi.org/10.1002/etc.5620200431>

Huang, J., Xu, C. C., Ridoutt, B. G., Wang, X. C., & Ren, P. A. (2017). Nitrogen and phosphorus losses and eutrophication potential associated with fertilizer application to cropland in China. *Journal of Cleaner Production*, 159, 171-179. <https://doi.org/10.1016/j.jclepro.2017.05.008>

Huang, K. M., Guan, Z., & Hammami, A. (2022). The US fresh fruit and vegetable industry: An overview of production and trade. *Agriculture*, 12(10), 1719. <https://doi.org/10.3390/agriculture12101719>

Ibisch, R. (2016). Technical Report N° 2: European assessment of eutrophication abatement measures across land-based sourced, inland, coastal and marine waters. European Environment Agency.

IEA, (2022). *World energy outlook 2022*. International Energy Agency, Paris, France. <https://www.iea.org/reports/world-energy-outlook-2022>. [Access date: 03.05.2024].

IEO, *International Energy Outlook (2021)*. U.S. Energy Information Administration. *International Energy Outlook 2021 (IEO2021)*. Reference Case; U.S. Energy Information Administration: Washington, DC, 2021.

International Federation of Institutes for Advanced Study (1974). *Guidelines for Energy Analysis* Stockholm.

Ingrao, C., Faccilongo, N., Valenti, F., De Pascale, G., Di Gioia, L., Messineo, A., Arcidiacono, C., 2019. Tomato puree in the Mediterranean region: An environmental Life Cycle Assessment, based upon data surveyed at the supply chain level. *J Clean Prod.* 233, 292-313. <https://doi.org/10.1016/j.jclepro.2019.06.056>

ISO, I., 2006a. 14040. Environmental management—life cycle assessment—principles and framework, 235-248. (Edition 2, 2006). <https://www.iso.org/standard/37456.html>. [Access date: 03.09.2023].

ISO, I., 2006b. f. S.(2006b): Environmental management—Life cycle assessment—Requirements and Guidelines, (Edition 1, 2006). <https://www.iso.org/standard/38498.html>. [Access date: 03.09.2023].

Josijević, M. M., Šušteršič, V. M., & Gordić, D. R. (2020). Ranking energy performance opportunities obtained with energy audit in dairies. *Thermal Science*, 24(5 Part A), 2865-2878. <https://doi.org/10.2298/TSCI191125100J>

Jungbluth, N., Tietje, O., & Scholz, R. W. (2000). Food purchases: impacts from the consumers' point of view investigated with a modular LCA. *The International Journal of Life Cycle Assessment*, 5, 134-142. <https://doi.org/10.1007/BF02978609>

Kahyaoglu, T. (2008). Optimization of the pistachio nut roasting process using response surface methodology and gene expression programming. *LWT-Food Science and Technology*, 41(1), 26-33. <https://doi.org/10.1016/j.lwt.2007.03.026>

Kallsen, C. E., Parfitt, D. E., Maranto, J., & Holtz, B. A. (2009). New pistachio varieties show promise for California cultivation. *California Agriculture*, 63(1). <https://doi.org/10.3733/ca.v063n01p18>

Kalnes, T., Marker, T., & Shonnard, D. R. (2007). Green Diesel: A Second Generation Biofuel. *International Journal of Chemical Reactor Engineering*, 5(1). <https://doi.org/10.2202/1542-6580.1554>

Kaltsas, A. M., Mamolos, A. P., Tsatsarelis, C. A., Nanos, G. D., & Kalburtji, K. L. (2007). Energy budget in organic and conventional olive groves. *Agriculture, Ecosystems & Environment*, 122(2), 243-251. <https://doi.org/10.1016/j.jclepro.2015.10.031>

Kameni Nematchoua, M. (2022). Strategies for studying acidification and eutrophication potentials, a case study of 150 countries. *J*, 5(1), 150-165. <https://doi.org/10.3390/j5010012>

KDA, (2019). Karacadağ Development Agency. (2019). Feasibility study of a solar energy vegetable drying facility. Ministry of Industry and Technology, Republic of Türkiye. <https://www.investsanliurfa.com/public/uploads/attachment/05-gunes-enerjili-sebze-kurutma-tesisi-yatirim-fizibilitesi-1587454849.pdf> [Accessed date: 02.03.2024].

Karakaya, A., & Özilgen, M. (2011). Energy utilization and carbon dioxide emission in the fresh, paste, whole-peeled, diced, and juiced tomato production processes. *Energy*, 36(8), 5101-5110. doi:10.1016/j.energy.2011.06.007

Kaynak-Duman, A. (2020). Life cycle assessment of waste in olive oil industry. (Master's Thesis). Ege University, Graduate School of Natural and Applied Sciences.

Kc, K. B., Dias, G. M., Veeramani, A., Swanton, C. J., Fraser, D., Steinke, D., Dunfield, K. (2018). When too much isn't enough: Does current food production meet global nutritional needs? PloS one, 13(10), e0205683. <https://doi.org/10.1371/journal.pone.0205683>

Khan, M. N., & Mohammad, F. (2014). Eutrophication: challenges and solutions. Eutrophication: Causes, Consequences and Control: Volume 2, 1-15.

Khanali, M., Kokei, D., Aghbashlo, M., Nasab, F. K., Hosseinzadeh-Bandbafha, H., & Tabatabaei, M. (2020). Energy flow modeling and life cycle assessment of apple juice production: Recommendations for renewable energies implementation and climate change mitigation. Journal of Cleaner Production, 246, 118997. <https://doi.org/10.1016/j.jclepro.2019.118997>

Khorasanizadeh, Z., Nasiri, F., & Mahyari, K. F. (2021). A detailed thermodynamic assessment and exergetic performance analysis of an industrial-scale orange juice production plant. International Journal of Exergy, 35(3), 291-326. <https://doi.org/10.1504/IJEX.2021.115896>

Khoshnevisan, B., Rafiee, S., Omid, M., Mousazadeh, H., & Clark, S. (2014). Environmental impact assessment of tomato and cucumber cultivation in greenhouses using life cycle assessment and adaptive neuro-fuzzy inference system. Journal of Cleaner Production, 73, 183-192. <https://doi.org/10.1016/j.jclepro.2013.09.057>

Kim, D., Lee, H., & Cho, I. (2019). Characteristics of a tea made with roasted red pepper (*Capsicum annum* L.) seeds. Korean Journal of Food and Cookery Science, 35, 280-287.

Kim, D., Park, H., & Cho, I. H. (2022). The effect of roasting on capsaicinoids, volatile compounds, and fatty acids in *Capsicum annum* L.(red pepper) seeds. Food Science and Biotechnology, 31(2), 211-220. <https://doi.org/10.1007/s10068-021-01023-6>

Kiperstok, O. J. R. K. A. (2013). Effluent stream treatment in a nitrogenous fertilizer. Process Biochemistry, 41, 1709-1721. <http://dx.doi.org/doi:10.1016/j.psep.2013.07.003>

Kirkin, F. (2013). Determination of the properties of some commercially produced tomato pastes. Gaziosmanpaşa University, Institute of Science and Technology, Department of Food Engineering, Master's Thesis, Tokat, Türkiye (In Turkish).

Kiyak, B., & Gunes, N. C. (2024). Life cycle assessment of apricot puree concentrate production. Journal of Food Engineering, 368, 111919. <https://doi.org/10.1016/j.jfoodeng.2023.111919>

Koca, İ., & Erdoğan, B. (2011, October 13-16). Red pepper production and evaluation in Samsun, Türkiye. Paper presented at the Samsun Symposium, Samsun, Türkiye (In Turkish).

Kongshaug, G. (1998). Energy consumption and greenhouse gas emissions in fertilizer production. In IFA Tech. Conf., Marrakech, Morocco, 1998. Int. Fertilizer Industry Assoc.<https://doi.org/10.11353/sesj.22.247>

- Kouloumpis, V., Pell, R. S., Correa-Cano, M. E., & Yan, X. (2020). Potential trade-offs between eliminating plastics and mitigating climate change: An LCA perspective on Polyethylene Terephthalate (PET) bottles in Cornwall. *Science of the Total Environment*, 727, 138681. <https://doi.org/10.1016/j.scitotenv.2020.138681>
- Kuchi, V. S., Gupta, R., & Kachwaya, D. S. (2014). A review on dehydration of chilli. *Plant Archives*, 14(2), 637-642.
- Kudra, T. (2004). Energy aspects in drying. *Drying Technology*, 22(5), 917-932. <https://doi.org/10.1081/DRT-120038572>
- Kulcu, R. (2018). Determination of the effects of different packaging methods and materials on storage time of dried apple. *MATTER: International Journal of Science and Technology* 4(2), 238-255. <https://dx.doi.org/10.20319/mijst.2018.42.238255>
- Kuleaşan, H., & Okur, M. (2012). Industrial production of traditional red pepper paste and prevention of spoilage during storage. *Journal of Food, Agriculture & Environment*, 10(2 Part 1), 241-246.
- Kumar, Y., Arora, V., & Kundli, D.-S. (2019). Energy and exergy analysis and its application of different drying techniques: a review. *ISME Journal of Thermofluid*, 5(2), 10-29.
- Latini, A., Giagnacovo, G., Campiotti, A., Bernardini, A., & Fuentes-Pila, J. (2017). Energy analysis and Current Value Stream Map applied to a typical triple concentrate tomato paste production plant with an average production capacity of 500 ton/day. *Journal of Agricultural Research*, 2(4), 00140.
- Lattouf, R., & Oliveira Júnior, S. D. (2003). Exergy analysis of environmental impact mitigation processes. In *Proceedings of 16th International Conference on Efficiency, Cost, Optimisation, Simulation, and Environmental Impact Of Energy Systems*, Copenhagen.
- Laurijssen, J., Marsidi, M., Westenbroek, A., Worrell, E., & Faaij, A. (2010). Paper and biomass for energy?: The impact of paper recycling on energy and CO₂ emissions. *Resources, Conservation and Recycling*, 54(12), 1208-1218. <https://doi.org/10.1016/j.resconrec.2010.03.016>
- Li, M. J., & Tao, W. Q. (2017). Review of methodologies and polices for evaluation of energy efficiency in high energy-consuming industry. *Applied Energy*, 187, 203-215. <https://doi.org/10.1016/j.apenergy.2016.11.039>
- Liu, X. W., Le Bourvellec, C., Yu, J. H., Zhao, L., Wang, K., Tao, Y., Hu, Z. Y. (2022). Trends and challenges on fruit and vegetable processing: Insights into sustainable, traceable, precise, healthy, intelligent, personalized and local innovative food products. *Trends in Food Science & Technology*, 125, 12-25. <https://doi.org/10.1016/j.tifs.2022.04.016>
- Liu, Y., Langemeier, M. R., Small, I. M., Joseph, L., Fry, W. E., Ristaino, J. B., & Preckel, P. V. (2018). A risk analysis of precision agriculture technology to manage tomato late blight. *Sustainability*, 10(9), 3108. <https://doi.org/10.3390/su10093108>

Liu Z., Bia J., Wang S., Meng J., Wang H., Yu X., Gao Z., Xiao H. (2019): Prediction of energy and exergy of mushroom slices drying in hot air impingement dryer by an artificial neural network. *Drying Technology*, 149510454. <https://doi.org/10.1080/07373937.2019.1607873>

Loizzo, M. R., Pugliese, A., Bonesi, M., Menichini, F., & Tundis, R. (2015). Evaluation of chemical profile and antioxidant activity of twenty cultivars from *Capsicum annuum*, *Capsicum baccatum*, *Capsicum chacoense* and *Capsicum chinense*: A comparison between fresh and processed peppers. *LWT - Food Science and Technology*, 64(2), 623-631. <https://doi.org/10.1016/j.lwt.2015.06.042>

Lynch, J., Cain, M., Pierrehumbert, R., & Allen, M. (2020). Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short-and long-lived climate pollutants. *Environmental Research Letters*, 15(4), 044023. <https://doi.org/10.1088/1748-9326/ab6d7e>

Maddalena, R. L., McKone, T. E., Layton, D. W., & Hsieh, D. P. (1995). Comparison of multi-media transport and transformation models: regional fugacity model vs. CalTOX. *Chemosphere*, 30(5), 869-889. [https://doi.org/10.1016/0045-6535\(94\)00447-3](https://doi.org/10.1016/0045-6535(94)00447-3)

Madival, S., Auras, R., Singh, S. P., & Narayan, R. (2009). Assessment of the environmental profile of PLA, PET and PS clamshell containers using LCA methodology. *Journal of Cleaner Production*, 17(13), 1183-1194. <https://doi.org/10.1016/j.jclepro.2009.03.015>

Manfredi, M., & Vignali, G. (2014). Life cycle assessment of a packaged tomato puree: a comparison of environmental impacts produced by different life cycle phases. *Journal of Cleaner Production*, 73, 275-284. <https://doi.org/10.1016/j.jclepro.2013.10.010>

Manzoor, M. F., Ali, M., Aadil, R. M., Ali, A., Goksen, G., Li, J., ... & Proestos, C. (2023). Sustainable emerging sonication processing: Impact on fungicide reduction and the overall quality characteristics of tomato juice. *Ultrasonics Sonochemistry*, 94, 106313. <https://doi.org/10.1016/j.ultsonch.2023.106313>

Martin-Gorriz, B., Maestre-Valero, J. F., Gallego-Elvira, B., Marín-Membrive, P., Terrero, P., & Martínez-Alvarez, V. (2021a). Recycling drainage effluents using reverse osmosis powered by photovoltaic solar energy in hydroponic tomato production: Environmental footprint analysis. *Journal of Environmental Management*, 297, 113326.

Martin-Gorriz, B., Martínez-Alvarez, V., Maestre-Valero, J. F., & Gallego-Elvira, B. (2021b). Influence of the Water Source on the Carbon Footprint of Irrigated Agriculture: A Regional Study in South-Eastern Spain. *Agronomy*, 11(2), 351. <https://doi.org/10.3390/agronomy11020351>

Martinho, V. J. P. D. (2021). Direct and indirect energy consumption in farming: Impacts from fertilizer use. *Energy*, 236, 121504. <https://doi.org/10.1016/j.energy.2021.121504>

Matlack, A., 2010. Introduction to green chemistry. CRC press. <https://doi.org/10.1201/9781003033615>

McKone, T. E. (1992). CalTOX: A multimedia total-exposure model for hazardous-wastes sites (No. UCRL-CR-111456-Pt. 3). Lawrence Livermore National Lab., CA (United States). <https://www.osti.gov/biblio/6113893>. [Access date: 08.06.2024]

MEA, (2023). Fresh Fruit and Vegetable Sector Global Sales Report. General Sekretariat of the Mediterranean Exporters' Associations: <https://www.akib.org.tr/files/downloads/2023/04/d19277556dea46d19277556dea46d19277556dea46d1927755.pdf>

Milčiuvienė, S., Kiršienė, J., Dohejko, E., Urbonas, R., & Milčius, D. (2019). The role of renewable energy prosumers in implementing energy justice theory. *Sustainability*, 11(19), 5286. <https://doi.org/10.3390/su11195286>

Mili, S., & Loukil, T. (2022). Sustainable value creation in fruit and vegetable companies: A case study. *Proceedings in Food System Dynamics*, 132-141.

Mohammadi, A., Tabatabaeefar, A., Shahin, S., Rafiee, S., & Keyhani, A. (2008). Energy use and economical analysis of potato production in Iran a case study: Ardabil province. *Energy Conversion and Management*, 49(12), 3566-3570. <https://doi.org/10.1016/j.enconman.2008.07.003>

Morosuk, T., Tsatsaronis, G., & Koroneos, C. (2016). Environmental impact reduction using exergy-based methods. *Journal of Cleaner Production*, 118, 118-123. <https://doi.org/10.1016/j.jclepro.2016.01.064>

Motamedzadegan, A., & Tabarestani, H. S. (2018). Tomato production, processing, and nutrition. *Handbook of Vegetables and Vegetable Processing*, 839-861. <https://doi.org/10.1002/9781119098935.ch36>

Murphy, F., McDonnell, K., Fagan, C.C., 2014. Sustainability and environmental issues in food processing. *Food processing: Principles and applications*, 207-232. <https://doi.org/10.1002/9781118846315.ch9>

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestad, J., Huang, J., Mendoza, B. (2014). Anthropogenic and natural radiative forcing. *Climate Change 2013-The Physical Science Basis*, 659-740. <https://dx.doi.org/10.1017/CBO9781107415324.018>

Naderi, S. A., Dehkordi, A. L., & Taki, M. (2019). Energy and environmental evaluation of greenhouse bell pepper production with life cycle assessment approach. *Environmental and Sustainability Indicators*, 3, 100011. <https://doi.org/10.1016/j.indic.2019.100011>

Naresh Kumar, S., & Chakabarti, B. (2019). Energy and Carbon Footprint of Food Industry. In: Muthu, S. (eds) *Energy Footprints of the Food and Textile Sectors*, 19-44. Springer, Singapore. https://doi.org/10.1007/978-981-13-2956-2_2

Navarro, A., Puig, R., Martí, E., Bala, A., & Fullana-i-Palmer, P. (2018). Tackling the relevance of packaging in life cycle assessment of virgin olive oil and the environmental consequences of regulation. *Environmental management*, 62(2), 277-294. <https://doi.org/10.1007/s00267-018-1021-x>

Neira, D. P., Montiel, M. S., Cabeza, M. D., & Reigada, A. (2018). Energy use and carbon footprint of the tomato production in heated multi-tunnel greenhouses in Almeria within an exporting agri-food system context. *Science of the Total Environment*, 628, 1627-1636. <https://doi.org/10.1016/j.scitotenv.2018.02.127>

Nejat, P., Jomehzadeh, F., Taheri, M. M., Gohari, M., & Abd Majid, M. Z. (2015). A global review of energy consumption, CO₂ emissions and policy in the residential sector (with an overview of the top ten CO₂ emitting countries). *Renewable & Sustainable Energy Reviews*, 43, 843-862. <https://doi.org/10.1016/j.rser.2014.11.066>

Neubauer, S.C. Global Warming Potential Is Not an Ecosystem Property. *Ecosystems* 24, 2079–2089 (2021). <https://doi.org/10.1007/s10021-021-00631-x>

Nguyen, T. L. T., & Hermansen, J. E. (2012). System expansion for handling co-products in LCA of sugar cane bio-energy systems: GHG consequences of using molasses for ethanol production. *Applied Energy*, 89(1), 254-261. <https://doi.org/10.1016/j.apenergy.2011.07.023>

Ocko, I. B., Hamburg, S. P., Jacob, D. J., Keith, D. W., Keohane, N. O., Oppenheimer, M., Roy-Mayhew, J. D., Schrag, D.P., & Pacala, S. W., (2017). Unmask temporal trade-offs in climate policy debates. *Science*, 356(6337), 492-493. <https://doi.org/10.1126/science.aaj2350>

Oke, M., Jacob, J. K., & Paliyath, G. (2012). Biochemistry of fruit processing. Simpson, B.K., (2nd Edition) (2012), *Food Biochemistry And Food Processing*. John Wiley & Sons, Inc. Oxford, U.K. 554-568. <https://doi.org/10.1002/9781118308035.ch28>

Oke, M., & Paliyath, G. (2006). Biochemistry of fruit processing. Hui., Y. H. (1st Edition), *Food Biochemistry And Food Processing*. John Wiley & Sons, Inc. Oxford, U.K. 537-554. <https://doi.org/10.1002/9780470277577.ch23>

Okur, M. (2011). Detection of microorganisms that cause problems in the production of pepper paste and determination of the methods of eliminating these problems (Doctoral dissertation, SDÜ Institute of Science and Technology) (In Turkish).

Østergaard, P. A., Duic, N., Noorollahi, Y., Mikulcic, H., & Kalogirou, S. (2020). Sustainable development using renewable energy technology. In (Vol. 146, pp. 2430-2437): Elsevier. https://doi.org/10.1007/978-3-030-00105-6_1

Ozdemir, A. C. (2023). Decomposition and decoupling analysis of carbon dioxide emissions in electricity generation by primary fossil fuels in Türkiye. *Energy*, 273, 127264. <https://doi.org/10.1016/j.energy.2023.127264>.

Ozilgen, M., & Oner, E. S. (2016). Biothermodynamics: Principles and applications: CRC Press. <https://doi.org/10.1201/9781315374147>

Ozturkoglu-Budak, S. (2017). A model for implementation of HACCP system for prevention and control of mycotoxins during the production of red dried chili pepper. *Food Science and Technology*, 37(suppl 1), 24-29. <https://doi.org/10.1590/1678-457x.30316>

Özdikmenli, S., & Demirel Zorba, N. (2015). Közlenmiş Kırmızı Biber (Kapy) Konservesi Üretiminde Gıda Güvenliği. *Journal of Tekirdag Agricultural Faculty*, 12(1), 55-64 <https://hdl.handle.net/20.500.11776/1922>

Özilgen, M. (2016). Energy utilization and carbon dioxide emission during production of snacks. *Journal of Cleaner Production*, 112, 2601-2612. <https://doi.org/10.1016/j.jclepro.2015.10.031>

Özilgen, M. (2018). Nutrition and production related energies and exergies of foods. *Renewable and Sustainable Energy Reviews*, 96, 275-295. <https://doi.org/10.1016/j.rser.2018.07.055>

Özilgen, M., & Sorgüven, E. (2011). Energy and exergy utilization, and carbon dioxide emission in vegetable oil production. *Energy*, 36(10), 5954-5967. <https://doi.org/10.1016/j.energy.2011.08.020>

Panagopoulos, A. (2021a). Beneficiation of saline effluents from seawater desalination plants: fostering the zero liquid discharge (ZLD) approach-a techno-economic evaluation. *Journal of Environmental Chemical Engineering*, 9(4), 105338. <https://doi.org/10.1016/j.jece.2021.105338>

Panagopoulos, A. (2021b). Study and evaluation of the characteristics of saline wastewater (brine) produced by desalination and industrial plants. *Environmental Science and Pollution Research*, 1-14. <https://doi.org/10.1007/s11356-021-17694-x>

Parajuli, R., Matlock, M.D., Thoma, G., (2021). Cradle to grave environmental impact evaluation of the consumption of potato and tomato products. *Science of Total Environment*. 758, 143662. <https://doi.org/10.1016/j.scitotenv.2020.143662>

Park, S. H., Lamsal, B. P., & Balasubramaniam, V. M. (2014). Principles of Food Processing. *Food Processing: Principles and Applications*, 2nd Edition, 1-15. <https://doi.org/10.1002/9781118846315.ch1>

Pasqualino, J., Meneses, M., & Castells, F. (2011). The carbon footprint and energy consumption of beverage packaging selection and disposal. *Journal of food Engineering*, 103(4), 357-365. <https://doi.org/10.1016/j.jfoodeng.2010.11.005>

Pata, U. K. (2018). The effect of urbanization and industrialization on carbon emissions in Türkiye: evidence from ARDL bounds testing procedure. *Environmental Science and Pollution Research*, 25(8), 7740-7747. <https://doi.org/10.1007/s11356-017-1088-6>

Patil Shirish, S., & Bhalerao, S. A. (2013). Precision farming: the most scientific and modern approach to sustainable agriculture. *International Research Journal of Science and Engineering*, 1(2), 21-30.

Peng, J. Q., Lu, L., & Yang, H. X. (2013). Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. *Renewable & Sustainable Energy Reviews*, 19, <https://doi.org/10.1016/j.rser.2012.11.035>

Perry, C. (2017). Glass Sector: Joint Industry—Government Industrial Decarbonisation and Energy Efficiency Roadmap Action Plan. BEIS: London, UK.

Pikoń, K. (2012). Abiotic depletion in energy and waste management systems. *Polityka Energetyczna*, 15(1), 87-101.

Pimentel, D. (1991). Ethanol fuels: Energy security, economics, and the environment. *Journal of agricultural and environmental ethics*, 4, 1-13. <https://doi.org/10.1007/BF02229143>

Pishgar-Komleh, S. H., Akram, A., Keyhani, A., Raei, M., Elshout, P. M. F., Huijbregts, M. A. J., & van Zelm, R. (2017). Variability in the carbon footprint of open-field tomato production in Iran - A case study of Alborz and East-Azerbaijan provinces. *Journal of Cleaner Production*, 142, 1510-1517. <https://doi.org/10.1016/j.jclepro.2016.11.154>

Rahman, M. M. (2020). Environmental degradation: The role of electricity consumption, economic growth and globalisation. *Journal of environmental management*, 253, 109742. <https://doi.org/10.1016/j.jenvman.2019.109742>

Rai, A. K., Al Makishah, N. H., Wen, Z. Q., Gupta, G., Pandit, S., & Prasad, R. (2022). Recent Developments in Lignocellulosic Biofuels, a Renewable Source of Bioenergy. *Fermentation-Basel*, 8(4), 161. <https://doi.org/10.3390/fermentation8040161>

Raj, S., Sajith, A., Sreenikethanam, A., Vadlamani, S., Satheesh, A., Ganguly, A., Bajhaiya, A. K. (2023). Renewable biofuels from microalgae: technical advances, limitations and economics. *Environmental Technology Reviews*, 12(1), 18-36. <https://doi.org/10.1080/21622515.2023.2167126>

Ramvalho do Rêgo, E., Monteiro do Rêgo, M., Finger, F. L., Pinto, C. M. F., dos Santos, I. C., de Araujo, F. F., & da Silva, T. P. (2016). Pepper importance and growth (*Capsicum* spp.). Production and breeding of chilli peppers (*Capsicum* spp.), 1-25. https://doi.org/10.1007/978-3-319-06532-8_1

Ramírez, J. A., Castañón-Rodríguez, J. F., & Uresti-Marín, R. M. (2020). An exploratory study of possible food waste risks in supermarket fruit and vegetable sections. *Food Science and Technology*, 41, 967-973. <https://doi.org/10.1590/fst.27320>

Reader, G. T. (2019). Energy and sustainability: policy, politics and practice. In *The Energy Mix for Sustaining Our Future: Selected Papers from Proceedings of Energy and Sustainability 2018* (pp. 1-17). Springer International Publishing.

Rehman, A., Ma, H., Ozturk, I., & Ulucak, R. (2022). Sustainable development and pollution: The effects of CO₂ emission on population growth, food production, economic development, and energy consumption in Pakistan. *Environmental Science and Pollution Research*, 1-12 . <https://doi.org/10.1007/s11356-021-16998-2>

Renzulli, P. A., Notarnicola, B., Tassielli, G., Arcese, G., & Di Capua, R. (2016). Life cycle assessment of steel produced in an Italian integrated steel mill. *Sustainability*, 8(8), 719. <https://doi.org/10.3390/su8080719>

Ronga, D., Galligani, T., Zaccardelli, M., Perrone, D., Francia, E., Milc, J., & Pecchioni, N. (2019). Carbon footprint and energetic analysis of tomato production in the organic vs the conventional cropping systems in Southern Italy. *Journal of Cleaner Production*, 220, 836-845. <https://doi.org/10.1016/j.jclepro.2019.02.111>

Rousseaux, P., Gremy-Gros, C., Bonnin, M., Henriel-Ricordel, C., Bernard, P., Floury, L., Staigre, G., Vincent, P., 2017. "Eco-tool-seeker": A new and unique business guide for choosing ecodesign tools. *Journal of Cleaner Production*. 151, 546-577. <https://doi.org/10.1016/j.jclepro.2017.03.089>

Roy, P., Nei, D., Okadome, H., Nakamura, N., Orikasa, T., Shiina, T., 2008. Life cycle inventory analysis of fresh tomato distribution systems in Japan considering the quality aspect. *Journal of Food Engineering*. 86, 225-233. <https://doi.org/10.1016/j.jfoodeng.2007.09.033>

Rybak, K., Parniakov, O., Samborska, K., Wiktor, A., Witrowa-Rajchert, D., & Nowacka, M. (2021). Energy and quality aspects of freeze-drying preceded by traditional and novel pre-treatment methods as exemplified by red bell pepper. *Sustainability*, 13(4), 2035. <https://doi.org/10.3390/su13042035>

Saarniit, K., Lang, H., Kuldjarv, R., Laaksonen, O., & Rosenvald, S. (2023). The Stability of Phenolic Compounds in Fruit, Berry, and Vegetable Purees Based on Accelerated Shelf-Life Testing Methodology. *Foods*, 12(9), 1777. doi:10.3390/foods12091777

Sabanci, S., & Icier, F. (2020). Enhancement of the performance of sour cherry juice concentration process in vacuum evaporator by assisting ohmic heating source. *Food and Bioproducts Processing*, 122, 269-279. <https://doi.org/10.1016/j.fbp.2020.05.004>

Sabanci, S. (2021). A study on electrical conductivity and performance evaluation of ohmic evaporation process of grape juice. *Journal of Food Processing and Preservation*, 45(5), e15487. <https://doi.org/10.1111/jfpp.15487>

Sahdev, R. K. (2014). Open sun and greenhouse drying of agricultural and food products: a review. *International Journal of Engineering Research*, 3(3).

Sakaldaş, M., Kaynaş, K., & Özdirek, F. (2014). Effects of different post-harvest treatments on the quality and biochemical properties of Capia pepper type. 10th Vegetable Agriculture Symposium Abstract Book, 2-4. (In Turkish).

Saleh, Y. (2016). Comparative life cycle assessment of beverages packages in Palestine. *Journal of Cleaner Production*, 131, 28-42. <https://doi.org/10.1016/j.jclepro.2016.05.080>

Salehi, N., Mahmoudi, M., Bazargan, A., & McKay, G. (2018). Exergy and life cycle-based analysis. *Handbook of Environmental Materials Management*. Springer, Cham. https://doi.org/10.1007/978-3-319-73645-7_84

Schenker, S., Heinemann, C., Huber, M., Pompizzi, R., Perren, R., & Escher, R. (2002). Impact of roasting conditions on the formation of aroma compounds in coffee beans. *Journal of Food Science*, 67(1), 60-66. <https://doi.org/10.1111/j.1365-2621.2002.tb11359.x>

Schubert, H., Schuchmann, H. P., Engel, R., & Knoerzer, K. (2013). Food Process Engineering Research and Innovation in a Fast-Changing World. Advances in food process engineering research and applications, 1-40. https://doi.org/10.1007/978-1-4614-7906-2_1

Sciubba, E., Bastianoni, S., & Tiezzi, E. (2008). Exergy and extended exergy accounting of very large complex systems with an application to the province of Siena, Italy. Journal of environmental Management, 86(2), 372-382. doi:10.1016/j.jenvman.2006.04.016

Sefeedpari, P. (2012). Assessment and optimization of energy consumption in dairy farm: energy efficiency. Iranica Journal of Energy & Environment, 3(3). DOI: 10.5829/idosi.ijee.2012.03.03.0924

Sellahewa, J., & Martindale, W. (2010). The impact of food processing on the sustainability of the food supply chain. Delivering food security with supply chain led innovations: understanding supply chains, providing food security, delivering choice, Royal Holloway, Egham, UK, 7-9 September 2010, Conference paper: Aspects of Applied Biology, 2010, No.102, 91-97 ref. 26.

Senyapar, H. N. D. (2023). Renewable Energy Literature in Türkiye: Mapping Analysis of the Field and Future Study Suggestions on Overlooked Issues. International Journal of Renewable Energy Research, 13(1), 221-235.

Shahbandeh, M. (2023), World vegetable production in 2021, by type. Statista., <https://www.statista.com/statistics/264065/global-production-of-vegetables-by-type/>. Accessed date: 01.12.2023

Shahvarooghi Farahani, S., Soheilifard, F., Ghasemi Nejad Raini, M., & Kokei, D. (2019). Comparison of different tomato puree production phases from an environmental point of view. The International Journal of Life Cycle Assessment, 24(10), 1817-1827. <https://doi.org/10.1007/s11367-019-01613-x>

Sharma, R., Joshi, V. K., & Kaushal, M. (2015). Effect of pre-treatments and drying methods on quality attributes of sweet bell-pepper (*Capsicum annum*) powder. Journal of Food Science and Technology, 52(6), 3433-3439. <https://doi.org/10.1007/s13197-014-1374-y>

Sheikhshoei, H., Dowlati, M., Aghbashlo, M., & Rosen, M. A. (2020). Exergy analysis of a pistachio roasting system. Drying Technology, 38(12), 1565-1583. <https://doi.org/10.1080/07373937.2019.1649276>

Shen, S., & Wu, J. S. (2018). Processing of vegetable juices and blends. Siddiq, M., Uebersax M.A., (2nd Edition). Handbook of Vegetables and Vegetable Processing, John Wiley & Sons, Oxford, U.K. <https://doi.org/10.1002/9781119098935>, 429-449.

Shimako, A. H., Tiruta-Barna, L., de Faria, A. B. B., Ahmadi, A., & Spérandio, M. (2018). Sensitivity analysis of temporal parameters in a dynamic LCA framework. Science of the total environment, 624, 1250-1262. <https://doi.org/10.1016/j.scitotenv.2017.12.220>

Sica, D., Malandrino, O., & Supino, S. (2018). The corporate social responsibility in the Italian agro-food sector. *Journal of Health Science*, 6, 358-364. <https://doi.org/10.17265/2328-7136/2018.05.005>

Sieti, N., Schmidt Rivera, X. C., Stamford, L., & Azapagic, A. (2019). Environmental sustainability assessment of ready-made baby foods: Meals, menus and diets. *Science of Total Environment*, 689, 899-911. <https://doi.org/10.1016/j.scitotenv.2019.06.363>

Singh, S., Singh, S., Mittal, J. P., & Pannu, C. J. S. (1998). Frontier energy use for the cultivation of wheat crop in Punjab. *Energy Conversion and Management*, 39(5-6), 485-491. [https://doi.org/10.1016/S0196-8904\(96\)00234-8](https://doi.org/10.1016/S0196-8904(96)00234-8)

Sinha, E., Calvin, K. V., Kyle, P. G., Hejazi, M. I., Waldhoff, S. T., Huang, M., Vishwakarma, S., & Zhang, X. (2022). Implication of imposing fertilizer limitations on energy, agriculture, and land systems. *Journal of environmental management*, 305, 114391. <https://doi.org/10.1016/j.jenvman.2021.114391>

Smith, M., & Lal, P. (2022). Environmental and economic assessment of hard apple cider using an integrated LCA-LCC approach. *Sustainable Production and Consumption*, 32, 282-295. <https://doi.org/10.1016/j.spc.2022.04.026>

Smith, P., Nkem, J., Calvin, K., Campbell, D., Cherubini, F., Grassi, G., McElwee, P. (2019). IPCC SRCCL chapter 6: Interlinkages between desertification, land degradation, food security and GHG fluxes: Synergies, trade-offs and integrated response options. IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. <https://dx.doi.org/10.1017/9781009157988.008>

So, K. H., Park, J. A., Huh, J. H., Shim, K. M., Ryu, J. H., Kim, G. Y., & Lee, D. B. (2010). Estimation of carbon emission and LCA (Life Cycle Assessment) from pepper (*Capsicum annuum* L.) production system. *Korean Journal of Soil Science and Fertilizer*, 43(6), 904-910.

Sofizadeh, T., Khodaei, J., Darvishi, H., Behrooz-Khazaei, N., & Koushesh Saba, M. (2023). Process parameters of microwave heating-assisted vacuum evaporation of tomato juice: quality, energy consumption, exergy performance, and kinetic processing. *Journal of Microwave Power and Electromagnetic Energy*, 57(3), 203-218. <https://doi.org/10.1080/08327823.2023.2235551>

Sogut, Z., Ilten, N., & Oktay, Z. (2010). Energetic and exergetic performance evaluation of the quadruple-effect evaporator unit in tomato paste production. *Energy*, 35(9), 3821-3826. <https://doi.org/10.1016/j.energy.2010.05.035>

Soheili-Fard, F., Kouchaki-Penchah, H., Raini, M. G. N., & Chen, G. N. (2018). Cradle to grave environmental-economic analysis of tea life cycle in Iran. *Journal of Cleaner Production*, 196, 953-960. <https://doi.org/10.1016/j.jclepro.2018.06.083>

Solimene, S., Coluccia, D., & Bernardo, A. (2023). Environmental Impact of Different Business Models: An LCA Study of Fresh Tomato Production in Italy. *Sustainability*, 15(13), 10365. <https://doi.org/10.3390/su151310365>

Solomon, B. D., & Banerjee, A. (2006). A global survey of hydrogen energy research, development and policy. *Energy Policy*, 34(7), 781-792. <https://doi.org/10.1016/j.enpol.2004.08.007>

Solomon, S., Mills, M., Heidt, L., Pollock, W., & Tuck, A. (1992). On the evaluation of ozone depletion potentials. *Journal of Geophysical Research: Atmospheres*, 97(D1), 825-842. <https://doi.org/10.1029/91JD02613>

Sorguven, E., & Ozilgen, M. (2010). Thermodynamic assessment of algal biodiesel utilization. *Renewable Energy*, 35(9), 1956-1966. <https://doi.org/10.1016/j.renene.2010.01.024>

Sorgüven, E., & Özilgen, M. (2012). Energy utilization, carbon dioxide emission, and exergy loss in flavored yogurt production process. *Energy*, 40(1), 214-225. <https://doi.org/10.1016/j.energy.2012.02.003>

Soufiyan, M. M., Dadak, A., Hosseini, S. S., Nasiri, F., Dowlati, M., Tahmasebi, M., & Aghbashlo, M. (2016). Comprehensive exergy analysis of a commercial tomato paste plant with a double-effect evaporator. *Energy*, 111, 910-922. <https://doi.org/10.1016/j.energy.2016.06.030>

Soysal, Y., Ayhan, Z., Eştürk, O., & Arıkan, M. (2009). Intermittent microwave-convective drying of red pepper: Drying kinetics, physical (colour and texture) and sensory quality. *Biosystems Engineering*, 103(4), 455-463. <https://doi.org/10.1016/j.biosystemseng.2009.05.010>

Srivastava, S., & Kulshreshtha, K. (2013). Nutritional content and significance of tomato powder. *Annals of Arid Zone*, 52(2), 121-124.

Stefanini, R., Borghesi, G., Ronzano, A., & Vignali, G. (2021). Plastic or glass: a new environmental assessment with a marine litter indicator for the comparison of pasteurized milk bottles. *The International Journal of Life Cycle Assessment*, 26, 767-784. <https://doi.org/10.1007/s11367-020-01804-x>

Sun, X. Y., Newham, L. T. H., Croke, B. F. W., & Norton, J. P. (2012). Three complementary methods for sensitivity analysis of a water quality model. *Environmental Modelling & Software*, 37, 19-29. <https://doi.org/10.1016/j.envsoft.2012.04.010>

Swart, P., Alvarenga, R.A.F., Dewulf, J. (2015). Abiotic Resource Use. In: Hauschild, M., Huijbregts, M. (eds) *Life Cycle Impact Assessment. LCA Compendium-The Complete World of Life Cycle Assessment*. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-9744-3_13

Szargut, J. (1987a). Analysis of Cumulative Exergy Consumption. *International Journal of Energy Research*, 11(4), 541-547. <https://doi.org/10.1002/er.4440110410>

Szargut, J., & Morris, D. R. (1987b). Cumulative Exergy Consumption and Cumulative Degree of Perfection of Chemical Processes. *International Journal of Energy Research*, 11(2), 245-261. doi:DOI 10.1002/er.4440110207

Szargut, J., Morris, D. R., & Steward, F. R. (1988). Exergy analysis of thermal, chemical, and metallurgical processes (Vol. 41): Springer.

Şanlı, B. G., & Uludamar, E. (2020). Energy and exergy analysis of a diesel engine fuelled with diesel and biodiesel fuels at various engine speeds. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 42(11), 1299-1313. <https://doi.org/10.1080/15567036.2019.1635229>

Teixeira, A. A., & Tucker, G. S. (1997). On-line retort control in thermal sterilization of canned foods. *Food Control*, 8(1), 13-20. [https://doi.org/10.1016/S0956-7135\(96\)00056-4](https://doi.org/10.1016/S0956-7135(96)00056-4)

The European Green Deal (2019). European Commission Brussels, Belgium. https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6691. Accessed date: 10.01.2023

Tola, Y. B., & Ramaswamy, H. S. (2012). Thermal processing principles. *Food Biochemistry and food processing*, 725-745. <https://doi.org/10.1002/9781118308035.ch38>

Torshizi, M. V., Azadbakht, M., & Kashaninejad, M. (2020). Application of response surface method to energy and exergy analyses of the ohmic heating dryer for sour orange juice. *Fuel*, 278, 118261. <https://doi.org/10.1016/j.fuel.2020.118261>

Tukker, A., Huppes, G., Guinée, J., Heijungs, R., Koning, A.d., Oers, L.v., Suh, S., Geerken, T., Holderbeke, v.M., Jansen, B., (2006). Environmental Impact of Products (EIPRO) Analysis of the life cycle environmental impacts related to the final consumption of the EU-25. Environmental Impact of Products (EIPRO) Analysis of the life cycle environmental impacts related to the final consumption of the EU-25, 1-136.

Turkish Food Codex, Ministry of Agriculture and Forestry, (2014). Turkish Food Codex Communiqué on tomatoes and red pepper paste and puree, Official Journal, 14 June 2014,29030.https://www.tarimorman.gov.tr/GKGM/Belgeler/Mevzuat/%C4%B0ngilizce%20Mevzuat/Turkish_Food_Codex_Legislation.docx. (In Turkish), [Access date: 10.07.2024]

TUIK, Turkish Statistical Institute Data (2022), <https://data.tuik.gov.tr/Bulten/Index?p=Bitkisel-Uretim-Istatistikleri-2022-45504> (In Turkish), [Access date: 13.08.2024].

Turkish Statistical Institute Data, March Report (2023), Foreign Trade Statistics, 49623, <https://data.tuik.gov.tr/Bulten/Index?p=Dis-Ticaret-Istatistikleri-Mart-2023-49623>, (In Turkish), [Access date: 25.09.2023].

Uçal, E., Yildizhan, H., Ameen, A., & Erbay, Z. (2023). Assessment of Whole Milk Powder Production by a Cumulative Exergy Consumption Approach. *Sustainability*, 15(4). <https://doi.org/10.3390/su15043475>

Uppili, B., LaFountain, L. J., & Johanningsmeier, S. D. (2023). A sensory lexicon to characterize the quality of fresh and preserved peppers. *Journal of Food Science*, 88(12), 5216-5235. <https://doi.org/10.1111/1750-3841.16814>

Urbano, B., Barquero, M., & González-Andrés, F. (2022). The environmental impact of fresh tomatoes consumed in cities: A comparative LCA of long-distance transportation and local production. *Scientia Horticulturae*, 301, 111126. <https://doi.org/10.1016/j.scienta.2022.111126>

Uzel, R. A. (2017). Alternative Methods To Preserve Sweet Red Pepper Paste Quality: Effeect of Temperature And Protective Agents. *Anadolu University Journal of Science and Technology A-Applied Sciences and Engineering*, 18(3), 695-704. doi: 10.18038/aubtda.310767

van Oers, L., Guinée, J. B., & Heijungs, R. (2020). Abiotic resource depletion potentials (ADPs) for elements revisited—updating ultimate reserve estimates and introducing time series for production data. *The International Journal of Life Cycle Assessment*, 25, 294-308.

Waheed, M. A., Jekayinfa, S. O., Ojediran, J. O., & Imeokparia, O. E. (2008). Energetic analysis of fruit juice processing operations in Nigeria. *Energy*, 33(1), 35-45. <https://doi.org/10.1016/j.energy.2007.09.001>

Wallace, T. C., Bailey, R. L., Blumberg, J. B., Burton-Freeman, B., Chen, C. O., Crowe-White, K. M., & Wang, D. D. (2020). Fruits, vegetables, and health: A comprehensive narrative, umbrella review of the science and recommendations for enhanced public policy to improve intake. *Critical Reviews in Food Science and Nutrition*, 60(13), 2174-2211. <https://doi.org/10.1080/10408398.2019.1632258>

Wang, L., & Sun, D.-W. (2012). Heat and mass transfer in thermal food processing. In *Thermal Food Processing: New Technologies and Quality Issues* (pp. 33-63): London, New York. CRC Press .

Wang, X., Lu, Y., Chen, C., Yi, X., & Cui, H. (2024). Total-factor energy efficiency of ten major global energy-consuming countries. *Journal of Environmental Sciences*, 137, 41-52. <https://doi.org/10.1016/j.jes.2023.02.031>

Wang, X., Liu, B., Wu, G., Sun, Y., Guo, X., Jin, Z., & Chen, X. (2018). Environmental costs and mitigation potential in plastic-greenhouse pepper production system in China: A life cycle assessment. *Agricultural Systems*, 167, 186-194. <https://doi.org/10.1016/j.agsy.2018.09.013>

Wittmus, H., Olson, L., & Lane, D. (1975). Energy requirements for conventional versus minimum tillage. *Journal of Soil and Water Conservation*, 30(2), 72-75.

Wohner, B., Gabriel, V. H., Krenn, B., Krauter, V., & Tacker, M. (2020). Environmental and economic assessment of food-packaging systems with a focus on food waste. Case study on tomato ketchup. *Science of Total Environment*, 738, 139846. <https://doi.org/10.1016/j.scitotenv.2020.139846>

Wojdalski, J., Drozd, B., & Lubach, M. (2007). Factors influencing electrical energy consumption in fruit and vegetables processing plants. *Polish Journal of Food and Nutrition Sciences*, 57(2 [A]), 195-199.

Worrell, E., Meuleman, B., & Blok, K. (1995). Energy savings by efficient application of fertilizer. *Resources, conservation and recycling*, 13(3-4), 233-250. [https://doi.org/10.1016/0921-3449\(94\)00045-7](https://doi.org/10.1016/0921-3449(94)00045-7)

Worrell, E., Phylipsen, D., Einstein, D., & Martin, N. (2000). Energy use and energy intensity of the US chemical industry. <https://escholarship.org/uc/item/2925w8g>

Wu, Y., Si, W., Yan, S., Wu, L., Zhao, W., Zhang, J., Fan, J. (2023). Water consumption, soil nitrate-nitrogen residue and fruit yield of drip-irrigated greenhouse tomato under various irrigation levels and fertilization practices. *Agricultural Water Management*, 277, 108092. <https://doi.org/10.1016/j.agwat.2022.108092>.

Xu, H., Ou, L., Li, Y., Hawkins, T. R., & Wang, M. (2022). Life cycle greenhouse gas emissions of biodiesel and renewable diesel production in the United States. *Environmental Science & Technology*, 56(12), 7512-7521. <https://doi.org/10.1021/acs.est.2c00289>

Yadav, P., & Jana, A. K. (2010). Simulation and control of a commercial double effect evaporator: tomato juice. *Chemical Product and Process Modeling*, 5(1). <https://doi.org/10.2202/1934-2659.1443>

Yang, M., Vladimirova, D., & Evans, S. (2017). Creating and Capturing Value Through Sustainability: The Sustainable Value Analysis Tool A new tool helps companies discover opportunities to create and capture value through sustainability. *Research-Technology Management*, 60(3), 30-39. <https://doi.org/10.1080/08956308.2017.1301001>

Yelmen, B. (2019). Energy Efficiency and Economic Analysis in Tomato Production: A Case Study of Mersin Province in the Mediterranean Region. *Applied Ecology and Environmental Research*, 17(4), 7371-7379. doi:10.15666/aeer/1704_73717379

Yelmen, B., Çakir, M., & Şahin, H. (2019). Performance evaluation of greenhouse type dryers for red pepper: technical and economic aspect. *Advances in Research*, 20(2), 1-13. <https://doi.org/10.9734/air/2019/v20i230152>

Yıldırım, D., & Cemek, B. (2013). Effects of Different Irrigation Treatments On Growth, Yield and Quality Parameters of Pepper Under greenhouse Conditions. A 437 Актуальные проблемы науки и агропромышленного комплекса в процессе европейской интеграции, Международная науч.-практичес, 152.

Yılmaz-Ozdere, B., (2023). Drying of Capia Pepper and Its Wastes in Different Conditions with Zero Waste Approach (Master's Thesis). Ege University, Institute of Science and Technology (In Turkish).

Yildiz, G., & Izli, G. (2020). Microwave and Hot Air Methods in Drying Foods. *İksad Yayınevi, Ankara, Türkiye*, 128p. (In Turkish)

Yildizhan, H., & Taki, M. (2018). Assessment of tomato production process by cumulative exergy consumption approach in greenhouse and open field conditions: Case study of Türkiye. *Energy*, 156, 401-408. doi:10.1016/j.energy.2018.05.117

Zarei, M. J., Kazemi, N., & Marzban, A. (2019). Life cycle environmental impacts of cucumber and tomato production in open-field and greenhouse. *Journal of the Saudi Society of Agricultural Sciences*, 18(3), 249-255. <https://doi.org/10.1016/j.jssas.2017.07.001>

Zheng, X., Lu, Y., Yuan, J., Baninla, Y., Zhang, S., Stenseth, N. C., & Ma, D. (2020). Drivers of change in China's energy-related CO₂ emissions. *Proceedings of the National Academy of Sciences*, 117(1), <https://doi.org/10.1073/pnas.1908513117>



APPENDICES

APPENDIX A-Mass balances calculations

APPENDIX B-Cumulative energy, exergy and CO₂ emissions for each steps of the tomato products production

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APPENDIX A

Mass balances calculations

Tomato juice factory processing mass balances

1. Washing



% 93 H₂O, %7 Dm

* Washing is carried out 3-5 times as much water as the tomato (Latini, Giagnacovo, Campiotti, Bernardini, & Fuentes-Pila, 2017). Three times was assumed in this study.

w₁: inlet washing water, w₁:9000 kg/h

w₂: outlet washing water

x₁:inlet tomato mass, x₁:3000 kg/h

x₂:outlet tomato mass, x₂: 3000 kg/h =y₁

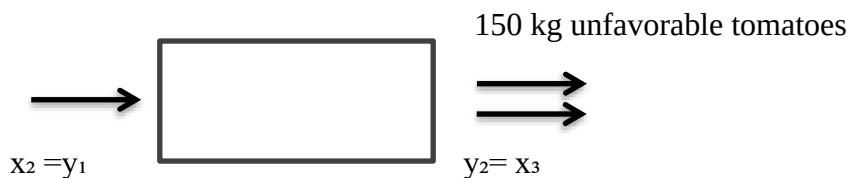
System inlet = System outlet

$$x_1 + w_1 = x_2 + w_2$$

$$3000+9000=9000+x_2$$

$$x_2 = 3000 \text{ kg/h} = y_1$$

2. Sorting



5% of tomatoes are sorted as waste (Karakaya and Özilgen, 2011).

$$y_1 = y_2 + (0.05 * 3000)$$

$$y_2 = 3000 - (0.05 * 3000), y_2 = 2850 \text{ kg/h}$$



150 kg of unfavorable tomatoes are ground and recycled for use as fertilizer. They are packed in 50 g polylactic acid bags (Karakaya ve Özilgen, 2011).

Waste shredder (Karakaya ve Özilgen, 2011):

Capacity: 500-2000 kg/h, Energy use: 324 MJ/h

Polilactic bag :

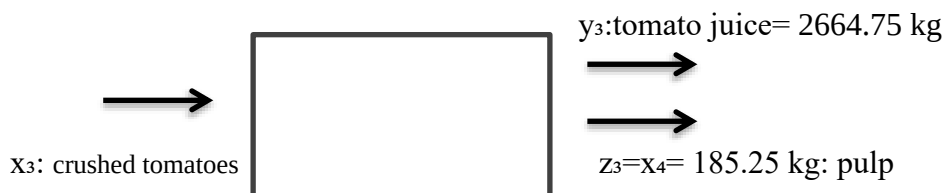
Ecenrgy use: 54 MJ/kg polilactic bag

CO₂ emission: 1.8 kg CO₂/ kg polylactic bag

Total energy use: 164.7 MJ/ton tomato → For 3 ton:494.1 MJ

CO₂ emission: 22.8 kg CO₂/ton tomato → For 3 ton:68.4 kg CO₂

3. Pulper

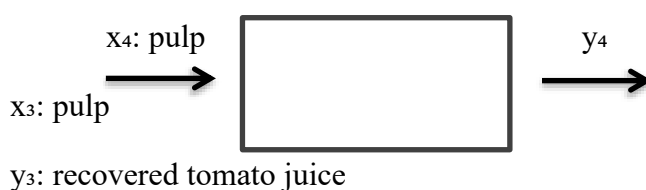


* 6.5% of tomatoes were considered as pulp (FAO, 2009).

$$2850 = (2850 * 0.065) + y_3$$

$$y_3 = 2664.75 \text{ kg tomato juice}$$

4. Refiner



z_3 : dewatered solid waste

* Tomato pulp and skins were found to contain high moisture content (about 80%).

x_4 : 185.25 kg

y_4 = pulp moisture*refinery efficiency

$$y_4 = 0.8 * 185.25 * 0.95$$

$$y_4 = 140.79 \text{ kg}$$

5. Homogenizer



$$y_5 = x_5 + z_5$$

$$y_5 = 2664.75 + 140.79$$

$$y_5 = 2805.54 \text{ kg} = x_6$$

2. Tomato paste production factory processing mass balances

1. Washing



% 93 H₂O, %7 Dm

* Washing is carried out 3-5 times as much water as the tomato (Latini et al., 2017). Three times was assumed in this study.

w_1 : inlet washing water, w_1 : 9000 kg/h

w_2 : outlet washing water

x_1 : inlet tomato mass, x_1 : 3000 kg/h

x_2 :outlet tomato mass, x_2 : 3000 kg/h = y_1

System inlet = System outlet

$$x_1 + w_1 = x_2 + w_2$$

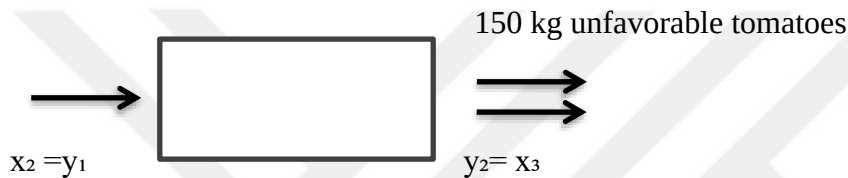
$$3000 + 9000 = 9000 + x_2$$

$$x_2 = 3000 \text{ kg/h} = y_1$$

$$3000 + 9000 = 9000 + x_2$$

$$x_2 = 3000 \text{ kg/h} = y_1$$

2. Sorting



5% of tomatoes are sorted as waste (Karakaya and Özilgen, 2011).

$$y_1 = y_2 + (0.05 * 3000)$$

$$y_2 = 3000 - (0.05 * 3000)$$

$$y_2 = 2850 \text{ kg/h}$$



*150 kg of unfavorable tomatoes are ground and recycled for use as fertilizer. They are packed in 50 g polylactic acid bags (Karakaya ve Özilgen, 2011).

Waste shredder (Karakaya ve Özilgen, 2011):

Capacity: 500-2000 kg/h, Energy use: 324 MJ/h

Polilactic bag:

Ecenrgy use: 54 MJ/kg polilactic bag

CO₂ emission: 1.8 kg CO₂/ kg polylactic bag

Total energy use: 164.7 MJ/ton tomato → For 3 ton:494.1 MJ

CO₂ emission: 22.8 kg CO₂/ton tomato → For 3 ton:68.4 kg CO₂

3. Pulper



* 6.5% of tomatoes were considered as pulp (FAO, 2009).

$$2850 = (2850 \times 0.065) + y_3$$

$$y_3 = 2664.75 \text{ kg tomato juice}$$

4. Refiner



x_3 : pulp

y_3 : recovered tomato juice

z_3 : dewatered solid waste

* Tomato pulp and skins were found to contain high moisture content (about 80%).

x_4 : 185.25 kg

y_4 = pulp moisture*refinery efficiency

$$y_4 = 0.8 \times 185.25 \times 0.95$$

$$y_4 = 140.79 \text{ kg}$$

5. Homogenizer



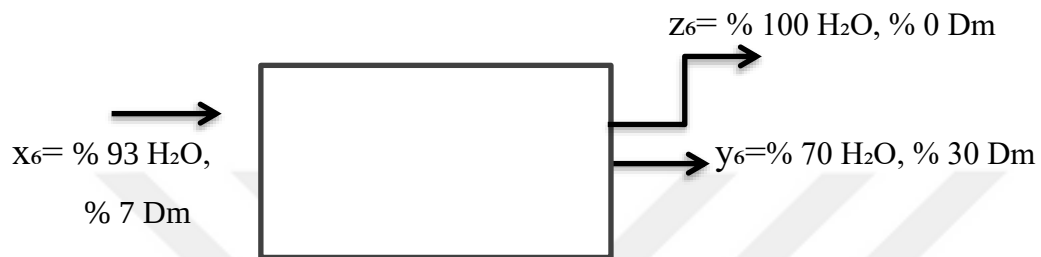
Z_5

$$y_5 = x_5 + Z_5$$

$$y_5 = 2664.75 + 140.79$$

$$y_5 = 2805.54 \text{ kg} = x_6$$

6. Evaporator



y_6 : tomato paste

Z_6 : evaporating water

x_6 : 2805.54 kg

Component balance:

$$2805.54 \cdot (0.93) = z_6 + (y_6 \cdot 0.7) \quad (1)$$

$$2805.54 \cdot (0.07) = 0 + (y_6 \cdot 0.3) \quad (2)$$

y_6 : 654.626 kg /h tomato paste is obtained.

$$X = 3000 / 654.626$$

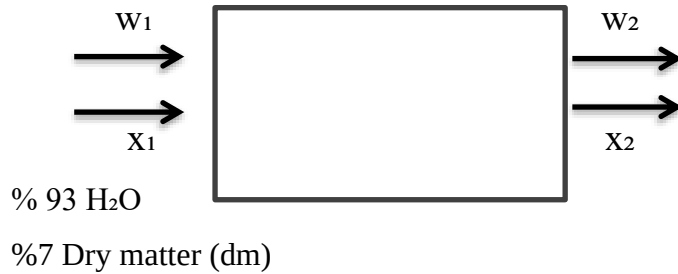
$X = 4.583$ kg of tomatoes processed to obtain 1 kg of tomato paste.

Table A 1. Mass flows obtained at each step in tomato paste production

Equipment	Mass flow rate (per 3000 kg feed)	Mass flow rate (per 1000 kg feed)
Mechanical water filter	3000	1000
Washing machine	3000	1000
Mechanical water filter	9000	3000
Elevator	3000	1000
Selecting and collecting conveyor	3000	1000
Collector elevator	2850	950
Waste shredder	150	50
Crusher (Fruit mill) (Water consumption: 5-7 ton)	2850	950
Mono pump	2805.54	935.18
Heat exchanger	2805.54	935.18
Turbo Extractor	2805.54	935.18
Pulp discharge screw	189.25	63.08
Pulp collecting tank and pump	2805.54	935.18
Evaporator (Electricity)	2805.54	935.18
Evaporator (Natural gas)	2805.54	935.18
Vacuum vessel	2805.54	935.18
Cooling water consumption: 3 ton/h	2805.54	935.18
Steam generator	654.626	218.21
Tubular sterilization machine (Electricity)	654.326	218.21
Tubular sterilization machine (Natural gas)	654.626	218.21
Aseptic filling (Electricity)	654.626	218.21
Aseptic filling (Natural gas)	654.626	218.21

3. Roasted SRP Factory Processing Mass Balances

1. Washing



* Red pepper is washed with three times the amount of water (Baysal, Güreş, & Yurdagel, 1990).

W₁: inlet washing water, W₁:9000 kg/h

W₂: outlet washing water

X₁:inlet SRP mass, X₁:3000 kg/h

X₂:outlet SRP mass , X₂: 3000 kg/h =y₁

Inlet mass = Outlet mass

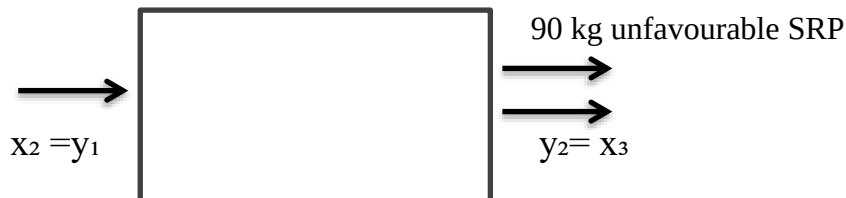
$$X_1 + W_1 = X_2 + W_2$$

$$3000+9000=9000+X_2$$

$$X_2 = 3000 \text{ kg/h} = y_1$$

2. Sorting

The waste produced during the selection and sorting of red peppers for roasted SRP production amounts to approximately 3% (Büğülü, 2023).

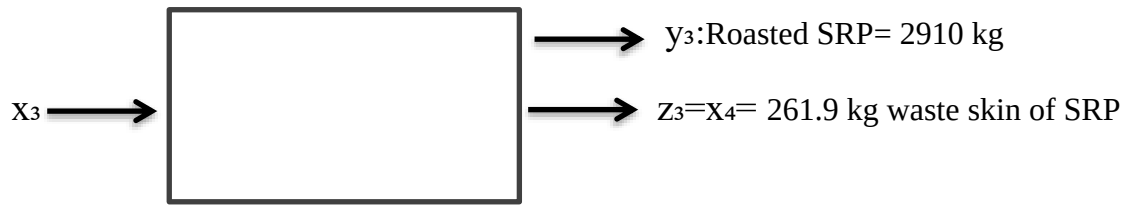


3 % of the SRP is separated as waste (Büğülü, 2023)

$$y_1 = y_2 + (0.03 \cdot 3000)$$

$$y_2 = 3000 - (0.03 \cdot 3000) \quad y_2 = 2910 \text{ kg/h}$$

3. Roasting tunnel



The roots and outer skins of the vegetables are incinerated in the process. On average, a loss of 9% of the product occurs (Doğaka, 2017).

x_3 : Roasted SRP

$z_3=x_4= 261.9$ kg waste

* 9 % of SRP is assumed to be waste skin of roasted SRP

$$2910 = (2910 \cdot 0.09) + y_3$$

$y_3 = 2648.1$ kg Roasted SRP is obtained.

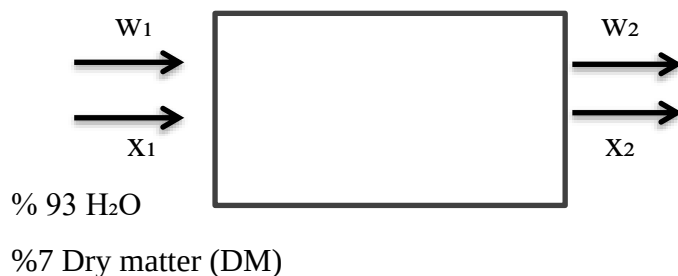
Finally;

$((3000 \text{ kg/h})/2648.1) = 1$ kg of roasted SRP is obtained from 1.133 kg of fresh SRP.

Finally, 882.612 kg of roasted SRP is obtained from 1 ton fresh SRP.

4.Dried Sweet Red Pepper Factory Processing Mass Balances

1. Washing



* Red pepper is washed with three times the amount of water (Baysal et al., 1990).

w_1 : inlet washing water, w_1 :9000 kg/h

W₂: outlet washing water

x₁:inlet SRP mass, x₁:3000 kg/h

x₂:outlet SRP mass , x₂: 3000 kg/h =y₁

Inlet mass = Outlet mass

$$x_1 + w_1 = x_2 + w_2$$

$$3000+9000=9000+x_2$$

$$x_2 = 3000 \text{ kg/h} = y_1$$

2. Sorting

The waste produced during the selection and sorting of red peppers for dried red pepper production amounts to approximately 3% (Büğülü, 2023).

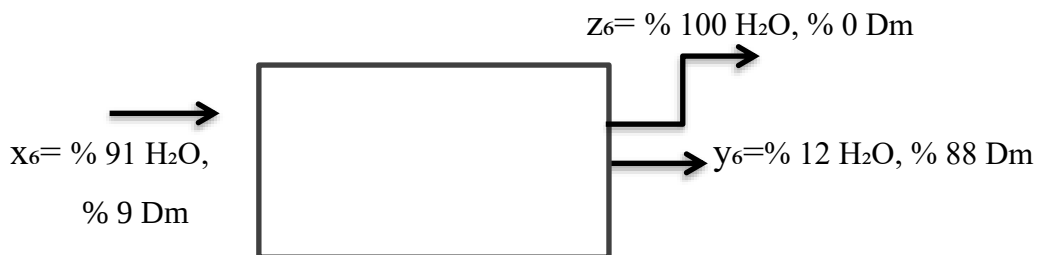


3% of the SRP is separated as waste (Büğülü, 2023)

$$y_1 = y_2 + (0.03 \cdot 3000)$$

$$y_2 = 3000 - (0.03 \cdot 3000) \quad y_2 = 2910 \text{ kg/h}$$

3. Drying oven



y₆: Dried SRP

z₆:evaporating water

x₆: 2910 kg

4.Component balance equations

$$2910*(0.91) = z_6 + (y_6*0.12)$$

$$2910*(0.09)=0 + (y_6*0.88)$$

y_6 : 297.6136 kg /h Dried SRP is obtained.

$((3000 \text{ kg/h})/297.6136)= 10.0801$ kg of fresh SRP.

Daily production capacity = $72.000 \text{ kg}/10.0801= 7.1427$ kg Dried SRP is produced.

$(7.1427 \text{ ton/ day})*120 \text{ day}= 857.1343$ ton/year Dried SRP producing capacity is obtained.

Finally, 99.2053 kg of Dried SRP is obtained from 1 ton fresh SRP.

APPENDIX B

Cumulative energy, exergy and CO₂ emissions for each steps of the tomato products production

1. Retail tomato

1.1. Tomato farming step cumulative energy, exergy and CO₂ emissions with different improvement scenarios for retail tomato production

Table B. 1. BC tomato farming cumulative energy, exergy and CO₂ emission results

Input (Unit)	CEnC (MJ/ton)	CExC (MJ/ton)	CCO ₂ C (kg/ton)
Fertilizer (kg)			
Nitrogen (N)	233.04	97.45	0.27
Phosphorus (P ₂ O ₅)	53.20	22.86	0.46
Potassium (K ₂ O)	15.32	5.06	0.57
Chemicals (kg)			
Pesticides	7.95	0.30	0.20
Fungicides	15.90	0.36	0.31
Herbicides	3.98	0.65	0.13
Diesel (kg)	359.95	333.03	19.91
Water for irrigation (kg)	31.44	131.01	18.34
Electricity (MJ/MJ)	124.55	519.37	17.44
Human labor (MJ)	0.43	16.94	0.21
Machinery (h)	7.37	30.73	0.03
Transport (MJ/kg)	170.41	151.43	11.38
Total	1023.54	1309.21	69.24

Table B. 2. PF tomato farming cumulative energy, exergy and CO₂ emission results

Input (Unit)	CEnC (MJ/ton)	CExC (MJ/ton)	CCO ₂ C (kg/ton)
Fertilizer (kg)			
Nitrogen (N)	116.52	48.72	0.13
Phosphorus (P ₂ O ₅)	26.60	11.43	0.23
Potassium (K ₂ O)	7.66	2.53	0.28
Chemicals (kg)			
Pesticides	7.95	0.30	0.20
Fungicides	15.90	0.36	0.31
Herbicides	3.98	0.65	0.13
Diesel (kg)	359.95	333.03	19.91
Water for irrigation (kg)	31.44	131.01	18.34
Electricity (MJ/MJ)	124.55	519.37	17.44
Human labor (MJ)	0.43	16.94	0.21
Machinery (h)	7.37	30.73	0.03
Transport (MJ/kg)	170.41	151.43	11.38
Total	872.76	1246.52	68.59

Table B. 3. BD tomato farming cumulative energy, exergy and CO₂ emission results

Input (Unit)	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Fertilizer (kg)			
Nitrogen (N)	233.04	97.45	0.27
Phosphorus (P ₂ O ₅)	53.20	22.86	0.46
Potassium (K ₂ O)	15.32	5.06	0.57
Chemicals (kg)			
Pesticides	7.95	0.30	0.20
Fungicides	15.90	0.36	0.31
Herbicides	3.98	0.65	0.13
Diesel (kg)	88.51	21.05	2.32
Water for irrigation (kg)	31.44	131.01	18.34
Electricity (MJ/MJ)	124.55	519.37	17.44
Human labor (MJ)	0.43	16.94	0.21
Machinery (h)	7.37	30.73	0.03
Transport (MJ/kg)	50.62	12.04	1.33
Total	632.30	857.83	41.59

1.2.Packaging and transportation step cumulative energy, exergy and CO₂ emissions with different improvement scenarios for retail tomato production

Table B. 4. BC tomato packaging and transportation step cumulative energy, exergy and CO₂ emission results

Input	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Carton printing and boxing machine	0.02	0.26	0.01
Carton filling machine	1.44	19.86	0.86
Palletizing machine	0.29	3.97	0.17
PE	2.79	25.80	0.14
Carton	90.00	187.11	6.79
500 km transport	2200.31	1955.32	147.00
Total	2296.59	2192.32	154.96

Table B. 5. BD tomato packaging and transportation step cumulative energy, exergy and CO₂ emission results

Input	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Carton printing and boxing machine	0.02	0.26	0.01
Carton filling machine	1.44	19.86	0.86
Palletizing machine	0.29	3.97	0.17
PE	2.79	25.80	0.14
Carton	90.00	187.11	6.79
500 km transport	653.57	155.44	17.13
Total	748.10	392.45	25.10

2. Tomato juice

2.1. Factory processing step cumulative energy, exergy and CO₂ emissions with different improvement scenarios for tomato juice production

Table B. 6. BC factory processing step cumulative energy, exergy and CO₂ emission results

Equipment	CEnC (MJ/ton)	CExC (MJ/ton)	CCO ₂ C (kg/ton)
Fruit-vegetable loading pool	1.45	20.02	0.86
Washing machine/ Blower	1.19	16.51	0.71
Washing machine / Reductor	0.87	12.01	0.52
Mechanical water filter	0.49	6.76	0.29
Elevator	0.4	5.5	0.24
Selecting and collecting conveyor	0.27	3.75	0.16
Elevator with collecting	0.15	2.14	0.09
Waste shredder machine	0.15	39.22	5.83
Crushing machine (Fruit mill))	2.84	135.11	1.69
Mono pump	0.77	10.67	0.46
Heat exchanger	1.12	15.44	0.67
Turbo Extractor	0.3	4.21	0.18
Pulp discharge screw	0.04	0.52	0.02
Pulp collecting tank and pump	11.34	156.77	6.77
Steam generator	5.08	70.19	3.03
Aseptic filling	0.75	10.29	0.44
Deaerator	1.43	19.74	0.85
Tubular sterilization machine (Electricity)	25.4	350.97	15.15
Tubular sterilization machine (Natural gas)	3039.33	2916.96	151.97
Aseptic filling	40.89	38.09	2.04
Total	3160.72	4333.69	213.49

Table B. 7. BD factory processing step cumulative energy, exergy and CO₂ emission results

Equipment	CEnC (MJ/ton)	CExC (MJ/ton)	CCO ₂ C (kg/ton)
Fruit-vegetable loading pool	1.45	20.02	0.86
Washing machine/ Blower	1.19	16.51	0.71
Washing machine / Reductor	0.87	12.01	0.52
Mechanical water filter	0.49	6.76	0.29
Elevator	0.40	5.50	0.24
Selecting and collecting conveyor	0.27	3.75	0.16
Elevator with collecting	0.15	2.14	0.09
Waste shredder machine	0.15	39.22	5.83
Crushing machine (Fruit mill))	2.84	135.11	1.69
Mono pump	0.77	10.67	0.46
Heat exchanger	1.12	15.44	0.67
Turbo Extractor	0.30	4.21	0.18
Pulp discharge screw	0.04	0.52	0.02
Pulp collecting tank and pump	11.34	156.77	6.77
Steam generator	5.08	70.19	3.03
Aseptic filling	0.75	10.29	0.44
Deaerator	1.43	19.74	0.85
Tubular sterilization machine (Biodiesel)	975.71	576.99	40.06
Aseptic filling (Biodiesel)	12.67	3.01	0.33
Total	1017.02	1108.85	63.21

2.2.Packaging and transportation step cumulative energy, exergy and CO₂ emissions with different improvement scenarios for tomato juice production

Table B. 8. BC factory processing step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Tin can filling machine	6.12	84.57	3.65
Carton printing and box making machine	0.08	1.08	0.05
Carton filling machine	5.95	82.22	3.55
Palletizing machine	1.19	16.44	0.71
PE	31.43	290.69	1.52
Steel	427.92	3166.59	42.75
Cardboard	16.15	33.57	1.22
Transportation	2200.31	1955.32	147.00
Total	2689.15	5630.49	200.44

Table B. 9. BD factory processing step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Tin can filling machine	6.12	84.57	3.65
Carton printing and box making machine	0.08	1.08	0.05
Carton filling machine	5.95	82.22	3.55
Palletizing machine	1.19	16.44	0.71
PE	31.43	290.69	1.52
Steel	427.92	3166.59	42.75
Cardboard	16.15	33.57	1.22
Transportation	653.57	155.44	17.13
Total	1142.41	3830.61	70.58

Table B. 10. GP factory processing step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Tin can filling machine	6.12	84.57	3.65
Carton printing and box making machine	0.08	1.08	0.05
Carton filling machine	5.95	82.22	3.55
Palletizing machine	1.19	16.44	0.71
PE	3.22	29.76	0.16
Glass packaging	3528.00	5863.20	163.80
Cardboard	496.18	69.77	60.47
Transportation	2200.31	1955.32	147.00
Total	6241.04	8102.36	379.38

Table B. 11. GP-BD factory processing step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Tin can filling machine	6.12	84.57	3.65
Carton printing and box making machine	0.08	1.08	0.05
Carton filling machine	5.95	82.22	3.55
Palletizing machine	1.19	16.44	0.71
PE	3.22	29.76	0.16
Glass packaging	3528.00	5863.20	163.80
Cardboard	496.18	69.77	60.47
Transportation	653.57	155.44	17.13
Total	4694.30	6302.49	249.52

3. Tomato paste

3.1.Factory processing step cumulative energy, exergy and CO₂ emissions with different improvement scenarios for tomato paste production

Table B. 12. BC factory processing step cumulative energy, exergy and CO₂ emission results

Equipment	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Fruit-vegetable loading pool	1.45	20.02	0.86
Washing machine/ Blower	1.19	16.51	0.71
Washing machine / Reductor	0.87	12.01	0.52
Mechanical water filter	0.49	6.76	0.29
Elevator	0.4	5.5	0.24
Selecting and collecting conveyor	0.27	3.75	0.16
Elevator with collecting	0.15	2.14	0.09
Waste shredder machine	0.15	39.22	5.83
Crushing machine (Fruit mill))	2.84	135.11	1.69
Mono pump	0.77	10.67	0.46
Heat exchanger	1.12	15.44	0.67
Turbo Extractor	0.3	4.21	0.18
Pulp discharge screw	0.04	0.52	0.02
Pulp collecting tank and pump	11.34	156.77	6.77
Evaporator (Electricity)	9.14	126.35	5.45
Evaporator (Natural gas)	511.15	476.16	25.56
Vacuum vessel/pump	7.62	105.29	4.54
Vacuum vessel/ Agitator motor reducer	2.24	30.89	1.33
Steam generator	5.08	70.19	3.03
Tubular sterilization machine (Electricity)	5.93	81.89	3.53
Tubular sterilization machine(Natural gas)	715.62	666.63	35.78
Aseptic filling	0.17	2.4	0.1
Aseptic filling (Natural gas)	9.54	8.89	0.48
Total	1287.88	1997.32	98.29

Table B. 13. BD factory processing step cumulative energy, exergy and CO₂ emission results

Equipment	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Fruit-vegetable loading pool	1.45	20.02	0.86
Washing machine/ Blower	1.19	16.51	0.71
Washing machine / Reductor	0.87	12.01	0.52
Mechanical water filter	0.49	6.76	0.29
Elevator	0.40	5.50	0.24
Selecting and collecting conveyor	0.27	3.75	0.16
Elevator with collecting	0.15	2.14	0.09
Waste shredder machine	0.15	39.22	5.83
Crushing machine (Fruit mill)	2.84	135.11	1.69
Mono pump	0.77	10.67	0.46
Heat exchanger	1.12	15.44	0.67
Turbo Extractor	0.30	4.21	0.18
Pulp discharge screw	0.04	0.52	0.02
Pulp collecting tank and pump	11.34	156.77	6.77
Evaporator (Electricity)	9.14	126.35	5.45
Evaporator(Biodiesel)	158.38	37.67	4.15
Vacuum vessel/pump	7.62	105.29	4.54
Vacuum vessel/ Agitator motor reducer	2.24	30.89	1.33
Steam generator	5.08	70.19	3.03
Tubular sterilization machine/ (Electricity)	5.93	81.89	3.53
Tubular sterilization machine(Biodiesel)	221.76	52.74	5.81
Aseptic filling (Electricity)	0.17	2.40	0.10
Aseptik dolum(Bidiesel)	2.96	0.70	0.08
Total	434.66	936.75	46.51

3.2.Packaging and transportation step cumulative energy, exergy and CO₂ emissions with different improvement scenarios for tomato paste production

Table B. 14. BC packaging and transportation step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Tin can filling machine	1.43	19.74	0.85
Carton printing and box making machine	0.02	0.25	0.01
Carton filling machine	1.39	19.18	0.83
Palletizing machine	0.28	3.82	0.16
PE	7.44	68.80	0.36
Steel	100.03	740.24	9.99
Cardboard	3.77	7.60	0.28
Transportation	2200.31	1955.32	147.00
Total	2314.66	2814.95	159.49

Table B. 15. BD packaging and transportation step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Tin can filling machine	1.43	19.74	0.85
Carton printing and box making machine	0.02	0.25	0.01
Carton filling machine	1.39	19.18	0.83
Palletizing machine	0.28	3.82	0.16
PE	7.44	68.80	0.36
Steel	100.03	740.24	9.99
Cardboard	3.77	7.60	0.28
Transportation	653.57	155.44	17.13
Total	767.92	1015.07	29.63

Table B. 16. GP packaging and transportation step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Tin can filling machine	1.43	19.74	0.85
Carton printing and box making machine	0.02	0.25	0.01
Carton filling machine	1.39	19.18	0.83
Palletizing machine	0.28	3.82	0.16
LDPE	125.68	121.76	5.5
Steel	34.95	258.66	3.49
Glass	824.83	1370.78	38.30
Cardboard	80.69	30.75	2.18
Transportation	2200.31	1955.32	147.00
Total	3269.57	3780.26	198.32

Table B. 17. GP-BD packaging and transportation step cumulative energy, exergy and CO₂ emission results

Input	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Tin can filling machine	1.43	19.74	0.85
Carton printing and box making machine	0.02	0.25	0.01
Carton filling machine	1.39	19.18	0.83
Palletizing machine	0.28	3.82	0.16
LDPE	125.68	121.76	5.5
Steel	34.95	258.66	3.49
Glass	824.83	1370.78	38.30
Cardboard	80.69	30.75	2.18
Transportation	653.57	155.44	17.13
Total	1722.83	1980.38	68.46

APPENDIX C

Cumulative energy, exergy and CO₂ emissions for each steps of the sweet red pepper products production

1. Retail sweet red pepper

1.1. SRP farming step cumulative energy, exergy and CO₂ emissions with different improvement scenarios for retail SRP production

Table C. 1. BC farming step cumulative energy, exergy and CO₂ emission results

Inputs and outputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO ₂ C (kg/ton)
Nitrogen (N) (kg)	1771.23	740.66	2.04
Phosphorus (P ₂ O ₅) (kg)	403.85	173.54	3.46
Potassium (K ₂ O) (kg)	199.33	65.86	7.37
Fungicides (kg)	22.86	0.86	0.59
Herbicides (kg)	16.40	0.38	0.32
Insecticides (kg)	14.51	2.39	0.46
Water for irrigation (m ³)	0.09	0.38	0.05
Electricity (kwh)	8.38	115.76	5.00
Human labor (MJ)	0.43	16.94	0.21
Agricultural machinery (Diesel kg)	134.71	119.71	8.98
Transport (Diesel)(MJ/kg)	170.41	151.43	11.36
Total	2742.20	1387.91	39.82

Table C. 2 .BD farming step cumulative energy, exergy and CO₂ emission results

Inputs and outputs	CEnC (MJ/ton)	CexC (MJ/ton)	CCO ₂ C (kg/ton)
Nitrogen (N) (kg)	1771.23	740.66	2.04
Phosphorus (P ₂ O ₅) (kg)	403.85	173.54	3.46
Potassium (K ₂ O) (kg)	199.33	65.86	7.37
Fungicides (kg)	22.86	0.86	0.59
Herbicides (kg)	16.40	0.38	0.32
Insecticides (kg)	14.51	2.39	0.46
Water for irrigation (m ³)	0.09	0.38	0.05
Electricity (kwh)	8.38	115.76	5.00
Human labor (MJ)	0.43	16.94	0.21
Agricultural machinery (Biodiesel)	40.01	9.52	1.05
Transport (Biodiesel)(MJ/kg)	50.62	12.04	1.33
Total	2527.71	1138.32	21.87

Table C. 3. PF farming step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CexC (MJ/ton)	CCO₂C (kg/ton)
Nitrogen (N) (kg)	885.62	370.33	1.02
Phosphorus (P ₂ O ₅)(kg)	201.92	86.77	1.73
Potassium (K ₂ O) (kg)	99.66	32.93	3.68
Fungicides (kg)	22.86	0.86	0.59
Herbicides (kg)	16.40	0.38	0.32
Insecticides (kg)	14.51	2.39	0.46
Water for irrigation (m3)	0.09	0.38	0.05
Electricity (kwh)	8.38	115.76	5.00
Human labor (MJ)	0.43	16.94	0.21
Agricultural machinery(Diesel kg)	134.71	119.71	8.98
Transport (Diesel)(MJ/kg)	170.41	151.43	11.36
Total	1554.99	897.88	33.39

Table C. 4. BD-PF farming step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CexC (MJ/ton)	CCO₂C (kg/ton)
Nitrogen (N) (kg)	885.62	370.33	1.02
Phosphorus (P ₂ O ₅)(kg)	201.92	86.77	1.73
Potassium (K ₂ O) (kg)	99.66	32.93	3.68
Fungicides (kg)	22.86	0.86	0.59
Herbicides (kg)	16.40	0.38	0.32
Insecticides (kg)	14.51	2.39	0.46
Water for irrigation (m3)	0.09	0.38	0.05
Electricity (kwh)	8.38	115.76	5.00
Human labor (MJ)	0.43	16.94	0.21
Agricultural machinery(Biodiesel)	40.01	9.52	1.05
Transport (Biodiesel)(MJ/kg)	50.62	12.04	1.33
Total	1340.51	648.29	15.43

1.2. SRP packaging and transportation step cumulative energy, exergy and CO₂ emissions with different improvement scenarios for retail SRP production

Table C. 5. BC packaging and transportation step cumulative energy, exergy and CO₂ emission results

Input	CEnC (MJ/ton)	CexC (MJ/ton)	CCO₂C (kg/ton)
Carton printing and boxing machine	0.02	0.30	0.01
Carton filling machine	1.66	22.95	0.99
Palletizing machine	0.25	3.50	0.15
PE	3.49	32.25	0.17
Carton	567.40	216.22	15.33
Transportation	2200.31	1955.32	147.00
Total	2773.14	2230.54	163.65

Table C. 6. BD packaging and transportation step cumulative energy, exergy and CO₂ emission results

Input	CEnC (MJ/ton)	CexC (MJ/ton)	CCO₂C (kg/ton)
Carton printing and boxing machine	0.02	0.30	0.01
Carton filling machine	1.66	22.95	0.99
Palletizing machine	0.25	3.50	0.15
PE	3.49	32.25	0.17
Carton	567.40	216.22	15.33
Transportation	653.61	155.45	17.14
Total	1226.43	430.67	33.79

2. Sweet red pepper paste

2.1. SRP factory processing step cumulative energy, exergy and CO₂ emissions with different improvement scenarios for SRP paste production

Table C. 7. BC factory processing step cumulative energy, exergy and CO₂ emission results

Equipment	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Mechanical water filter	0.49	6.76	0.29
Case tipping machine	3.98	55.04	2.38
Fruit-vegetable loading pool	1.45	20.02	0.86
Air Bubble type washing machine	1.22	16.86	0.73
Pedicle taking machine	0.16	2.25	0.10
Elevator	0.39	5.34	0.23
Selecting and collecting conveyor with roll	0.16	2.18	0.09
Elevator with collecting	0.16	2.18	0.09
Pepper crushing machine	1.40	19.42	0.84
Selecting and collecting conveyor	0.25	3.40	0.15
Elevator	0.36	4.99	0.22
Pepper mill	12.15	167.92	7.25
Heat exchanger	1.08	14.98	0.65
Turbo Extractor	0.30	4.08	0.18
Pulp collecting tank and pump	11.00	152.04	6.56
Filling (balance) tank	0.99	13.62	0.59
Steam generator	4.93	68.08	2.94
Evaporator (Electric)	8.87	122.54	5.29
Evaporator (Natural gas)	495.73	461.79	0.45
Tubular sterilization machine (Electric)	5.07	70.08	3.02
Tubular sterilization machine (Natural gas)	612.37	570.44	0.55
Aseptic filling (Electric)	0.15	2.06	0.09
Aseptic filling (Natural gas)	103.63	96.54	0.09
Total	1266.29	1882.60	33.63

Table C. 8. BD factory processing step cumulative energy, exergy and CO₂ emission results

Equipment	CEnC (MJ/ton)	CExC (MJ/ton)	CCO ₂ C (kg/ton)
Mechanical water filter	0.49	6.76	0.29
Case tipping machine	3.98	55.04	2.38
Fruit-vegetable loading pool	1.45	20.02	0.86
Air Bubble type washing machine	1.22	16.86	0.73
Pedicle taking machine	0.16	2.25	0.10
Elevator	0.39	5.34	0.23
Selecting and collecting conveyor with roll	0.16	2.18	0.09
Elevator with collecting	0.16	2.18	0.09
Pepper crushing machine	1.40	19.42	0.84
Selecting and collecting conveyor	0.25	3.40	0.15
Elevator	0.36	4.99	0.22
Pepper mill	12.15	167.92	7.25
Heat exchanger	1.08	14.98	0.65
Turbo Extractor	0.30	4.08	0.18
Pulp collecting tank and pump	11.00	152.04	6.56
Filling (balance) tank	0.99	13.62	0.59
Steam generator	4.93	68.08	2.94
Evaporator (Electricity)	8.87	122.54	5.29
Evaporator (Biodiesel)	460.84	109.61	12.08
Tubular sterilization mach.(Electricity)	5.07	70.08	3.02
Tubular sterilization mach.(Biodiesel)	408.67	97.20	10.71
Aseptic filling (Electricity)	3.925	0.934	0.103
Aseptic filling (Biodiesel)	32.15	7.65	0.84
Total	959.99	967.15	56.19

2.2. SRP packaging and transportation step cumulative energy, exergy and CO₂ emissions with different improvement scenarios for SRP paste production

Table C. 9. BC packaging and transportation step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO ₂ C (kg/ton)
Carton printing and boxing machine	0.00303	0.04181	0.00180
Carton filling machine	0.36307	5.01726	0.21657
Palletizing machine	0.05070	0.70056	0.03024
Ink jet	0.27629	3.81805	0.16481
LDPE	165.64	160.46	7.25
Glass	652.18	1083.85	30.28
Steel (Primary pack.)	29.96	221.69	2.99
Steel (Jar lid)	9.66	71.50	0.97
Cardboard	78.94	30.08	2.13
Transportation	2200.31	1955.32	147.00
Total	3137.38	3532.49	191.03

Table C. 10. BD packaging and transportation step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Carton printing and boxing machine	0.027	0.006	0.001
Carton filling machine	3.194	0.760	0.084
Palletizing machine	0.451	0.107	0.012
Ink jet	2.442	0.581	0.064
LDPE	165.640	160.464	7.247
Glass	652.176	1083.854	30.280
Steel (Primary pack.)	29.960	221.694	2.993
Steel (Jar lid)	9.662	71.500	0.965
Cardboard	78.936	30.080	2.133
Transportation	653.516	155.431	17.133
Total	1596.004	1724.477	60.910

Table C. 11. PF packaging and transportation step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Carton printing and boxing machine	0.00303	0.04181	0.00180
Carton filling machine	0.36307	5.01726	0.21657
Palletizing machine	0.05070	0.70056	0.03024
Ink jet	0.27629	3.81805	0.16481
LDPE	165.64	160.46	7.25
Glass	652.18	1083.85	30.28
Steel (Primary pack.)	29.96	221.69	2.99
Steel (Jar lid)	9.66	71.50	0.97
Cardboard	78.94	30.08	2.13
Transportation	2200.31	1955.32	147.00
Total	3137.38	3532.49	191.03

Table C. 12. BD-PF packaging and transportation step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Carton printing and boxing machine	0.02662	0.00633	0.00070
Carton filling machine	3.19352	0.75954	0.08372
Palletizing machine	0.45122	0.10732	0.01183
Ink jet	2.44189	0.58077	0.06402
LDPE	165.64	160.46	7.25
Glass	652.18	1083.85	30.28
Steel (Primary pack.)	29.96	221.69	2.99
Steel (Jar lid)	9.66	71.50	0.97
Cardboard	78.94	30.08	2.13
Transportation	653.52	155.43	17.13
Total	1596.00	1724.48	60.91

Table C. 13. PET packaging and transportation step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Carton printing and boxing machine	0.0023	0.031	0.0014
Carton filling machine	0.272	3.764	0.162
Palletizing machine	0.042	0.587	0.025
Ink jet	0.276	3.818	0.165
HDPE (Lid)	167.856	162.611	7.344
PET	606.38	628.08	16.86
Label (PET)	299.501	310.223	8.327
Cardboard	59.217	22.565	1.600
Transportation	2200.310	1955.318	146.996
Steel	29.959	221.694	2.993
Total	3363.81	3308.70	184.47

Table C. 14. PET-BD-PF packaging and transportation step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Carton printing and boxing machine	0.0023	0.031	0.0014
Carton filling machine	0.272	3.764	0.162
Palletizing machine	0.042	0.587	0.025
Ink jet	0.276	3.818	0.165
HDPE (Lid)	167.856	162.611	7.344
PET	606.377	628.085	16.860
Label (PET)	299.501	310.223	8.327
Steel	29.959	221.694	2.993
Cardboard	59.217	22.565	1.600
Transportation	653.516	155.431	17.133
Total	1817.02	1508.81	54.61

3. Roasted sweet red pepper

3.1. SRP factory processing step cumulative energy, exergy and CO₂ emissions with different improvement scenarios for roasted SRP production

Table C. 15. BC factory processing step cumulative energy, exergy and CO₂ emission results

Equipment	CEnC (MJ/ton)	CExC (MJ/ton)	CCO ₂ C (kg/ton)
Mechanical water filter	0.49	6.76	0.29
Case tipping machine	3.98	55.04	2.38
Fruit-vegetable loading pool	1.45	20.02	0.86
Air Bubble type washing machine	1.22	16.86	0.73
Selecting and collecting conveyor	0.16	2.25	0.10
Pedicle taking machine	0.16	2.18	0.09
Elevator	0.39	5.34	0.23
Roasting tunnel	7.24	100.11	4.32
Elevator	0.35	4.86	0.21
Pepper crushing machine	1.28	17.67	0.76
Selecting and collecting conveyor with water channel	0.24	3.31	0.14
Steam generator	5.27	72.81	3.14
Water	45.60	188.92	6.38
Vinegar	387.08	783.76	590.96
Sugar	644.84	951.47	62.51
Salt	283.04	566.09	12.64
Total	1382.79	2797.45	685.76

Table C. 16. BD factory processing step cumulative energy, exergy and CO₂ emission results

Equipment	CEnC (MJ/ton)	CExC (MJ/ton)	CCO ₂ C (kg/ton)
Mechanical water filter	4.30	1.02	0.11
Case tipping machine	35.04	8.33	0.92
Fruit-vegetable loading pool	12.74	3.03	0.33
Air Bubble type washing machine	10.73	2.55	0.28
Selecting and collecting conveyor	1.43	0.34	0.04
Pedicle taking machine	1.39	0.33	0.04
Elevator	3.40	0.81	0.09
Roasting tunnel	63.72	15.16	1.67
Elevator	3.09	0.74	0.08
Pepper crushing machine	11.25	2.67	0.29
Selecting and collecting conveyor with water channel	2.11	0.50	0.06
Steam generator	46.34	11.02	1.21
Water	45.60	188.92	6.38
Vinegar	387.08	783.76	590.96
Sugar	644.84	951.47	62.51
Salt	283.04	566.09	12.64
Total	1556.11	2536.74	677.62

3.2. SRP packaging and transportation step cumulative energy, exergy and CO₂ emissions with different improvement scenarios for roasted SRP production

Table C. 17. BC packaging and transportation step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Carton printing and boxing machine	0.00303	0.04181	0.00180
Carton filling machine	0.36307	5.01726	0.21657
Palletizing machine	0.23105	3.19280	0.13782
Ink jet	0.27629	3.81805	0.16481
LDPE	2016.84	1953.81	88.24
Glass	8235.42	13686.48	382.36
Steel (Primary pack.)	141.46	1046.76	14.13
Steel (Jar lid)	117.53	869.69	11.74
Cardboard	1011.06	385.28	27.32
Transportation	2200.31	1955.32	146.63
Total	13723.47	19909.36	670.93

Table C. 18. BD packaging and transportation step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Carton printing and boxing machine	0.00303	0.04181	0.00180
Carton filling machine	0.36307	5.01726	0.21657
Palletizing machine	0.23105	3.19280	0.13782
Ink jet	0.27629	3.81805	0.16481
LDPE	2016.84	1953.81	88.24
Glass	8235.42	13686.48	382.36
Steel (Primary pack.)	141.46	1046.76	14.13
Steel (Jar lid)	117.53	869.69	11.74
Cardboard	1011.06	385.28	27.32
Transportation	653.52	155.43	17.13
Total	12176.68	18109.52	541.44

Table C. 19. Tin can (steel) packaging and transportation step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Carton printing and boxing machine	0.0230	0.317	0.0137
Carton filling machine	2.76	38.08	1.64
Palletizing machine	0.43	5.94	0.26
Ink jet	0.28	3.82	0.16
Steel (Primary pack.)	141.46	1046.76	14.13
Steel (Tin can)	640.83	4742.08	64.02
Cardboard	1011.06	385.28	27.32
Transportation	2200.31	1955.32	146.63
Total	3997.13	8177.58	254.17

4. Dried sweet red pepper

4.1. SRP factory processing step cumulative energy, exergy and CO₂ emissions with different improvement scenarios for dried SRP production

Table C. 20. BC factory processing step cumulative energy, exergy and CO₂ emission results

Equipment	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Mechanical water filter	0.49	6.76	0.29
Case tipping machine	3.98	55.04	2.38
Fruit-vegetable loading pool	1.45	20.02	0.86
Air bubble type washing machine	1.22	16.86	0.73
Selecting and collecting conveyor	0.16	2.25	0.10
Elevator	0.39	5.34	0.23
Cutting machine	0.79	10.87	0.47
Linear vibrating sieve	0.26	3.59	0.16
Drying oven (Electricity)	27.40	378.60	16.34
Natural gas	1096.84	1021.74	54.84
Selecting and collecting conveyor	0.16	2.18	0.09
Steam generator	5.27	72.81	3.14
Total	1138.40	1596.07	79.63

Table C. 21. BD factory processing step cumulative energy, exergy and CO₂ emission results

Equipment	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Mechanical water filter	1.47	20.27	0.87
Case tipping machine	11.95	165.13	7.13
Fruit-vegetable loading pool	4.35	60.05	2.59
Air bubble type washing machine	3.66	50.59	2.18
Selecting and collecting conveyor	0.49	6.76	0.29
Elevator	1.16	16.02	0.69
Cutting machine	2.36	32.62	1.41
Linear vibrating sieve	0.78	10.78	0.47
Drying oven	82.19	1135.81	49.03
Biodiesel	319.85	76.07	8.39
Selecting and collecting conveyor	0.47	6.55	0.28
Steam generator	15.81	218.42	9.43
Total	444.54	1799.06	82.76

4.2. SRP packaging and transportation step cumulative energy, exergy and CO₂ emissions with different improvement scenarios for dried SRP production

Table C. 22. BC packaging and transportation step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Carton printing and boxing machine	0.004	0.049	0.002
Carton filling machine	0.423	5.844	0.252
Palletizing machine	0.017	0.241	0.010
Automatic 1kg Doypack Packing Machine	0.001	0.012	0.001
Ink jet	0.276	3.818	0.165
PE	5.008	46.311	0.242
PP	0.386	18.262	0.054
Paper	0.652	1.863	0.016
PET	22.452	23.256	0.624
Cardboard	33.460	12.750	0.904
Transportation	2200.310	1955.318	146.626
Total	2262.989	2067.724	148.896

Table C. 23. BD packaging and transportation step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Carton printing and boxing machine	0.00352	0.04870	0.00210
Carton filling machine	0.42290	5.84402	0.25226
Palletizing machine	0.01745	0.24113	0.01041
Automatic 1kg Doypack Packing Machine	0.00090	0.01241	0.00054
Ink jet	0.28	3.82	0.16
PE	5.01	46.31	0.24
PP	0.39	18.26	0.05
Paper	0.65	1.85	0.02
PET	22.45	23.26	0.62
Cardboard	33.46	12.75	0.90
Transportation	653.52	155.43	17.13
Total	716.19	267.83	19.40

Table C. 24. 25KP-BC packaging and transportation step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Automatic 25 kg Kraft Packing Machine	0.00079	0.01096	0.00047
PE	1.86	17.20	0.0900
Paper	26.38	75.43	0.6540
Transportation	2200.31	1955.32	146.63
Total	2228.55	2047.96	147.37

Table C. 25. 25KP-BD packaging and transportation step cumulative energy, exergy and CO₂ emission results

Inputs	CEnC (MJ/ton)	CExC (MJ/ton)	CCO₂C (kg/ton)
Automatic 25 kg Kraft Packing Machine	0.00079	0.0109	0.00047
PE	1.86	17.20	0.09
Paper	26.38	75.43	0.66
Transportation	653.52	155.44	17.13
Total	681.75	248.07	17.88

APPENDIX D

Life cycle assessment results for each steps of the tomato products production

1. Retail tomato

Table D. 1. BC-Life cycle assessment analysis results* of retail tomato production for each step

Impact category	Tomato farming	Packaging and transportation	Whole process
Abiotic depletion potential	5.2E-04	2.5E-04	7.6E-04
Abiotic (fossil) depletion potential	1.2E+03	1.2E+03	2.4E+03
Acidification potential	6.6E-01	2.8E-01	9.4E-01
Eutrophication potential	2.3E-01	6.3E-02	2.9E-01
Fresh water aquatic ecotoxicity potential	5.6E+01	9.1E+00	6.5E+01
Global warming (GWP100a) potential	1.2E+02	8.5E+01	2.0E+02
Human toxicity potential	6.0E+01	2.9E+01	8.9E+01
Ozone layer depletion potential	1.3E-05	1.5E-05	2.9E-05
Photochemical oxidation potential	3.5E-02	1.4E-02	4.9E-02
Terrestrial ecotoxicity potential	4.2E+00	1.1E-01	4.3E+00

*Normalized results

Table D. 2. BD-Life cycle assessment analysis results* of retail tomato production for each step

Impact category	Tomato farming	Packaging and transportation	Whole process
Abiotic depletion potential	5.7E-05	7.6E-07	5.7E-05
Abiotic (fossil) depletion potential	3.4E+02	2.6E+02	6.1E+02
Acidification potential	1.8E-01	6.1E-03	1.9E-01
Eutrophication potential	8.1E-02	2.5E-03	8.4E-02
Fresh water aquatic ecotoxicity potential	2.5E+01	1.4E+00	2.6E+01
Global warming (GWP100a) potential	3.5E+01	1.3E+00	3.6E+01
Human toxicity potential	1.7E+01	1.6E+00	1.8E+01
Ozone layer depletion potential	2.9E-06	1.7E-06	4.6E-06
Photochemical oxidation potential	7.8E-03	2.4E-03	1.0E-02
Terrestrial ecotoxicity potential	3.9E+00	3.0E-03	3.9E+00

*Normalized results

Table D. 3. PF-Life cycle assessment analysis results* of retail tomato production for each step

Impact category	Tomato farming	Packaging and transportation	Whole process
Abiotic depletion potential	4.9E-04	2.5E-04	7.4E-04
Abiotic (fossil) depletion potential	1.1E+03	1.2E+03	2.3E+03
Acidification potential	6.3E-01	2.8E-01	9.1E-01
Eutrophication potential	2.2E-01	6.3E-02	2.8E-01
Fresh water aquatic ecotoxicity potential	5.5E+01	9.1E+00	6.4E+01
Global warming (GWP100a) potential	1.2E+02	8.5E+01	2.0E+02
Human toxicity potential	5.8E+01	2.9E+01	8.7E+01
Ozone layer depletion potential	1.3E-05	1.5E-05	2.8E-05
Photochemical oxidation potential	3.4E-02	1.4E-02	4.8E-02
Terrestrial ecotoxicity potential	4.1E+00	1.1E-01	4.2E+00

*Normalized results

2. Tomato juice

Table D. 4. BC-Life cycle assessment analysis results* of tomato juice production for each step

Impact category	Tomato farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	5.5E-04	2.1E-05	6.1E-04	1.2E-03
Abiotic (fossil) depletion potential	1.2E+03	3.0E+03	2.9E+03	7.2E+03
Acidification potential	7.1E-01	1.8E-01	2.9E+00	3.7E+00
Eutrophication potential	2.4E-01	4.3E-02	1.3E+00	1.6E+00
Fresh water aquatic ecotoxicity potential	6.0E+01	9.8E+00	2.3E+02	3.0E+02
Global warming (GWP100a) potential	1.3E+02	4.7E+01	7.1E+02	8.9E+02
Human toxicity potential	6.4E+01	1.8E+01	3.8E+02	4.6E+02
Ozone layer depletion potential	1.4E-05	1.8E-05	4.9E-05	8.2E-05
Photochemical oxidation potential	3.7E-02	2.1E-02	4.8E-01	5.3E-01
Terrestrial ecotoxicity potential	4.4E+00	5.9E-02	1.2E+00	5.7E+00

*Normalized results

Table D. 5. BD-Life cycle assessment analysis results* of tomato juice production for each step

Impact category	Tomato farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	6.0E-05	6.1E-06	3.9E-04	4.5E-04
Abiotic (fossil) depletion potential	3.7E+02	4.9E+01	2.1E+03	2.5E+03
Acidification potential	1.9E-01	4.4E-02	2.6E+00	2.9E+00
Eutrophication potential	8.7E-02	2.8E-02	1.2E+00	1.3E+00
Fresh water aquatic ecotoxicity potential	2.6E+01	5.0E+00	2.2E+02	2.6E+02
Global warming (GWP100a) potential	3.8E+01	7.5E+00	6.4E+02	6.8E+02
Human toxicity potential	1.8E+01	3.7E+00	3.6E+02	3.8E+02
Ozone layer depletion potential	3.1E-06	8.0E-07	3.7E-05	4.1E-05
Photochemical oxidation potential	8.3E-03	1.6E-03	4.7E-01	4.8E-01
Terrestrial ecotoxicity potential	4.2E+00	3.1E-02	1.1E+00	5.4E+00

*Normalized results

Table D. 6. PF-Life cycle assessment analysis results* of tomato juice production for each step

Impact category	Tomato farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	5.5E-04	2.1E-05	6.1E-04	1.2E-03
Abiotic (fossil) depletion potential	1.2E+03	3.0E+03	2.9E+03	7.2E+03
Acidification potential	7.1E-01	1.8E-01	2.9E+00	3.7E+00
Eutrophication potential	2.4E-01	4.3E-02	1.3E+00	1.6E+00
Fresh water aquatic ecotoxicity potential	6.0E+01	9.8E+00	2.3E+02	3.0E+02
Global warming (GWP100a) potential	1.3E+02	4.7E+01	7.1E+02	8.9E+02
Human toxicity potential	6.4E+01	1.8E+01	3.8E+02	4.6E+02
Ozone layer depletion potential	1.4E-05	1.8E-05	4.9E-05	8.2E-05
Photochemical oxidation potential	3.7E-02	2.1E-02	4.8E-01	5.3E-01
Terrestrial ecotoxicity potential	4.4E+00	5.9E-02	1.2E+00	5.7E+00

*Normalized results

Table D. 7. GP-Life cycle assessment analysis results* of tomato juice production for each step

Impact category	Tomato farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	5.5E-04	2.1E-05	1.2E-03	1.7E-03
Abiotic (fossil) depletion potential	1.2E+03	3.0E+03	1.2E+04	1.6E+04
Acidification potential	7.1E-01	1.8E-01	4.4E+00	5.2E+00
Eutrophication potential	2.4E-01	4.3E-02	7.1E-01	1.0E+00
Fresh water aquatic ecotoxicity potential	6.0E+01	9.8E+00	3.4E+02	4.1E+02
Global warming (GWP100a) potential	1.3E+02	4.7E+01	8.7E+02	1.0E+03
Human toxicity potential	6.4E+01	1.8E+01	4.1E+02	4.9E+02
Ozone layer depletion potential	1.4E-05	1.8E-05	6.3E-05	9.6E-05
Photochemical oxidation potential	3.7E-02	2.1E-02	2.0E-01	2.6E-01
Terrestrial ecotoxicity potential	4.4E+00	5.9E-02	7.9E-01	5.3E+00

*Normalized results

Table D. 8. GP-BD-Life cycle assessment analysis results* of tomato juice production for each step

Impact category	Tomato farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	6.0E-05	6.1E-06	1.0E-03	1.1E-03
Abiotic (fossil) depletion potential	3.7E+02	4.9E+01	1.1E+04	1.1E+04
Acidification potential	1.9E-01	4.4E-02	4.1E+00	4.4E+00
Eutrophication potential	8.7E-02	2.8E-02	6.5E-01	7.7E-01
Fresh water aquatic ecotoxicity potential	2.6E+01	5.0E+00	3.4E+02	3.7E+02
Global warming (GWP100a) potential	3.8E+01	7.5E+00	8.2E+02	8.6E+02
Human toxicity potential	1.8E+01	3.7E+00	3.9E+02	4.1E+02
Ozone layer depletion potential	3.1E-06	8.0E-07	5.4E-05	5.8E-05
Photochemical oxidation potential	8.3E-03	1.6E-03	1.9E-01	2.0E-01
Terrestrial ecotoxicity potential	4.2E+00	3.1E-02	7.1E-01	4.9E+00

*Normalized results

3. Tomato paste

Table D. 9. BC-Life cycle assessment analysis results* of tomato paste production for each step

Impact category	Tomato farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	2.4E-03	4.8E-05	4.7E-05	2.5E-03
Abiotic (fossil) depletion potential	5.3E+03	5.0E+03	2.6E+02	1.1E+04
Acidification potential	3.0E+00	4.0E-01	2.7E-01	3.7E+00
Eutrophication potential	1.0E+00	1.3E-01	1.2E-01	1.3E+00
Fresh water aquatic ecotoxicity potential	2.6E+02	2.7E+01	2.2E+01	3.1E+02
Global warming (GWP100a) potential	5.5E+02	9.3E+01	6.6E+01	7.1E+02
Human toxicity potential	2.8E+02	3.8E+01	3.6E+01	3.5E+02
Ozone layer depletion potential	6.2E-05	3.2E-05	4.1E-06	9.7E-05
Photochemical oxidation potential	1.6E-01	3.8E-02	4.5E-02	2.4E-01
Terrestrial ecotoxicity potential	1.9E+01	1.7E-01	1.1E-01	1.9E+01

*Normalized results

Table D. 10. BD-Life cycle assessment analysis results* of tomato paste production for each step

Impact category	Tomato farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	2.6E-04	2.4E-05	3.8E-05	3.2E-04
Abiotic (fossil) depletion potential	1.6E+03	1.9E+02	2.3E+02	2.0E+03
Acidification potential	8.2E-01	1.7E-01	2.6E-01	1.3E+00
Eutrophication potential	3.7E-01	1.1E-01	1.2E-01	6.0E-01
Fresh water aquatic ecotoxicity potential	1.1E+02	1.9E+01	2.2E+01	1.5E+02
Global warming (GWP100a) potential	1.6E+02	2.9E+01	6.3E+01	2.5E+02
Human toxicity potential	7.6E+01	1.5E+01	3.5E+01	1.3E+02
Ozone layer depletion potential	1.3E-05	3.1E-06	3.6E-06	2.0E-05
Photochemical oxidation potential	3.6E-02	6.3E-03	4.5E-02	8.7E-02
Terrestrial ecotoxicity potential	1.8E+01	1.2E-01	1.1E-01	1.8E+01

*Normalized results

Table D. 11. PF-Life cycle assessment analysis results* of tomato paste production for each step

Impact category	Tomato farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	2.2E-03	4.8E-05	4.7E-05	2.3E-03
Abiotic (fossil) depletion potential	5.0E+03	5.0E+03	2.6E+02	1.0E+04
Acidification potential	2.9E+00	4.0E-01	2.7E-01	3.6E+00
Eutrophication potential	9.9E-01	1.3E-01	1.2E-01	1.2E+00
Fresh water aquatic ecotoxicity potential	2.5E+02	2.7E+01	2.2E+01	3.0E+02
Global warming (GWP100a) potential	5.3E+02	9.3E+01	6.6E+01	6.9E+02
Human toxicity potential	2.7E+02	3.8E+01	3.6E+01	3.4E+02
Ozone layer depletion potential	5.9E-05	3.2E-05	4.1E-06	9.5E-05
Photochemical oxidation potential	1.5E-01	3.8E-02	4.5E-02	2.4E-01
Terrestrial ecotoxicity potential	1.9E+01	1.7E-01	1.1E-01	1.9E+01

*Normalized results

Table D. 12. GP-Life cycle assessment analysis results* of tomato paste production for each step

Impact category	Tomato farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	2.4E-03	4.8E-05	6.6E-05	2.5E-03
Abiotic (fossil) depletion potential	5.3E+03	5.0E+03	3.5E+02	1.1E+04
Acidification potential	3.0E+00	4.0E-01	1.9E-01	3.6E+00
Eutrophication potential	1.0E+00	1.3E-01	3.3E-02	1.2E+00
Fresh water aquatic ecotoxicity potential	2.6E+02	2.7E+01	6.5E+00	2.9E+02
Global warming (GWP100a) potential	5.5E+02	9.3E+01	2.8E+01	6.7E+02
Human toxicity potential	2.8E+02	3.8E+01	1.6E+01	3.3E+02
Ozone layer depletion potential	6.2E-05	3.2E-05	3.2E-06	9.6E-05
Photochemical oxidation potential	1.6E-01	3.8E-02	7.7E-03	2.1E-01
Terrestrial ecotoxicity potential	1.9E+01	1.7E-01	4.2E-02	1.9E+01

*Normalized results

Table D. 13. GP-BD-Life cycle assessment analysis results* of tomato paste production for each step

Impact category	Tomato farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	2.6E-04	2.4E-05	5.4E-05	3.4E-04
Abiotic (fossil) depletion potential	1.6E+03	1.9E+02	3.0E+02	2.1E+03
Acidification potential	8.2E-01	1.7E-01	1.8E-01	1.2E+00
Eutrophication potential	3.7E-01	1.1E-01	3.0E-02	5.1E-01
Fresh water aquatic ecotoxicity potential	1.1E+02	1.9E+01	6.1E+00	1.4E+02
Global warming (GWP100a) potential	1.6E+02	2.9E+01	2.4E+01	2.1E+02
Human toxicity potential	7.6E+01	1.5E+01	1.5E+01	1.1E+02
Ozone layer depletion potential	1.3E-05	3.1E-06	2.6E-06	1.9E-05
Photochemical oxidation potential	3.6E-02	6.3E-03	7.1E-03	4.9E-02
Terrestrial ecotoxicity potential	1.8E+01	1.2E-01	3.7E-02	1.8E+01

*Normalized results

APPENDIX E

Life cycle assessment results for each steps of the sweet red pepper products production

1. Retail sweet red pepper

Table E. 1. BC-Life cycle assessment analysis results* of retail SRP production for each step

Impact category	SRP farming	Packaging and transportation	Whole process
Abiotic depletion potential	5.06E-04	2.49E-04	7.55E-04
Abiotic (fossil) depletion potential	1.42E+03	1.19E+03	2.61E+03
Acidification potential	6.10E-01	2.74E-01	8.84E-01
Eutrophication potential	2.38E-01	6.29E-02	3.01E-01
Fresh water aquatic ecotoxicity potential	2.99E+01	9.22E+00	3.91E+01
Global warming (GWP100a) potential	9.54E+01	8.39E+01	1.79E+02
Human toxicity potential	4.56E+01	2.90E+01	7.46E+01
Ozone layer depletion potential	1.36E-05	1.52E-05	2.88E-05
Photochemical oxidation potential	2.60E-02	1.39E-02	3.99E-02
Terrestrial ecotoxicity potential	5.77E-01	1.14E-01	6.91E-01

*Normalized results

Table E. 2. BD-Life cycle assessment analysis results* of retail SRP production for each step

Impact category	SRP farming	Packaging and transportation	Whole process
Abiotic depletion potential	4.37E-04	8.05E-07	4.38E-04
Abiotic (fossil) depletion potential	1.26E+03	2.64E+02	1.52E+03
Acidification potential	5.74E-01	6.86E-03	5.81E-01
Eutrophication potential	2.43E-01	2.65E-03	2.46E-01
Fresh water aquatic ecotoxicity potential	3.27E+01	1.58E+00	3.43E+01
Global warming (GWP100a) potential	8.78E+01	1.53E+00	8.93E+01
Human toxicity potential	4.26E+01	1.83E+00	4.44E+01
Ozone layer depletion potential	1.07E-05	1.70E-06	1.24E-05
Photochemical oxidation potential	2.47E-02	2.39E-03	2.71E-02
Terrestrial ecotoxicity potential	5.69E-01	3.48E-03	5.72E-01

*Normalized results

Table E. 3. PF-Life cycle assessment analysis results* of retail SRP production for each step

Impact category	SRP farming	Packaging and transportation	Whole process
Abiotic depletion potential	2.90E-04	2.49E-04	5.39E-04
Abiotic (fossil) depletion potential	8.80E+02	1.19E+03	2.07E+03
Acidification potential	3.68E-01	2.74E-01	6.42E-01
Eutrophication potential	1.38E-01	6.29E-02	2.00E-01
Fresh water aquatic ecotoxicity potential	1.78E+01	9.22E+00	2.70E+01
Global warming (GWP100a) potential	6.16E+01	8.39E+01	1.46E+02
Human toxicity potential	2.82E+01	2.90E+01	5.72E+01
Ozone layer depletion potential	8.89E-06	1.52E-05	2.41E-05
Photochemical oxidation potential	1.57E-02	1.39E-02	2.96E-02
Terrestrial ecotoxicity potential	3.47E-01	1.14E-01	4.61E-01

*Normalized results

Table E. 4. PF-Life cycle assessment analysis results* of retail SRP production for each step

Impact category	SRP farming	Packaging and transportation	Whole process
Abiotic depletion potential	2.89E-04	8.05E-07	2.90E-04
Abiotic (fossil) depletion potential	7.70E+02	2.64E+02	1.03E+03
Acidification potential	3.64E-01	6.86E-03	3.71E-01
Eutrophication potential	1.52E-01	2.65E-03	1.55E-01
Fresh water aquatic ecotoxicity potential	2.31E+01	1.58E+00	2.47E+01
Global warming (GWP100a) potential	5.91E+01	1.53E+00	6.06E+01
Human toxicity potential	2.99E+01	1.83E+00	3.17E+01
Ozone layer depletion potential	6.60E-06	1.70E-06	8.31E-06
Photochemical oxidation potential	1.58E-02	2.39E-03	1.82E-02
Terrestrial ecotoxicity potential	3.51E-01	3.48E-03	3.55E-01

*Normalized results

2. Sweet red pepper paste

Table E. 5. BC-Life cycle assessment analysis results* of SRP paste production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	2.71E-03	2.27E-05	2.21E-04	3.92E-03
Abiotic (fossil) depletion potential	7.61E+03	1.09E+03	1.25E+03	1.55E+04
Acidification potential	3.27E+00	1.11E-01	7.52E-01	7.42E+00
Eutrophication potential	1.27E+00	4.21E-02	1.57E-01	2.16E+00
Fresh water aquatic ecotoxicity potential	1.60E+02	8.93E+00	3.05E+01	3.33E+02
Global warming (GWP100a) potential	5.11E+02	2.43E+01	1.17E+02	1.16E+03
Human toxicity potential	2.44E+02	1.07E+01	6.86E+01	6.24E+02
Ozone layer depletion potential	7.26E-05	7.23E-06	1.09E-05	1.39E-04
Photochemical oxidation potential	1.39E-01	9.55E-03	4.41E-02	3.86E-01
Terrestrial ecotoxicity potential	3.09E+00	8.44E-02	1.79E-01	4.14E+00

*Normalized results

Table E. 6. BD-Life cycle assessment analysis results* of SRP paste production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	2.34E-03	2.27E-05	2.13E-04	2.58E-03
Abiotic (fossil) depletion potential	6.73E+03	1.82E+02	1.23E+03	8.14E+03
Acidification potential	3.07E+00	1.59E-01	7.46E-01	3.98E+00
Eutrophication potential	1.30E+00	7.64E-02	1.57E-01	1.53E+00
Fresh water aquatic ecotoxicity potential	1.75E+02	1.55E+01	3.07E+01	2.22E+02
Global warming (GWP100a) potential	4.70E+02	3.44E+01	1.15E+02	6.20E+02
Human toxicity potential	2.28E+02	1.41E+01	6.81E+01	3.10E+02
Ozone layer depletion potential	5.75E-05	1.84E-06	1.05E-05	6.99E-05
Photochemical oxidation potential	1.32E-01	6.65E-03	4.39E-02	1.83E-01
Terrestrial ecotoxicity potential	3.05E+00	1.15E-01	1.78E-01	3.34E+00

*Normalized results

Table E. 7. PET-Life cycle assessment analysis results* of SRP paste production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	2.71E-03	2.27E-05	6.62E-05	2.80E-03
Abiotic (fossil) depletion potential	7.61E+03	1.09E+03	4.64E+02	9.16E+03
Acidification potential	3.27E+00	1.11E-01	1.64E-01	3.54E+00
Eutrophication potential	1.27E+00	4.21E-02	5.97E-02	1.38E+00
Fresh water aquatic ecotoxicity potential	1.60E+02	8.93E+00	1.62E+01	1.85E+02
Global warming (GWP100a) potential	5.11E+02	2.43E+01	4.36E+01	5.79E+02
Human toxicity potential	2.44E+02	1.07E+01	2.07E+01	2.76E+02
Ozone layer depletion potential	7.26E-05	7.23E-06	2.41E-06	8.22E-05
Photochemical oxidation potential	1.39E-01	9.55E-03	1.84E-02	1.67E-01
Terrestrial ecotoxicity potential	3.09E+00	8.44E-02	5.84E-02	3.23E+00

*Normalized results

Table E. 8. PF-Life cycle assessment analysis results* of SRP paste production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	1.55E-03	2.27E-05	2.21E-04	1.80E-03
Abiotic (fossil) depletion potential	4.71E+03	1.09E+03	1.25E+03	7.05E+03
Acidification potential	1.97E+00	1.11E-01	7.52E-01	2.83E+00
Eutrophication potential	7.37E-01	4.21E-02	1.57E-01	9.36E-01
Fresh water aquatic ecotoxicity potential	9.53E+01	8.93E+00	3.05E+01	1.35E+02
Global warming (GWP100a) potential	3.30E+02	2.43E+01	1.17E+02	4.71E+02
Human toxicity potential	1.51E+02	1.07E+01	6.86E+01	2.30E+02
Ozone layer depletion potential	4.76E-05	7.23E-06	1.09E-05	6.57E-05
Photochemical oxidation potential	8.40E-02	9.55E-03	4.41E-02	1.38E-01
Terrestrial ecotoxicity potential	1.86E+00	8.44E-02	1.79E-01	2.12E+00

*Normalized results

Table E. 9. BD-PF-Life cycle assessment analysis results* of SRP paste production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	1.55E-03	2.27E-05	2.13E-04	1.79E-03
Abiotic (fossil) depletion potential	4.13E+03	1.82E+02	1.23E+03	5.53E+03
Acidification potential	1.95E+00	1.59E-01	7.46E-01	2.85E+00
Eutrophication potential	8.16E-01	7.64E-02	1.57E-01	1.05E+00
Fresh water aquatic ecotoxicity potential	1.24E+02	1.55E+01	3.07E+01	1.70E+02
Global warming (GWP100a) potential	3.17E+02	3.44E+01	1.15E+02	4.66E+02
Human toxicity potential	1.60E+02	1.41E+01	6.81E+01	2.42E+02
Ozone layer depletion potential	3.54E-05	1.84E-06	1.05E-05	4.77E-05
Photochemical oxidation potential	8.47E-02	6.65E-03	4.39E-02	1.35E-01
Terrestrial ecotoxicity potential	1.88E+00	1.15E-01	1.78E-01	2.17E+00

*Normalized results

Table E. 10. PET-BD-PF-Life cycle assessment analysis results* of SRP paste production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	1.55E-03	2.27E-05	5.86E-05	1.63E-03
Abiotic (fossil) depletion potential	4.13E+03	1.82E+02	4.35E+02	4.74E+03
Acidification potential	1.95E+00	1.59E-01	1.53E-01	2.26E+00
Eutrophication potential	8.16E-01	7.64E-02	5.70E-02	9.49E-01
Fresh water aquatic ecotoxicity potential	1.24E+02	1.55E+01	1.59E+01	1.55E+02
Global warming (GWP100a) potential	3.17E+02	3.44E+01	4.10E+01	3.92E+02
Human toxicity potential	1.60E+02	1.41E+01	1.98E+01	1.94E+02
Ozone layer depletion potential	3.54E-05	1.84E-06	1.98E-06	3.92E-05
Photochemical oxidation potential	8.47E-02	6.65E-03	1.80E-02	1.09E-01
Terrestrial ecotoxicity potential	1.88E+00	1.15E-01	5.46E-02	2.05E+00

*Normalized results

3. Roasted sweet red pepper

Table E. 11. BC-Life cycle assessment analysis results* of roasted SRP production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	5.74E-04	3.69E-03	2.64E-03	6.90E-03
Abiotic (fossil) depletion potential	1.61E+03	9.06E+03	1.50E+04	2.56E+04
Acidification potential	6.91E-01	6.57E+00	8.80E+00	1.61E+01
Eutrophication potential	2.69E-01	1.96E+00	1.68E+00	3.91E+00
Fresh water aquatic ecotoxicity potential	3.39E+01	4.31E+02	3.30E+02	7.95E+02
Global warming (GWP100a) potential	1.08E+02	8.38E+02	1.31E+03	2.25E+03
Human toxicity potential	5.17E+01	5.13E+02	7.77E+02	1.34E+03
Ozone layer depletion potential	1.54E-05	1.18E-04	1.25E-04	2.59E-04
Photochemical oxidation potential	2.94E-02	2.21E-01	4.45E-01	6.96E-01
Terrestrial ecotoxicity potential	6.54E-01	1.09E+01	1.97E+00	1.36E+01

*Normalized results

Table E. 12. BD-Life cycle assessment analysis results* of roasted SRP production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	4.96E-04	3.69E-03	2.60E-03	6.79E-03
Abiotic (fossil) depletion potential	1.42E+03	9.06E+03	1.48E+04	2.53E+04
Acidification potential	6.50E-01	6.57E+00	8.75E+00	1.60E+01
Eutrophication potential	2.75E-01	1.96E+00	1.67E+00	3.91E+00
Fresh water aquatic ecotoxicity potential	3.71E+01	4.31E+02	3.29E+02	7.97E+02
Global warming (GWP100a) potential	9.95E+01	8.38E+02	1.29E+03	2.23E+03
Human toxicity potential	4.83E+01	5.13E+02	7.73E+02	1.33E+03
Ozone layer depletion potential	1.22E-05	1.18E-04	1.23E-04	2.54E-04
Photochemical oxidation potential	2.80E-02	2.21E-01	4.43E-01	6.93E-01
Terrestrial ecotoxicity potential	6.45E-01	1.09E+01	1.96E+00	1.35E+01

*Normalized results

Table E. 13. Tin packaging-TPC-Life cycle assessment analysis results* of roasted SRP production for each step

*Normalized results

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	5.74E-04	3.69E-03	3.24E-04	4.59E-03
Abiotic (fossil) depletion potential	1.61E+03	9.06E+03	1.43E+03	1.21E+04
Acidification potential	6.91E-01	6.57E+00	1.99E+00	9.26E+00
Eutrophication potential	2.69E-01	1.96E+00	9.33E-01	3.17E+00
Fresh water aquatic ecotoxicity potential	3.39E+01	4.31E+02	1.70E+02	6.35E+02
Global warming (GWP100a) potential	1.08E+02	8.38E+02	4.84E+02	1.43E+03
Human toxicity potential	5.17E+01	5.13E+02	2.72E+02	8.37E+02
Ozone layer depletion potential	1.54E-05	1.18E-04	2.91E-05	1.63E-04
Photochemical oxidation potential	2.94E-02	2.21E-01	3.50E-01	6.00E-01
Terrestrial ecotoxicity potential	6.54E-01	1.09E+01	8.57E-01	1.25E+01

Table E. 14. PF-Life cycle assessment analysis results* of roasted SRP production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	3.29E-04	3.69E-03	2.64E-03	6.65E-03
Abiotic (fossil) depletion potential	9.97E+02	9.06E+03	1.50E+04	2.50E+04
Acidification potential	4.17E-01	6.57E+00	8.80E+00	1.58E+01
Eutrophication potential	1.56E-01	1.96E+00	1.68E+00	3.80E+00
Fresh water aquatic ecotoxicity potential	2.02E+01	4.31E+02	3.30E+02	7.81E+02
Global warming (GWP100a) potential	6.98E+01	8.38E+02	1.31E+03	2.21E+03
Human toxicity potential	3.19E+01	5.13E+02	7.77E+02	1.32E+03
Ozone layer depletion potential	1.01E-05	1.18E-04	1.25E-04	2.54E-04
Photochemical oxidation potential	1.78E-02	2.21E-01	4.45E-01	6.84E-01
Terrestrial ecotoxicity potential	3.93E-01	1.09E+01	1.97E+00	1.33E+01

*Normalized results

Table E. 15. BD-PF-Life cycle assessment analysis results* of roasted SRP production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	3.28E-04	3.69E-03	2.60E-03	6.62E-03
Abiotic (fossil) depletion potential	8.73E+02	9.06E+03	1.48E+04	2.48E+04
Acidification potential	4.12E-01	6.57E+00	8.75E+00	1.57E+01
Eutrophication potential	1.73E-01	1.96E+00	1.67E+00	3.80E+00
Fresh water aquatic ecotoxicity potential	2.62E+01	4.31E+02	3.29E+02	7.87E+02
Global warming (GWP100a) potential	6.70E+01	8.38E+02	1.29E+03	2.20E+03
Human toxicity potential	3.38E+01	5.13E+02	7.73E+02	1.32E+03
Ozone layer depletion potential	7.48E-06	1.18E-04	1.23E-04	2.49E-04
Photochemical oxidation potential	1.79E-02	2.21E-01	4.43E-01	6.82E-01
Terrestrial ecotoxicity potential	3.98E-01	1.09E+01	1.96E+00	1.33E+01

*Normalized results

4. Dried sweet red pepper

Table E. 16. BC-Life cycle assessment analysis results* of dried SRP production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	5.10E-03	9.15E-05	9.63E-06	5.20E-03
Abiotic (fossil) depletion potential	1.43E+04	1.06E+04	9.64E+01	2.51E+04
Acidification potential	6.15E+00	8.12E-01	2.09E-02	6.98E+00
Eutrophication potential	2.40E+00	2.56E-01	6.15E-03	2.66E+00
Fresh water aquatic ecotoxicity potential	3.01E+02	5.31E+01	1.18E+00	3.56E+02
Global warming (GWP100a) potential	9.61E+02	1.92E+02	4.99E+00	1.16E+03
Human toxicity potential	4.60E+02	7.68E+01	1.66E+00	5.38E+02
Ozone layer depletion potential	1.37E-04	6.76E-05	4.27E-07	2.05E-04
Photochemical oxidation potential	2.62E-01	8.03E-02	1.09E-03	3.43E-01
Terrestrial ecotoxicity potential	5.81E+00	3.06E-01	8.74E-03	6.13E+00

*Normalized results

Table E. 17. BD-Life cycle assessment analysis results* of dried SRP production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	4.41E-03	1.65E-05	5.60E-06	4.43E-03
Abiotic (fossil) depletion potential	1.27E+04	3.57E+01	8.10E+01	1.28E+04
Acidification potential	5.79E+00	3.12E-02	1.48E-02	5.83E+00
Eutrophication potential	2.45E+00	1.67E-02	4.69E-03	2.47E+00
Fresh water aquatic ecotoxicity potential	3.30E+02	3.86E+00	1.04E+00	3.35E+02
Global warming (GWP100a) potential	8.85E+02	5.50E+00	3.59E+00	8.94E+02
Human toxicity potential	4.29E+02	3.39E+00	1.16E+00	4.34E+02
Ozone layer depletion potential	1.08E-04	5.69E-07	1.99E-07	1.09E-04
Photochemical oxidation potential	2.49E-01	1.81E-03	8.89E-04	2.52E-01
Terrestrial ecotoxicity potential	5.74E+00	6.42E-02	6.72E-03	5.81E+00

Table E. 18. PF-Life cycle assessment analysis results* of dried SRP production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	2.92E-03	9.15E-05	9.63E-06	3.03E-03
Abiotic (fossil) depletion potential	8.87E+03	1.06E+04	9.64E+01	1.96E+04
Acidification potential	3.71E+00	8.12E-01	2.09E-02	4.54E+00
Eutrophication potential	1.39E+00	2.56E-01	6.15E-03	1.65E+00
Fresh water aquatic ecotoxicity potential	1.79E+02	5.31E+01	1.18E+00	2.34E+02
Global warming (GWP100a) potential	6.21E+02	1.92E+02	4.99E+00	8.18E+02
Human toxicity potential	2.84E+02	7.68E+01	1.66E+00	3.62E+02
Ozone layer depletion potential	8.96E-05	6.76E-05	4.27E-07	1.58E-04
Photochemical oxidation potential	1.58E-01	8.03E-02	1.09E-03	2.39E-01
Terrestrial ecotoxicity potential	3.50E+00	3.06E-01	8.74E-03	3.81E+00

*Normalized results

Table E. 19. PF-BD-Life cycle assessment analysis results* of dried SRP production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	2.92E-03	1.65E-05	5.60E-06	2.94E-03
Abiotic (fossil) depletion potential	7.77E+03	3.57E+01	8.10E+01	7.88E+03
Acidification potential	3.67E+00	3.12E-02	1.48E-02	3.71E+00
Eutrophication potential	1.54E+00	1.67E-02	4.69E-03	1.56E+00
Fresh water aquatic ecotoxicity potential	2.33E+02	3.86E+00	1.04E+00	2.38E+02
Global warming (GWP100a) potential	5.96E+02	5.50E+00	3.59E+00	6.05E+02
Human toxicity potential	3.01E+02	3.39E+00	1.16E+00	3.06E+02
Ozone layer depletion potential	6.65E-05	5.69E-07	1.99E-07	6.73E-05
Photochemical oxidation potential	1.59E-01	1.81E-03	8.89E-04	1.62E-01
Terrestrial ecotoxicity potential	3.54E+00	6.42E-02	6.72E-03	3.61E+00

*Normalized results

Table E. 20. 25KP-Life cycle assessment analysis results* of dried SRP production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	5.10E-03	9.15E-05	7.39E-06	5.20E-03
Abiotic (fossil) depletion potential	1.43E+04	1.06E+04	4.99E+01	2.50E+04
Acidification potential	6.15E+00	8.12E-01	1.99E-02	6.98E+00
Eutrophication potential	2.40E+00	2.56E-01	8.37E-03	2.66E+00
Fresh water aquatic ecotoxicity potential	3.01E+02	5.31E+01	1.02E+00	3.56E+02
Global warming (GWP100a) potential	9.61E+02	1.92E+02	3.64E+00	1.16E+03
Human toxicity potential	4.60E+02	7.68E+01	1.54E+00	5.38E+02
Ozone layer depletion potential	1.37E-04	6.76E-05	4.96E-07	2.05E-04
Photochemical oxidation potential	2.62E-01	8.03E-02	9.86E-04	3.43E-01
Terrestrial ecotoxicity potential	5.81E+00	3.06E-01	3.25E-02	6.15E+00

*Normalized results

Table E. 21. 25KP-BD-Life cycle assessment analysis results* of dried SRP production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	4.41E-03	1.65E-05	3.37E-06	4.43E-03
Abiotic (fossil) depletion potential	1.27E+04	3.57E+01	3.45E+01	1.27E+04
Acidification potential	5.79E+00	3.12E-02	1.38E-02	5.83E+00
Eutrophication potential	2.45E+00	1.67E-02	6.91E-03	2.47E+00
Fresh water aquatic ecotoxicity potential	3.30E+02	3.86E+00	8.85E-01	3.35E+02
Global warming (GWP100a) potential	8.85E+02	5.50E+00	2.24E+00	8.93E+02
Human toxicity potential	4.29E+02	3.39E+00	1.04E+00	4.34E+02
Ozone layer depletion potential	1.08E-04	5.69E-07	2.68E-07	1.09E-04
Photochemical oxidation potential	2.49E-01	1.81E-03	7.88E-04	2.52E-01
Terrestrial ecotoxicity potential	5.74E+00	6.42E-02	3.05E-02	5.83E+00

*Normalized results

Table E. 22. 25KP-BD-PF-Life cycle assessment analysis results* of dried SRP production for each step

Impact category	SRP farming	Factory processing	Packaging and transportation	Whole process
Abiotic depletion potential	2.92E-03	1.65E-05	3.37E-06	2.94E-03
Abiotic (fossil) depletion potential	7.77E+03	3.57E+01	3.45E+01	7.84E+03
Acidification potential	3.67E+00	3.12E-02	1.38E-02	3.71E+00
Eutrophication potential	1.54E+00	1.67E-02	6.91E-03	1.56E+00
Fresh water aquatic ecotoxicity potential	2.33E+02	3.86E+00	8.85E-01	2.38E+02
Global warming (GWP100a) potential	5.96E+02	5.50E+00	2.24E+00	6.04E+02
Human toxicity potential	3.01E+02	3.39E+00	1.04E+00	3.05E+02
Ozone layer depletion potential	6.65E-05	5.69E-07	2.68E-07	6.74E-05
Photochemical oxidation potential	1.59E-01	1.81E-03	7.88E-04	1.62E-01
Terrestrial ecotoxicity potential	3.54E+00	6.42E-02	3.05E-02	3.64E+00

*Normalized results

APPENDIX F

Equipments utilized in various processing steps and specific inputs of various processes

Table F. 1. Equipment and technical specifications of 1 ton fresh tomato packaging and transportation

Equipment	Capacity (unit/h)	Power (kW)	Company name
Carton printing and boxing machine	7200	11	Dongguang Xinglong Packaging Machinery Co., Ltd.
Carton filling machine	60-720 box/min	7	Jiangsu Ketchview Machinery Technology Co., Ltd.
Palletizing machine	300-720 carton/min	7.2	Shangai LWT Machinery Co., Ltd.
Ink jet	19200 message/min	120-150	Zhangjiagang Fillex Beverage Machinery Co., Ltd

Table F. 2. Technical equipment specifications and main mass inputs in factory processing step of tomato juice production

Equipment	Capacity (h)	Mass (kg)	Power (kW)
Mechanical water filter	3 ton	3000	4
Washing machine	5-9 ton Blower: 5,5 kW	3000	5.50
	Reducer: 4 kW	3000	4
Mechanical water filter	3-5 ton	9000	0.75
Elevator	3-5 ton	3000	1.1
Selecting and collecting conveyor	3-6 ton	3000	0.75
Collector elevator	5-9 ton	2850	0.75
Crusher (Fruit mill) (Water consumption: 5-7 ton)	4-9 ton	2850	11
Waste shredder	500-2000 kg/h	150	90
Mono pump	5-9 ton	2664.75	4
Heat exchanger	2 ton/h	2805.54	2.2
Turbo Extractor	5 ton	2805.54	1.5
Pulp discharge screw	2-4 ton	189.25	1.10
Pulp collecting tank and pump	3 ton	2805.54	33.5
Steam generator	3 ton	2805.54	15
Tubular sterilization machine	500 l/h	2.805.54	
		500.00	12.5
Cooling water consumption: 3 ton/h	Steam consumption:500 kg/h	2.805.54	
Aseptic filling	3 ton	2.805.54	2.2
	Steam consumption: 40 kg/h		
Deaerator	2500-3000 l/h	2805.54	4.15

Table F. 3 Equipment and technical specifications of packaging and transportation of tomato juice produced from 1 ton fresh tomato

Equipment	Capacity (unit/h)	Power (kW)	Company name
Carton printing and boxing machine	7200	11	Dongguang Xinglong Packaging Machinery Co., Ltd.
Carton filling machine	60-720 box/min	7	Jiangsu Ketchview Machinery Technology Co., Ltd.
Palletizing machine	300-720 carton/min	7.2	Shangai LWT Machinery Co., Ltd.
Ink jet	19200 message/min	120-150	Zhangjiagang Fillex Beverage Machinery Co., Ltd

Table F. 4. Technical equipment specifications and main mass inputs in factory processing step of tomato juice production

Equipment	Capacity (h)	Power (kW)	Company/Model
Fruit loading pool	3 ton	4	Frumak, 2016/ELV0101
Washing machine (Water consumption: 3-5 ton/h)	5-9 ton	Blower: 5.5 Reductor: 4	Frumak, 2015/MYM0511
Mechanical water filter	3-5 ton	0.75	Frumak, 2015/SAF1201
Elevator	3-5 ton	1.1	Frumak, ELV300.01
Selecting and collecting conveyor	3-6 ton	0.75	Frumak, SAB900.01
Sorting band with roller	5-9 ton	0.75	Frumak, 2015/SAB0502
Collecting elevator	5-9 ton	0.75	Frumak, 2015/KE0503
Crusher (Fruit mill) (Water consumption: 5-7 ton)	4-9 ton	11	Frumak, 2015/KRC0510
Mono pump	5-9 ton	4	Frumak, 2015/MNPM1205
Heat exchanger	2 ton/h	2.2	Chenfei Machinery, China
Turbo Extractor	5 ton	1.5	Shase Machinery, SUS304
Pulp discharge screw	2-4 ton	1.10	Frumak, 2015/PAH0516
Pulp collecting tank and pump	3 ton	33.5	Frumak, 2015/PTT1210
Evaporator	Capacity: 2500 kg/h	22.5	Shangai Chengdong Co.Ltd.
Evaporation capacity:1500kg/h Steam consumption: 500 kg/h			
Vacuum vessel	1000 kg	Vacuum pump:7.5 Mixer motor reductor: 2.2	Frumak Machinery
Balancing tank	1400 kg	1.5	Frumak Machinery
Steam generator	3 ton	15	BK0540
Tubular sterilization machine	500 L	12.5	Shase Machinery, SUS304
Cooling water consumption: 3 ton/h Steam consumption:500 kg/h			
Aseptic filling	3 ton	2.2	
	Steam consumption: 40 kg/h		Shase Machinery, SUS304

Table F. 5. Equipment and technical specifications of packaging and transportation of tomato paste produced from 1 ton fresh tomato

Equipment	Capacity(unit/h)	Power(kW)	Company
Tin can filling machine (50-5000 mL)	600-6000	3-5	Shangai Honest Machinery Co., Ltd.
Carton printing and box making machine	7200	11	Dongguang Xinglong Packacing Machinery Co., Ltd.
Carton filling machine	60-720 box/min	7	JiangsuKetchview Machinery Technology Co., Ltd.
Palletizing machine	300-720 carton/min	7.2	Shangai LWT Machinery Co., Ltd.
Inkjet printer	19200 message/min	120-150	Zhangjiagang Fillex Beverage Machinery Co., Ltd

Table F. 6. The equipment and their specifications utilized to produce sweet red pepper paste

Equipment	Capacity (h)	Power (kW)	Model
Mechanical water filter	3-5 ton	0.75	Frumak, 2015/SAF1201
Case tipping machine	3 ton	11	Mekatronik Mak. San. ve Tic. Ltd. Şti.
Fruit-vegetable loading pool	3 ton	4	Frumak, 2016/ELV0101
Air bubble type washing machine	3-4 ton	3.37	Zhengzhou Inber Machinery Co., Ltd /Model:IB-5000
Pedicle taking machine	5 ton	0.75	Shanghai Genyond Technology Co., Ltd./ GYC
Elevator	3-5 ton	1.1	Frumak, ELV300.01
Selecting and collecting conveyor with roll	5-9 ton	0.75	Frumak, 2015/SAB0502
Elevator with collecting	5-9 ton	0.75	Frumak, 2015/KE0503
Pepper crushing machine	2-3 ton	4	Ateş Krom Gıda Makine Sanayi ve Ticaret Ltd. Şti.
Selecting and collecting conveyor	3-6 ton	0.75	Frumak, SAB900.01
Elevator	3-5 ton	1.1	Frumak, ELV300.01
Pepper mill	1-6 ton	37	Qingdao Glad Engineering Technology Co., Ltd. /GL-JMS-180A
Heat exchanger	2 ton/h	2.2	Chenfei Machinery, China
Turbo Extractor	5 ton	1.5	Shase Machinery, SUS304
Pulp collecting tank and pump	3 ton	33.5	Frumak, 2015/PTT1210
Evaporator Steam consumption: 500 kg/h	Capacity: 2500 kg/h Evaporating capacity:1500kg/h	22.5	Shangai Chengdong Co.Ltd.
Tubular sterilization machine Steam consumption:500 kg/h	500 L Cooling water consumption: 3 ton/h	12.5	Shase Machinery, SUS304
Steam generator	3 ton	15	BK0540
Filling balance tank	1400 kg	1.5	Frumach Machinery
Aseptic filling (5-220 L)	3 ton	2.2	
Steam consumption: 40 kg/h			Shase Machinery, SUS304

Table F. 7. The equipment and their specifications utilized to produce roasted sweet red pepper

Equipment	Capacity (h)	Power (kW)	Model
Fruit-vegetable loading pool	3 ton	4	Frumak, 2016/ELV0101
Air bubble type washing machine	3-4 ton	3.37	Zhengzhou Inber Machinery Co., Ltd /Model:IB-5000
Mechanical water filter	3-5 ton	0.75	Frumak, 2015/SAF1201
Selecting and collecting conveyor with roll	3-6 ton	0.75	Frumak, SAB900.01
Elevator	3-5 ton	1.1	Frumak, ELV300.01
Pedicle taking machine	5 ton	0.75	Shanghai Genyond Technology Co., Ltd./ GYC
Roasting tunnel	800 kg	5.5	Frumak, FRM.20KT.800
Elevator	3-5 ton	1.1	Frumak, ELV300.01
Pepper crushing machine	2-3 ton	4	Ateş Krom Gıda Makine Sanayi ve Ticaret Ltd. Şti.
Selecting and collecting conveyor with water canal	3 ton	0.75	Zhengzhou Syoung Machinery Co., Ltd
Steam generator	3 ton	15	BK0540

Table F. 8. The equipment and their specifications utilized to produce dried sweet red pepper

Equipment	Capacity(h)	Power (kW)	Model
Fruit-vegetable loading pool	3 ton	4	Frumak, 2016/ELV0101
Air bubble type washing machine	3-4 ton	3.37	Zhengzhou Inber Machinery Co., Ltd /Model:IB-5000
Mechanical water filter	3-5 ton	0.75	Frumak, 2015/SAF1201
Selecting and collecting conveyor	3-6 ton	0.75	Frumak, SAB900.01
Elevator	3-5 ton	1.1	Frumak, ELV300.01
Cutting machine	2-3 ton	2.24	Chongqing Qiaoxing Machinery & Equipment Company/Model: AST-QC1500
Linear vibrating sieve	0.05-5	0.74	Xinxiang Dahan Vibrating Machinery Co., Ltd./DZSF-520-1S
Selecting and collecting conveyor	3-6 ton	0.75	Frumak, SAB900.01
Drying oven (Steam capacity: 750 kg/h)	2-2.5 ton	65	Frumak, FRM.16KF-12
Steam generator	3 ton	15	BK0540

Table F. 9. Specific CEnC values of packaging and transportation step inputs of SRP products

Inputs	Specific CEnC	Unit	Reference
Diesel	47.6	MJ/kg	(B. D. Solomon & Banerjee, 2006)
Electricity	11.93	MJ/kWh	(Sefeedpari, 2012)
Natural gas	55.5	MJ/kg	(B. D. Solomon & Banerjee, 2006)
PP	9.3	MJ/kg	(Worrell, Phylipsen, Einstein, & Martin, 2000)
Cardboard	43.3	MJ/kg	(Chow et al., 2005)
Paper	12.1	MJ/kg	(De Beer, Worrell, & Blok, 1998)
PP	1.8	MJ/kg	(Gielen & Tam, 2006)
PET	83.8	MJ/kg	(Özilgen, 2018)
Biodiesel	37	MJ/kg	(Carraretto, 2004)
Water	0.07	MJ/L	(Özilgen, 2018)
Vinegar	5.24	MJ/kg	(Degerli, Nazir, Sorgüven, Hitzmann, & Özilgen, 2015)
Sugar	9.8	MJ/kg	(Sorgüven & Özilgen, 2012)
Salt	10.3	MJ/kg	(Degerli et al., 2015)

Table F. 10. Specific CExC values of packaging and transportation step inputs of tomato products

Inputs	Specific CExC	Unit	Reference
Diesel	42.3	MJ/kg	(B. D. Solomon & Banerjee, 2006)
Electricity	4.17	MJ/kg	(Cengel & Boles, 2006)
Natural gas	51.7	MJ/kg	(B. D. Solomon & Banerjee, 2006)
PE	86	MJ/kg	(Dewulf & Van Langenhove, 2004)
Cardboard	16.5	MJ/kg	(Lattouf & Oliveira Júnior, 2003)
Paper	34.6	MJ/kg	(De Beer et al., 1998)
PP	85.2	MJ/kg	(Dewulf & Van Langenhove, 2004)
PET	86.8	MJ/kg	(Dewulf & Van Langenhove, 2004)
Biodiesel	8.8	MJ/kg	(Sorguven & Özilgen, 2010)
Water	0.29	MJ/L	(Özilgen, 2018)
Vinegar	10.61	MJ/kg	(Özilgen, 2018)
Sugar	14.46	MJ/kg	(Sorgüven & Özilgen, 2012)
Salt	20.6	MJ/kg	(Degerli et al., 2015)

Table F. 11. Specific CCO₂C values of packaging and transportation step inputs

Inputs	Specific CCO ₂ C	Unit	Reference
Diesel	3.17	kg/kg	(Kalnes et al., 2007)
Electricity	0.14	MJ/kg	(Özilgen & Oner, 2016)
Natural gas	0.05	kg/MJ	(Nejat, Jomehzadeh, Taheri, Gohari, & Abd. Majid, 2015)
PE	0.45	kg/kg	(Sorgüven & Özilgen, 2012)
Cardboard	1.17	kg/kg	(Chow et al., 2005)
Paper	0.3	kg/kg	(Laurijssen, Marsidi, Westenbroek, Worrell, & Faaij, 2010)
PP	0.25	kg/kg	(Sorgüven & Özilgen, 2012)
PET	2.33	kg/kg	(Doğan, 2008)
Biodiesel	0.97	kg/kg	(Cavalett & Ortega, 2010; Kalnes et al., 2007)
Water	9.8x10 ⁻³	kg/L	(Özilgen, 2018)
Vinegar	1.94 – 2.54	kg/kg	(Bartocci, Fantozzi, & Fantozzi, 2017)
Sugar	0.95	kg/kg	(Sorgüven & Özilgen, 2012)
Salt	0.46	kg/kg	(Degerli et al., 2015)

Table F. 12. Specific energy data of inputs for fresh (field) tomato production

Inputs	Specific CEnC	References
Fertilizers (kg)		
Nitrogen (N) (MJ/kg)	78.2	(Özilgen & Sorgüven, 2011)
Phosphorus (P ₂ O ₅) (MJ/kg)	17.5	(Özilgen & Sorgüven, 2011)
Potassium (K ₂ O) (MJ/kg)	13.8	(Özilgen & Sorgüven, 2011)
Chemicals (kg)		
Pesticides (MJ/kg)	198.8	(Wittmus et al., 1975)
Fungicides (MJ/kg)	198.8	(Wittmus et al., 1975)
Herbicides (MJ/kg)	198.8	(Wittmus et al., 1975)
Water for irrigation (kg) (MJ/kg)	0.00102	(Wittmus et al., 1975)
Electricity (MJ/MJ)	1	(Cengel & Boles, 2006)
Human labor (MJ)	1.96	(Mohammadi, Tabatabaeefer, Shahin, Rafiee, & Keyhani, 2008)
Machinery use (MJ)	64.8	(Singh et al., 1998)
Seed (MJ)	1.0	(Esengun et al., 2007)
Diesel (MJ/kg)	47.6	(Solomon & Banerjee, 2006)

Table F. 13. Specific exergy data of inputs for fresh (field) tomato production

Inputs	Specific CExC	References
Fertilizers (kg)		
Nitrogen (N) (MJ/kg)	32.7	(Cengel & Boles, 2006)
Phosphorus (P ₂ O ₅) (MJ/kg)	7.52	(Berthiaume & Bouchard, 1999)
Potassium (K ₂ O) (MJ/kg)	4.56	(Berthiaume, Bouchard, & Rosen, 2001)
Chemicals (kg)		
Pesticides (MJ/kg)	7.52	(Berthiaume et al., 2001)
Fungicides (MJ/kg)	4.56	(Berthiaume et al., 2001)
Herbicides (MJ/kg)	32.70	(Berthiaume et al., 2001)
Diesel (kg) (MJ/kg)	53.20	(Cengel & Boles, 2006)
Water for irrigation (kg) (MJ/kg)	0.00425	(Jan Szargut et al., 1988)
Electricity (MJ/MJ)	4.17	(Cengel & Boles, 2006)
Diesel (MJ/kg)	42.3	(B. D. Solomon & Banerjee, 2006)

Table F. 14. Specific CO₂ data of inputs for fresh (field) tomato production

Inputs	Specific CCO₂C	References
Fertilizers (kg)		
Nitrogen (N) (kg/kg)	0.09	(Helsel, 1992)
Phosphorus (P ₂ O ₅) (kg/kg)	0.15	(Helsel, 1992)
Potassium (K ₂ O) (kg/kg)	0.51	(Helsel, 1992)
Chemicals (kg)		
Pesticides(kg/kg)	5.1	(Kongshaug,1998)
Fungicides (kg/kg)	3.9	(Kongshaug,1998)
Herbicides (kg/kg)	6.3	(Kongshaug,1998)
Diesel (kg) (kg/kg)	0.94	(Kongshaug,1998)
Water for irrigation (kg/kg)	0.000595	(Szargut et al., 1988)
Electricity (MJ/kg)	0.14	(Özilgen & Oner, 2016)
Diesel (MJ/kg)	3.17	(Roy et al., 2008)

Table F. 15. Specific CEnC values of SRP farming inputs

Inputs(Units)	Specific CEnC	References
Fertilizers (kg)		
Nitrogen (N) (MJ/kg)	78.2	(Özilgen & Sorgüven, 2011)
Phosphorus (P ₂ O ₅) (MJ/kg)	17.5	(Özilgen & Sorgüven, 2011)
Potassium (K ₂ O) (MJ/kg)	13.8	(Özilgen & Sorgüven, 2011)
Chemicals (kg)		
Pesticides (MJ/kg)	198.8	(Wittmus et al., 1975)
Fungicides (MJ/kg)	198.8	(Wittmus et al., 1975)
Herbicides (MJ/kg)	198.8	(Wittmus et al., 1975)
Diesel (MJ/kg)	47.6	(B. D. Solomon & Banerjee, 2006)
Water for irrigation(MJ/kg)	0.00102	(Wittmus et al., 1975)
Electricity (MJ/kwh)	11,93	(Sefeedpari, 2012)
Human labor (MJ)	1.96	(Mohammadi et al., 2008)

Table F. 16. Specific CExC values of SRP farming inputs

Inputs(Units)	Specific CExC	References
Nitrogen (N) (MJ/kg)	32.7	(Cengel & Boles, 2006)
Phosphorus (P ₂ O ₅) (MJ/kg)	7.52	(Berthiaume & Bouchard, 1999)
Potassium (K ₂ O) (MJ/kg)	4.56	(Berthiaume et al., 2001)
Pesticides (MJ/kg)	7.52	(Pimentel, 1991)
Fungicides (MJ/kg)	4.56	(Pimentel, 1991)
Herbicides (MJ/kg)	32.70	(Pimentel, 1991)
Diesel (MJ/kg)	42.3	(B. D. Solomon & Banerjee, 2006)
Water for irrigation(MJ/kg)	0.00425	(Szargut et al., 1988)
Electricity (MJ/MJ)	4.17	(Cengel & Boles, 2006)
Human labor (MJ/h)	71.9	(Chen & Chen, 2009)

Table F. 17. Specific CCO₂C values of farming inputs

Inputs(Units)	Specific CCO₂C	References
Nitrogen (N) (MJ/kg)	0.09	(Helsel, 1992)
Phosphorus (P ₂ O ₅) (MJ/kg)	0.15	(Helsel, 1992)
Potassium (K ₂ O) (MJ/kg)	0.51	(Helsel, 1992)
Pesticides (MJ/kg)	5.1	(Kongshaug, 1998)
Fungicides (MJ/kg)	3.9	(Kongshaug, 1998)
Herbicides (MJ/kg)	6.3	(Kongshaug, 1998)
Diesel (kg) (MJ/kg)	3.17	(Kalnes et al., 2007)
Water for irrigation(MJ/kg)	0.000595	(Szargut et al., 1988)
Electricity (MJ/MJ)	0.18	(Nejat et al., 2015)
Human labor (kg CO ₂ /man-h)	0.7	(Nguyen & Hermansen, 2012)

APPENDIX G

OpenLCA user interface and step-by-step instructions for completing an LCA analysis with OpenLCA software

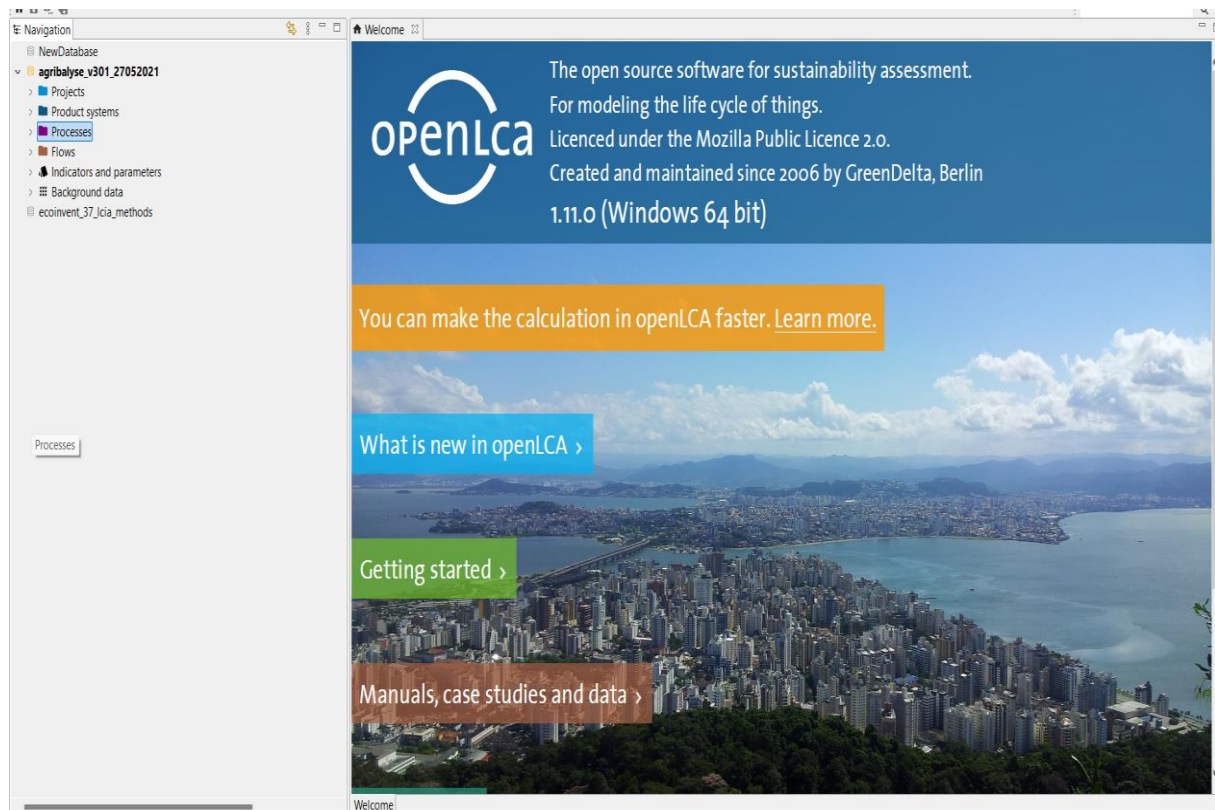


Figure G. 1. OpenLCA introduction interface

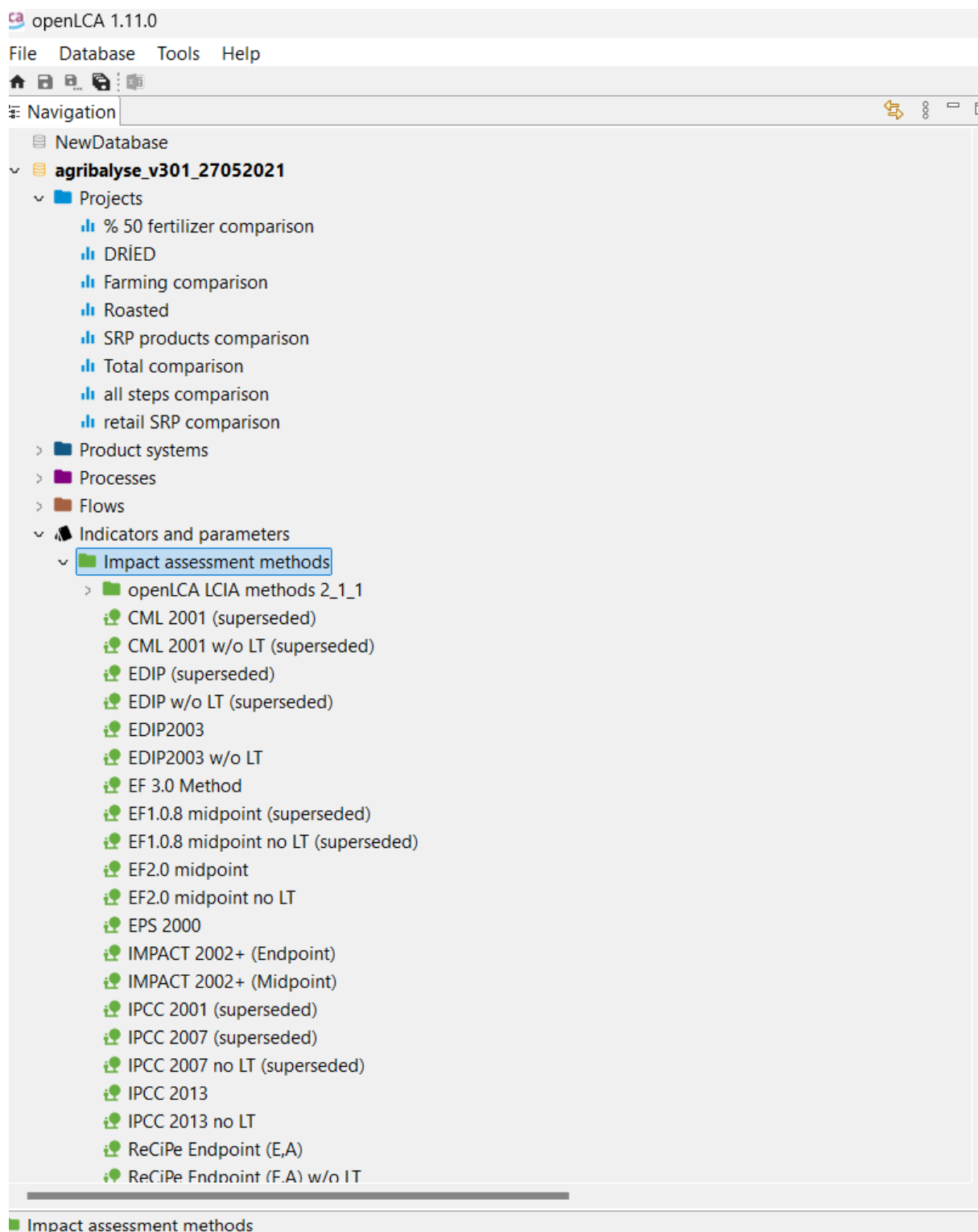


Figure G. 2. OpenLCA Navigation tab interface including databases

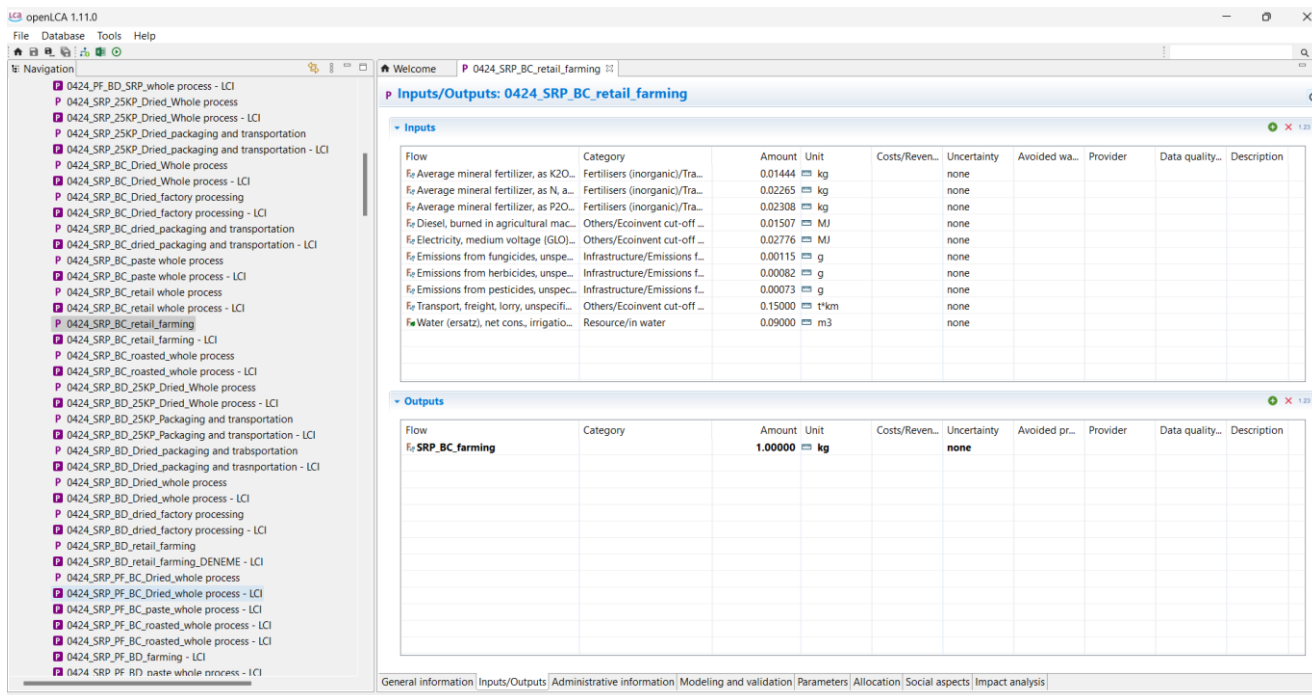


Figure G. 3. OpenLCA inventory data entry tab interface

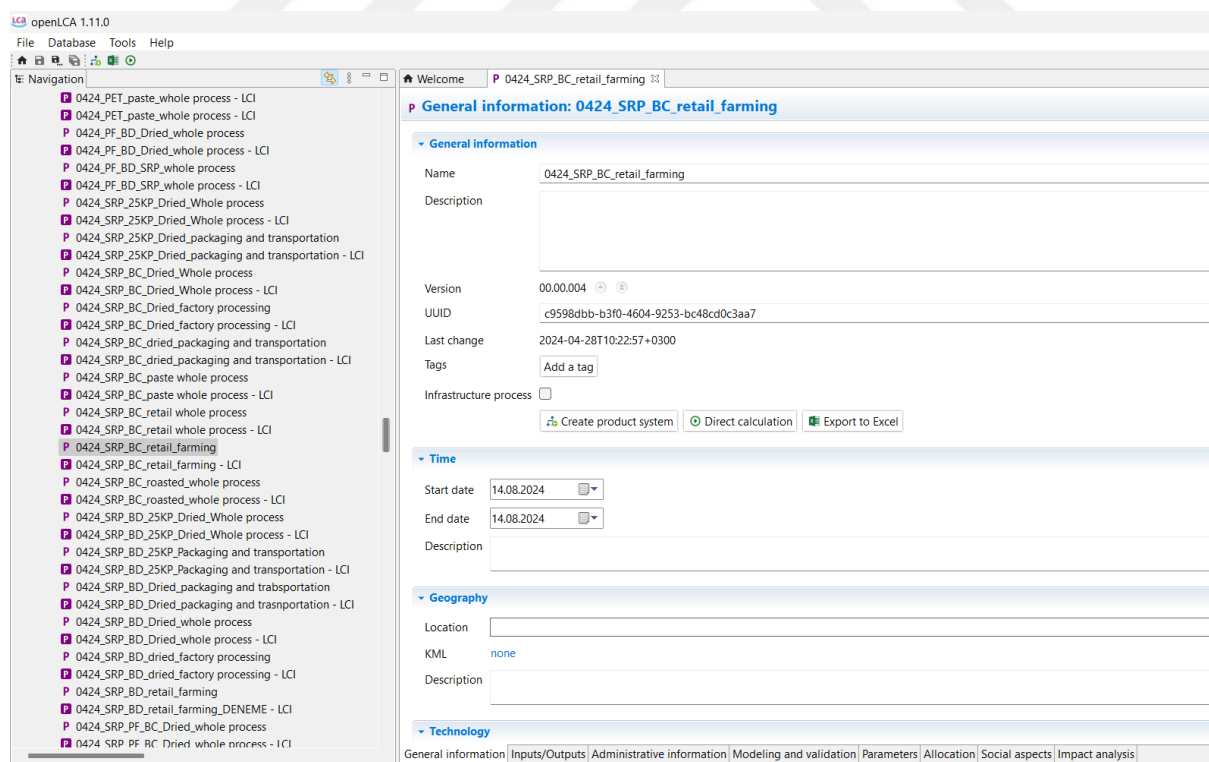


Figure G. 4. OpenLCA product system creation step interface

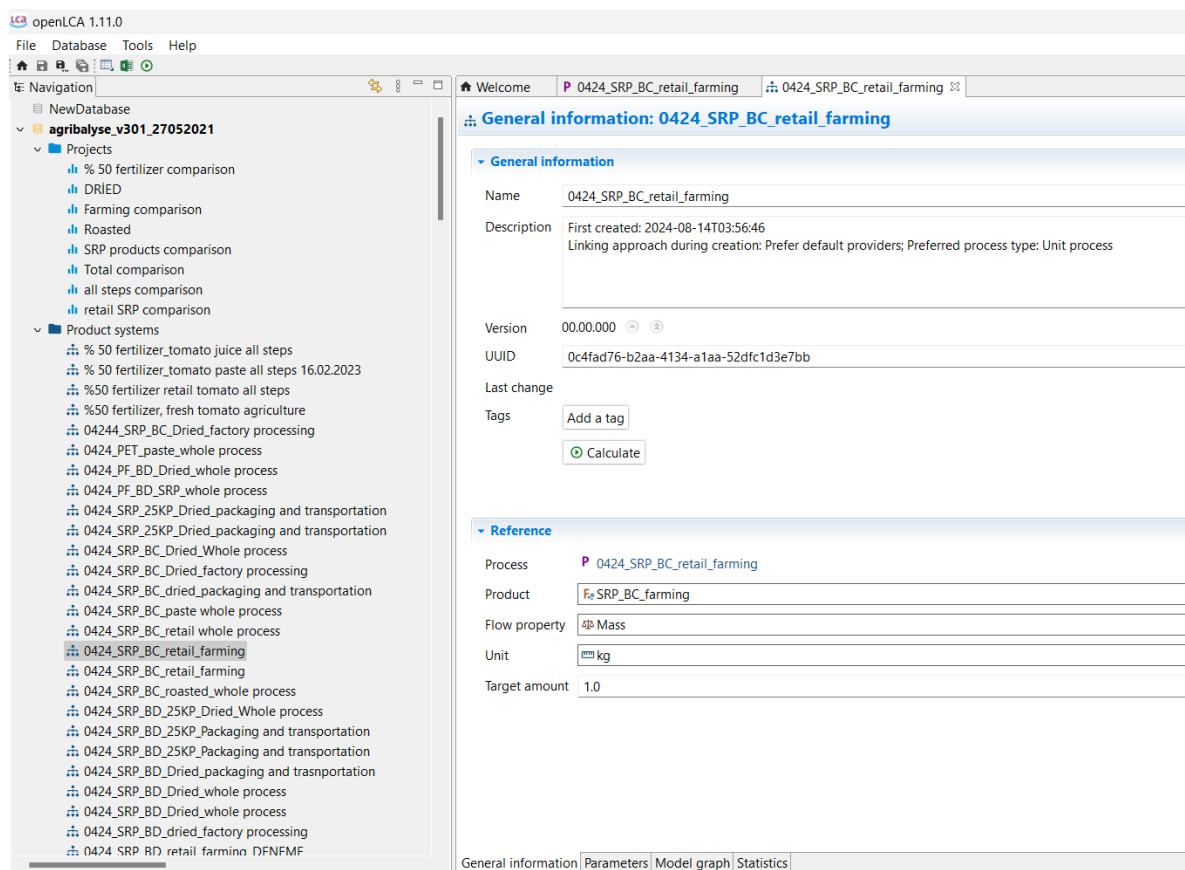


Figure G. 5. OpenLCA process calculation step 1st interface

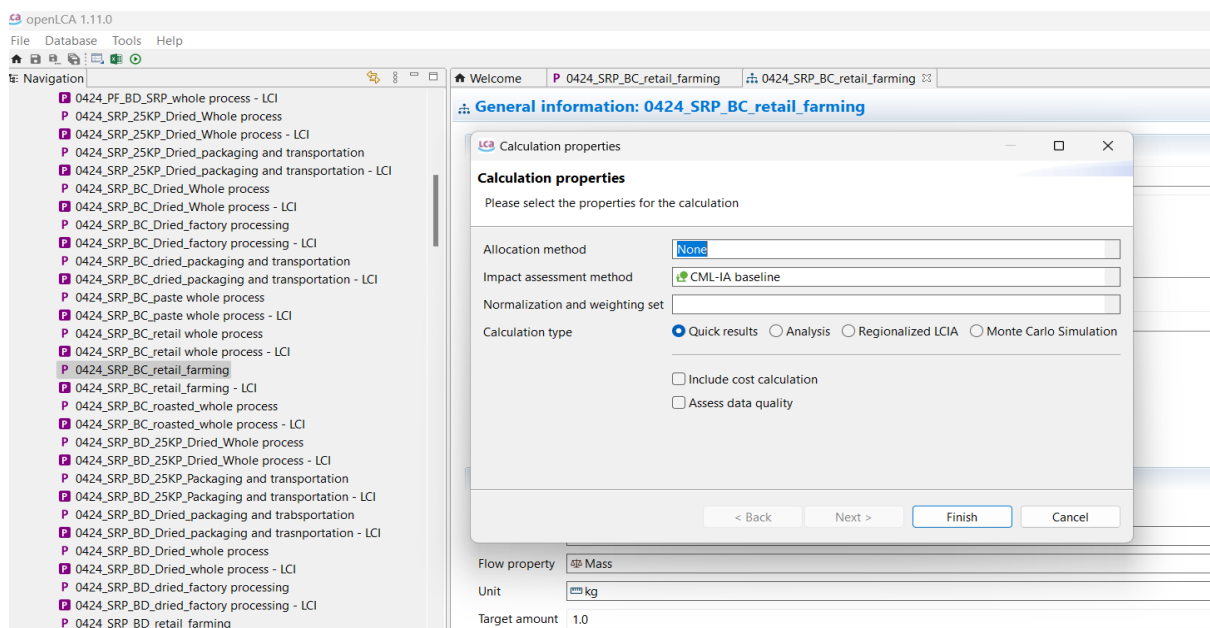


Figure G. 6. OpenLCA process calculation step 2nd interface

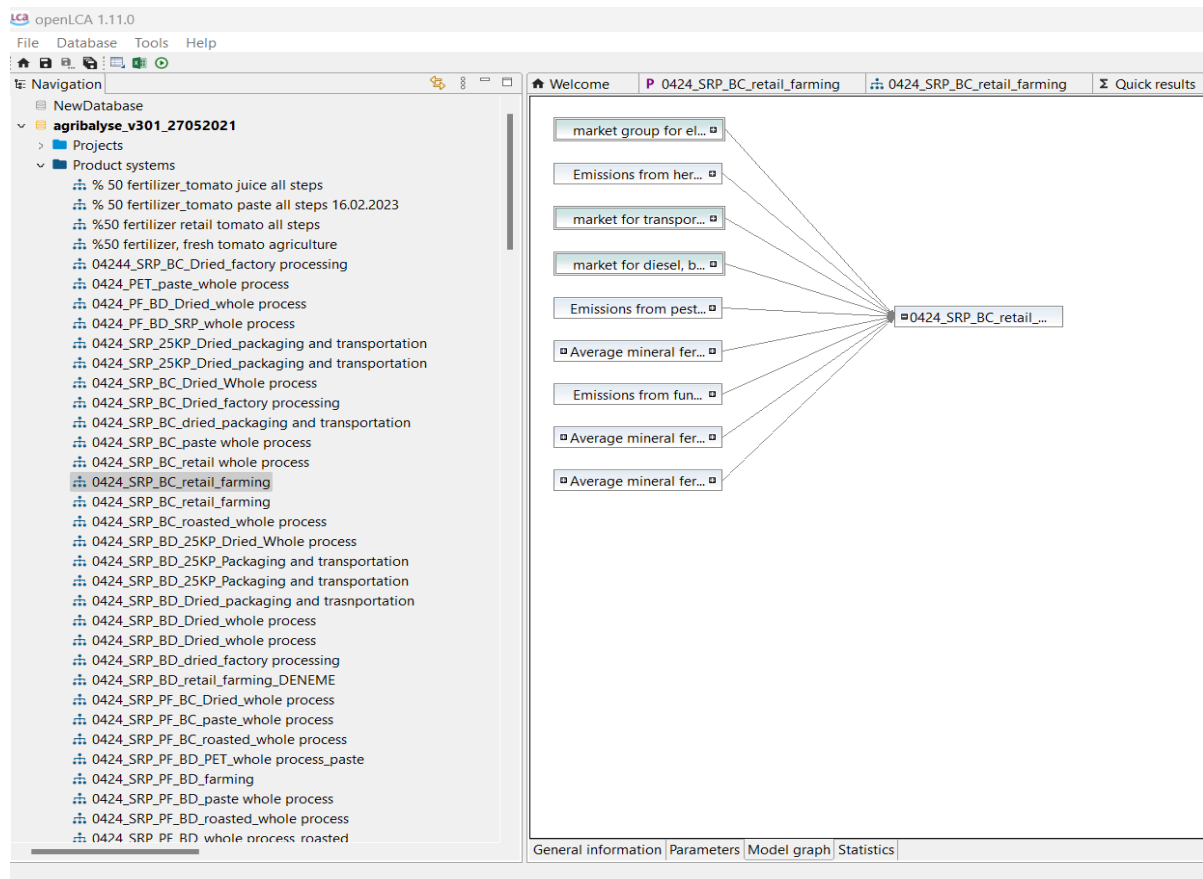


Figure G. 7. OpenLCA process model graph tab for the first flows

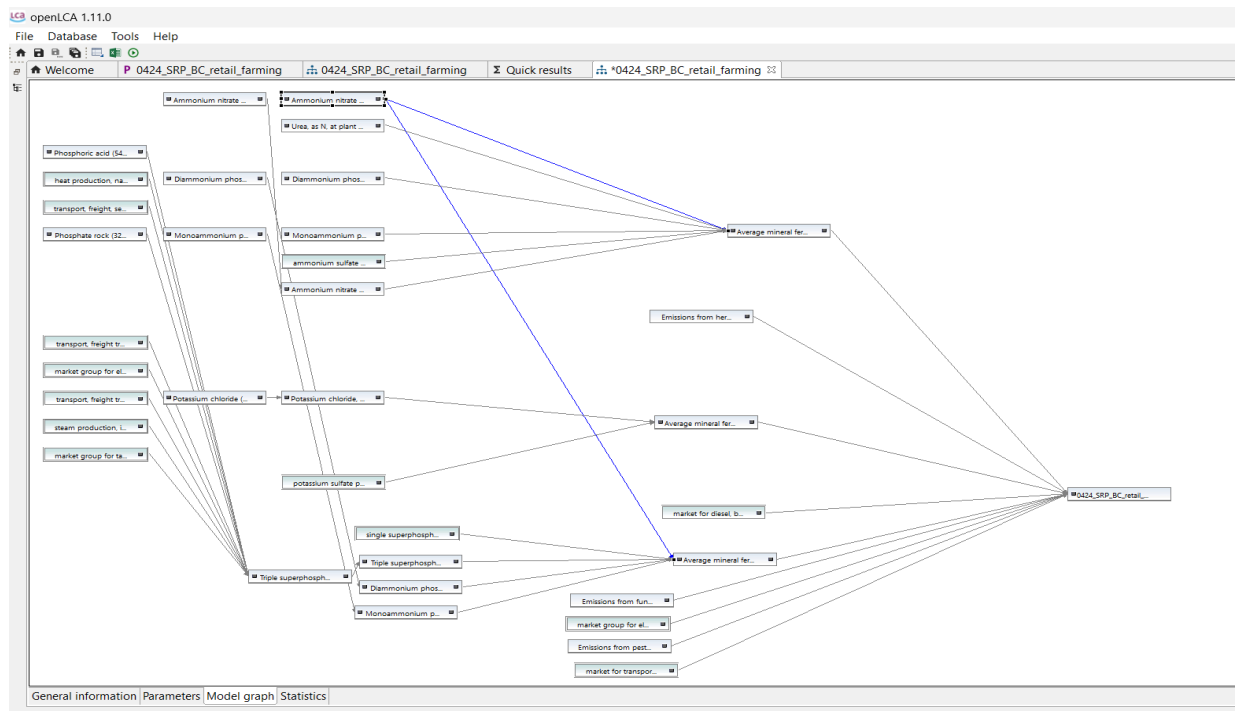


Figure G. 8. OpenLCA process model graph tab for the first and other flows

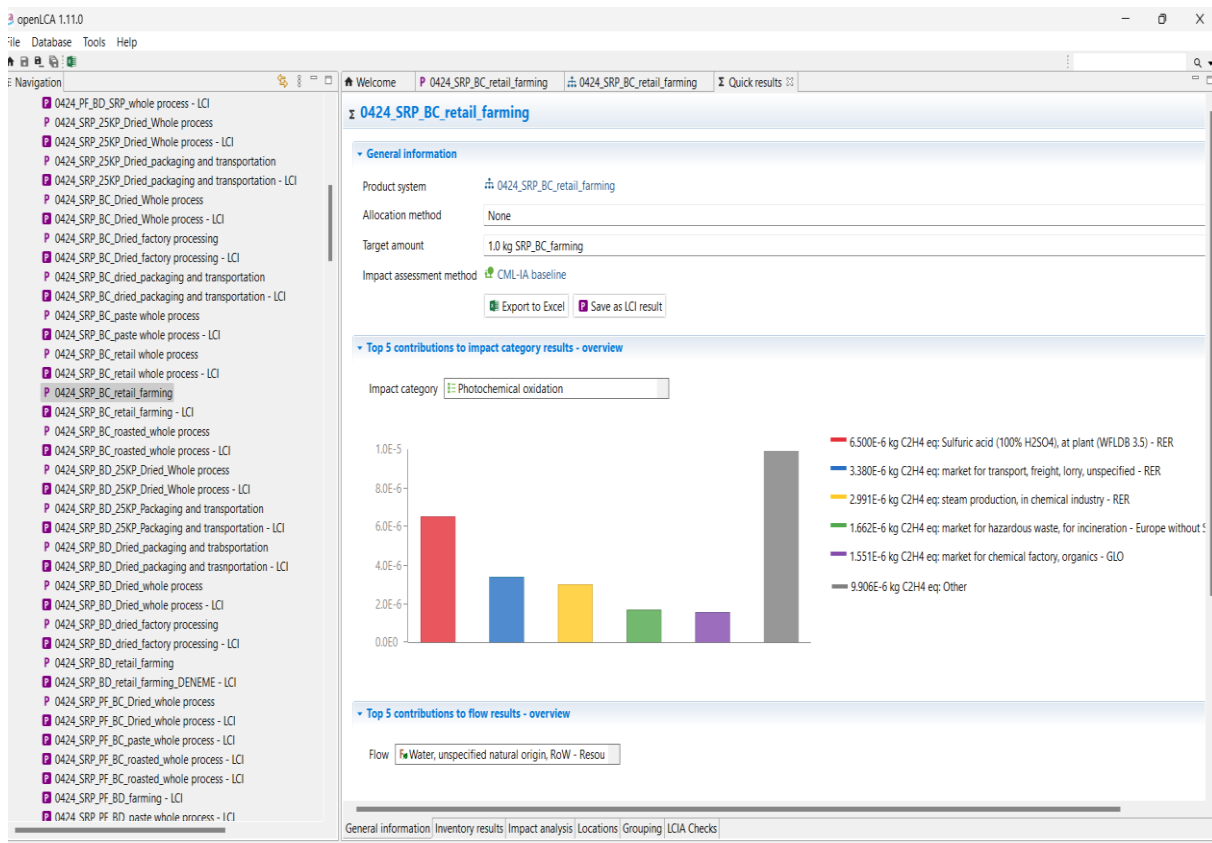


Figure G. 9. OpenLCA whole results interface

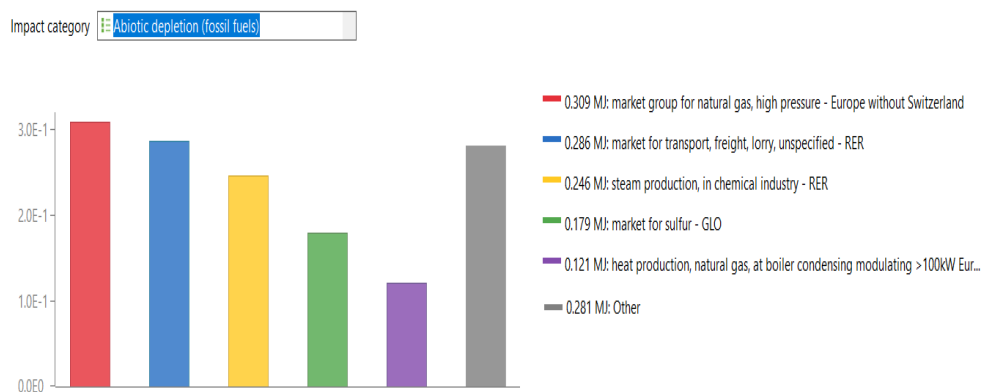


Figure G. 10. OpenLCA individual results of calculation step