TÜRKİYE CUMHURİYETİ
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GRADUATE SCHOOL
MATERIALS ENGINEERING DEPARTMENT

AN ASSESSMENT OF BIOPLASTIC APPLICATIONS IN AGRICULTURE WITHIN A SUSTAINABLE FRAMEWORK

PINAR TÜRKMEN

M.Sc.

ADANA 2024

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THESIS ADVISOR
Asst. Prof. Dr. Mine TAYKURT DADAY

ADANA, 2024

CERTIFICATION OF APPROVAL

(AN ASSESSMENT OF BIOPLASTIC APPLICATIONS IN AGRICULTURE WITHIN A SUSTAINABLE FRAMEWORK)

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In this thesis study, which was prepared following the thesis writing rules of Adana Alparslan Türkeş Science and Technology University Institute of Graduate School, I declare that I provide all the information, documents, evaluations and results in accordance with scientific ethics and moral codes without resorting to any means or assistance that would be contrary to scientific ethics and traditions. I also declare that I refer to all of the articles I used in this study with appropriate references and accept all moral and legal consequences if a situation is found contrary to my statement regarding my work.

22/04/2024

[Signature]

Pınar TÜRKMEN

ÖZET

TARIMDA BİYOPLASTİK UYGULAMALARININ SÜRDÜRÜLEBİLİR BİR ÇERÇEVEDE DEĞERLENDİRİLMESİ

Pınar TÜRKMEN
Yüksek Lisans, Malzeme Mühendisliği Anabilim Dalı
Danışman: Dr. Öğr.Üy. Mine TAYKURT DADAY
Nisan 2024, 87 sayfa

Dünyanın yüzey sıcaklığı 1950'lerden itibaren normalin üzerinde seyretmektedir. Küresel ısınmanın insan ve canlı sağlığını tehdit eden etkileri bulunmaktadır. Bunlardan biri kuraklık tehlikesidir. Su kaynaklarını korumak için çeşitli çözümler denenmektedir. İnsanlığın diğer bir problemi ise nüfus artışına bağlı olarak artan gıda talebidir. Bu talebi karşılayabilmek için tarımsal verimliliğin artırılması gerekmektedir. Tarımda kullanılan plastik malçların suyun etkin kullanımı, verimlilik ve kaliteye pozitif etkisi birçok araştırmayla kanıtlanmıştır. Ancak petrol bazlı plastikler küresel ısınmaya neden olan karbon emisyonlarını artırmakta, yıllarca doğada bozunmadan kalmakta ve bozunmaya başlasa dahi küçük parçacıklara ayrılarak toprağa, suya ve besinlere karışarak insan, canlı ve çevre sağlığına zarar vermektedir. Tarımda toprağı ve çevreyi kirletmeyen doğal olarak kendiliğinden bozunabilen biyoplastik malç malzemelerinin kullanımı elzem hale gelmiştir.

Petrol bazlı biyoplastik malçların yerini alabilecek biyobozunur ve çevre dostu malçların kullanımı için öncelikle su buharı geçirgenliği, mekanik özellikler başta olmak üzere ürünün belirgin bir kalite seviyesine ulaşması ve pazardaki ekonomik beklentiyi arz ve talebe uygun olarak karşılaması gerekmektedir. Bu çalışma sürdürülebilirlik ile tarım sektörü arasındaki güçlü ilişkiyi göstermekte, biyoplastik malç malzemeleri ile ilgili yapılan araştırmaları incelemekte, piyasadaki mevcut ürünlerin durumunu ortaya koymakta ve özelliklerini karşılaştırmakta ve günümüze dek yapılmış araştırmaları üretim, uygulama ve karakterizasyon bakış açısıyla değerlendirmektedir.

Anahtar Kelimeler: Biyobozunur Malç, Biyoplastik, Sürdürülebilirlik, Sürdürülebilir Tarım

ABSTRACT

AN ASSESSMENT OF BIOPLASTIC APPLICATIONS IN AGRICULTURE WITHIN A SUSTAINABLE FRAMEWORK

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The Earth's surface temperature has been exceeding normal levels since the 1950s. Global warming poses threats to human and living health. Various solutions are being explored to protect water resources. Another challenge facing humanity is the increasing demand for food due to population growth. Enhancing agricultural productivity is necessary to meet this demand. The effective use of plastic mulches in agriculture, as evidenced by numerous studies, positively impacts water efficiency, productivity, and quality. However, petroleum-based plastics contribute to global warming by increasing carbon emissions and can persist in the environment for years, even when they begin to degrade, breaking down into small particles that mix into soil, water, and food, posing risks to human, animal, and environmental health. The use of biodegradable bioplastic mulch materials, which naturally decompose without polluting soil and the environment, has become essential in agriculture.

To replace petroleum-based mulches with biodegradable and eco-friendly bioplastic alternatives, it is imperative to achieve significant product quality, including water vapor permeability and mechanical properties, to meet the economic expectations of supply and demand. This study demonstrates the strong relationship between sustainability and the agricultural sector, examines research related to bioplastic mulch materials, evaluates the current state of products in the market, compares their characteristics, and also assesses research conducted to the perspectives of production, application, and characterization.

Keywords: Biodegredable Mulch, Bioplastics, Sustainability, Sustainable Agriculture

Dedication

Dedication to my beautiful, little girl Rengin Ela Türkmen,

to be an exemplary mother to her and for her to have a beautiful memory from me.

ACKNOWLEDGEMENTS

I am happy to have completed my thesis, which I will remember with pride for the rest of my life. Although we were tested with various difficulties throughout my thesis process, I would like to thank my thesis advisor, my esteemed teacher, Asst. Prof. Dr. Mine TAYKURT DADAY.

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I am deeply indebted to my dear family for their understanding and support throughout my thesis journey. Special thanks to my husband, Sebahattin TÜRKMEN, for his patience and support at home while I dedicated to my thesis after work and to my sweet daughter for her understanding of the reduced time I spent with her. Lastly, I would like to express my profound gratitude to my mother, father, and brother, who have always encouraged me daily to persevere and complete my thesis.

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LIST OF ABBREVIATIONS

ASTM International	: American Society for Testing and Materials
BDM	: Biodegradable Mulch
CE	: Chain Extender
CSA	: Climate-Smart Agriculture
EAB	: Elongation at Break
EU	: European Union
FAO	: Food and Agriculture Organization of the United Nations
FTIR	: Fourier Transform Infrared Spectroscopy
FW	: Fennel Waste
IFAD	: International Fund for Agricultural Development
IPCC	: Intergovernmental Panel on Climate Change
LDPE	: Low Density Polyethylene
LLDPE	: Linear Low-Density Polyethylene
NASA	: National Aeronautics and Space Administration
PAGEV Foundation	: Turkish Plastic Industrialists Research, Development and Education
PBAT	: Polybutylene Adipate Terephthalate
PBS	: Polybutadiene Succinate
PBSA	: Poly(butylene succinate-co-butylene adipate)
PCL	: Polycaprolactone
PE	: Polyethylene
PEM	: Petroleum-Based Polyethylene Mulch
PET	: Polyethylene Terephthalate
Pha	: Phaseolin
PHA	: Polyhydroxyalkanoate

PHB	: Polyhydroxybutyrate
PLA	: Polyactic Acid
PP	: Polypropylene
PS	: Polystyrene
PVA	: Polyvinyl Alcohol
PVC	: Polyvinyl Chloride
SEM	: Scanning Electron Microscopy
TG	: Transglutaminase
TPS	: Thermoplastic Starch
TS	: Tensile Strenght
UN	: United Nations
UNDP	: United Nations Development Programme
USDA	: United States Department of Agriculture
YM	: Young's Modulus
WFP	: World Food Programme
WUE	: Water Use Efficiency
WVP	: Water Vapor Permeability
XRD	: X-Ray Diffraction

LIST OF SYMBOLS

C	: Carbon
°C	: Celsius
cm	: Centimeter
CO_2	: Carbon dioxide
$CaCO_3$	: Calcium carbonate
ha	: Hectare
N	: Nitrogen
t	: Tons
µm	: Micrometer

1. INTRODUCTION

In the 21st century, the Climate Crisis has emerged as the world's most pressing global challenge, characterized by threats to human and all life forms due to climate change and ecosystem shifts resulting from the excessive accumulation of greenhouse gases in the atmosphere (Intergovernmental Panel on Climate Change (IPCC), 2023). According to a graph (Figure 1) published by the National Aeronautics and Space Administration (NASA) in 2020, the yellow line represents solar energy received by the Earth, while the red line depicts the change in global surface temperature. Since the 1950s, a significant and unnatural increase in global temperatures has been observed.

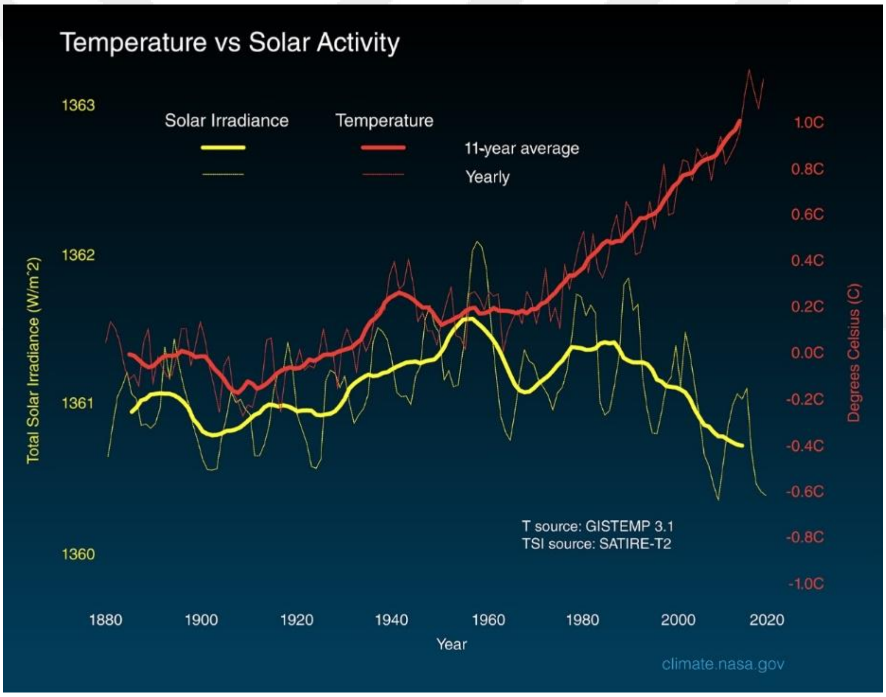


Figure 1. Global Temperature and Solar Activity (NASA, 2020)

Based on NASA's analysis of satellite data in 2021, Turkey is currently facing its driest period in 15 years, with 2020 registering temperatures above normal seasonal levels, posing a threat to agricultural productivity. Figure 2 illustrates water scarcity in Turkey, depicted by the orange and red areas on the map below (NASA, 2021).

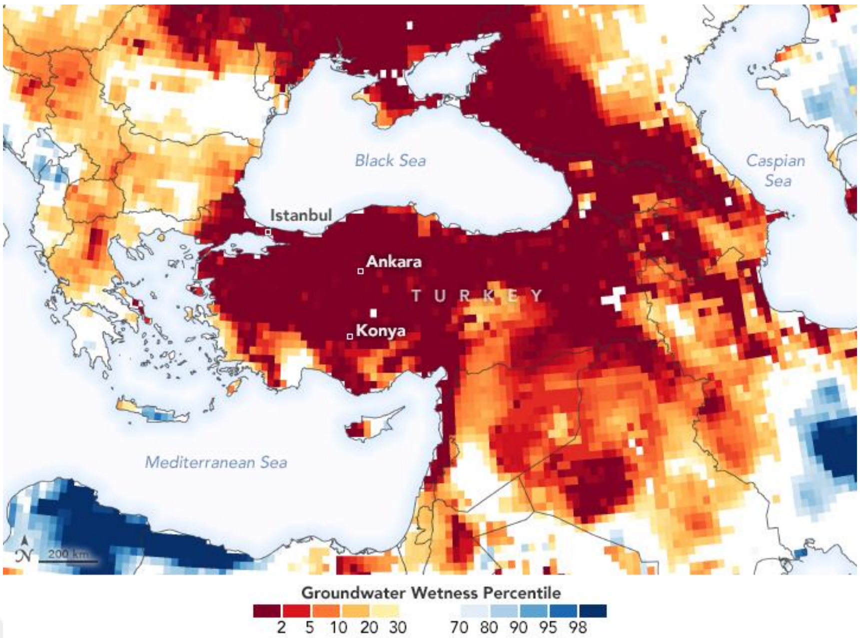


Figure 2. Groundwater Wetness Percentile (NASA, 2021)

In the 21st century, many regions worldwide are anticipated to face increased challenges of intense and frequent extreme heat and drought. The water demand is rising in tandem with population growth and industrial expansion. Therefore, proper management and conservation of limited water resources are critically important. Freshwater sources, constituting only 2.5% of the world's total water, are progressively diminishing (Mishra, 2023). Furthermore, up to 25% of global water usage is lost through evaporation. There is an urgent need for rapid, accessible, and technology-driven solutions to mitigate this water loss (Haghighi et al., 2018).

Water evaporation diminishes the quantity and quality of water stored in pools, ponds, and rivers. Floating small plastic spheres, commonly referred to as shade balls or bird balls (Figure 3a), serve to mitigate water evaporation and inhibit the reaction of sunlight with chemical compounds in the water. Research indicates that using such balls on the water surface can yield approximately 43-45% water savings. Notably, the Los Angeles Department of Water and Power implemented a project in 2008 involving 400,000 balls deployed in the Ivanhoe reservoir (Figure 3b), resulting in an annual water savings of 1.1 billion liters (Maniyar et al., 2020).

Figure 3. (a) A Shade Ball (Wikipedia, 2019), (b) Shade Balls in the Ivanhoe Reservoir (Wikipedia, 2015)

The global human population has experienced rapid growth since the dawn of civilization. Over the past 173 years, the human population has surged from 1.1 billion during the Industrial Revolution in the 1850s to an estimated 8.5 billion in 2023, marking a staggering 673% increase. Projections suggest that at the current growth rate, the world population will reach 10 billion by 2055 (United Nations Department of Economic and Social Affairs, 2022).

The rapid growth of the global population presents a significant challenge. This population surge escalates the demand for food, a fundamental necessity. To meet the needs of a rapidly expanding population and to supply feedstock for various sectors, current food production must increase by 60% (Timsina, 2018). However, the global climate crisis and rising temperatures jeopardize agricultural production's sustainability. According to a report by the IPCC in 2014, significant shifts in temperature and precipitation patterns resulting from climate change will directly impact the agricultural sector. The report highlights that a 4.5 - 5 °C increase in global average soil temperature could lead to a 16% reduction in agricultural productivity. By the 2030s, it is estimated that staple food crops such as wheat, corn, and rice may experience lower or stagnant production levels due to the adverse effects of climate change (Kebeda, 2019). The global economic toll of climate change from 2000 to 2019 is estimated at $2.8 trillion (Newman & Noy, 2023).

It is anticipated that the agricultural sector will endure the most severe economic repercussions, potentially precipitating a global food crisis, due to rising global temperatures, rapid depletion of freshwater resources, shifting climatic conditions, and extreme weather events that have devastating effects on agricultural production (The World Agriculture Organization's Food and Agriculture Organization (FAO), 2020).

FAO of the United Nations (UN) 2020 publication titled "The State of Food Security and Nutrition in the World 2020" emphasizes that currently world, over 820 million people are still suffering from hunger. According to the publication, two billion people worldwide face moderate to extreme levels of food insecurity. It is estimated that the food crisis will affect 9.8% of the world's population in 2030. The global COVID-19 pandemic in 2020 showed that despite the high grain stocks of most countries, there could be a major crisis in food access and food security. Moreover, as shown in Figure 4, according to the FAO World Food Price Index, global food costs have risen rapidly from the past to the present. Food access challenges and rising food prices have a greater impact on poor populations with limited purchasing power (FAO, 2023).

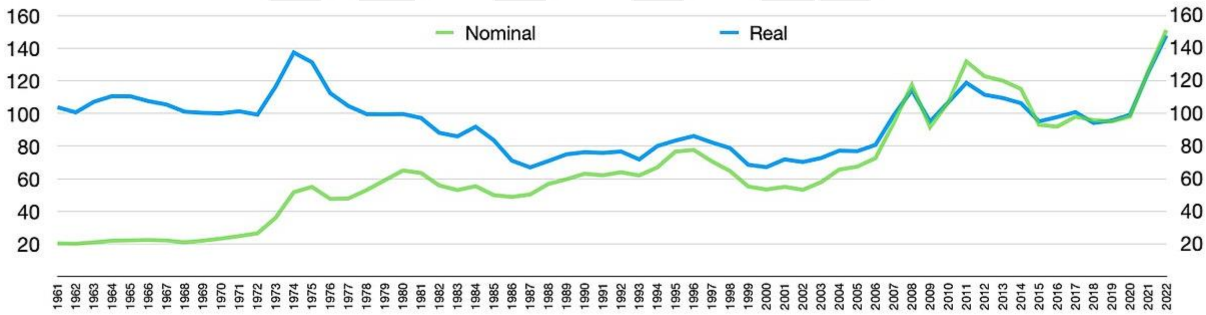


Figure 4. The FAO Food Price Index for 1961-2021 (FAO, 2023)

In 2015, the Sustainable Development Goals (SDGs) were agreed by UN member nations to cover the period up to 2030. These goals are a roadmap to promote global sustainability. The titles of these 17 global goals are indicated in Figure 5 below.

Figure 5. The Sustainable Development Goals (United Nations, 2015a)

The sustainability and safety of food production are environmentally friendly, reliable food production and systems for consumers, considering future generations with the conscious use of natural and renewable energy resources, without harming nature to ensure safe food access to societies. Food security and sustainability are directly linked to SDGs “Goal 1: Fight Hunger, Goal 2: End Hunger, Goal 3: Healthy and Quality Life, Goal 6: Clean Water and Hygiene”. The definition of Sustainable Agriculture, which will ensure food security and sustainability, is the systems and practices that ensure conscious production by using renewable raw materials and energy resources in the production of quality and sufficient crops, protecting the soil and environment in all rings of the food production chain from soil to plate (Soylu, 2022).

Supporting sustainable agricultural practices, protecting limited natural resources, and developing solutions that protect the environment have become necessary to solve the global food problem. In this direction, the decision-making public and relevant institutions of countries initiate prohibitions and deterrent penalties to stop environmentally damaging activities and practices while initiating supportive policies, regulations, and programs to promote environmentally friendly, sustainable, and environmentally friendly solutions. International organizations such as the FAO, the World Food Programme (WFP), the United Nations Development Programme (UNDP), and the International Fund for Agricultural Development (IFAD) directly or indirectly fight hunger in the world and carry out studies to support the sustainability of agricultural production to ensure food security and accessibility (FAO, 2013). One such initiative is Climate-Smart Agriculture (CSA), which was launched in 2010 under the leadership of FAO, a specialized agency of the UN. CSA is a collaborative effort between private, public, and non-governmental organizations to ensure global food security and environmental sustainability. Different organizations, such as the World Bank, researchers, policymakers, and investors, are carrying out local and global studies and projects to encourage the development of CSA methods and the dissemination of its practices worldwide. With these studies, CSA has been supported and commissioned by many institutions and public and non-governmental organizations (Barasa et al., 2021).

The main objectives of Climate-Smart Agriculture (CSA) are:

- To sustainably increase agricultural productivity and income,
- To facilitate the adaptation of companies and nations to climate change,
- To ensure that countries achieve their food security and development goals by reducing or completely eliminating greenhouse gases generated by agricultural production (Abd El Mowla & Abd El Aziz, 2020; Nongmaithem et al., 2019; Basak, 2017; FAO, 2016).

From a CSA perspective, the aim is to enhance resource and food security by improving natural resource production, processing, and management. Increasing the climate resilience of the agricultural sector has become essential for ensuring food security. The climate-compatible agriculture system minimizes greenhouse gas emissions while enhancing resilience and adaptation to global climate changes, thus sustainably increasing agricultural yield, production, and income (FAO, 2013).

According to the 2023 IPCC report, greenhouse gases are generated by human activities, including fossil fuel use, electricity and heat production, industry, agriculture, deforestation, transport, and waste disposal. The report emphasizes that agriculture will be among the sectors most affected by the global climate crisis, and agricultural production practices contribute to increasing carbon emissions that drive climate change. Among the anthropogenic factors contributing to global greenhouse gas emissions, agriculture, forestry, and other land use account for 22% (IPCC, 2023). The excessive use of chemicals in agriculture, overgrazing, deforestation, soil erosion, and soil pollution, air, and water pose significant environmental threats (Meyer et al., 2017; United Nations, 2015b). Furthermore, improper agricultural land use and practices lead to the inefficient use of the world's limited agricultural lands. To address malnutrition caused by global population growth, food production needs to increase by 70%, but the current agricultural sector is falling short due to a lack of innovative practices, decreasing agricultural areas, and the adverse impacts of climate change (FAO, 2009).

More than 75% of the world's agricultural land is now irreversibly degraded, a figure projected to rise to over 90% by 2050, according to the European Commission's World Atlas of Desertification report. Africa and Asia are among the most affected regions, with approximately 4.18 million km² of agricultural land lost annually (Nunez, 2019). NASA's data indicates that 2020 was the third hottest year in Turkey in the last 50 years, with temperatures exceeding seasonal norms. The report highlights that Turkey is experiencing its driest period in the last 15 years, threatening crop yields if regular rainfall does not occur (NASA, 2020). As shown in Figure 6, many countries declared drought emergencies in 2022 and 2023, accompanied by numerous wildfire disasters. Inadequate water resource management practices and droughts driven by the climate crisis are jeopardizing the anticipated increase in agricultural yields. For all these reasons, there is an urgent need for technologies and solutions that promote effective water management and conservation (United Nations Convention to Combat Desertification, 2023).

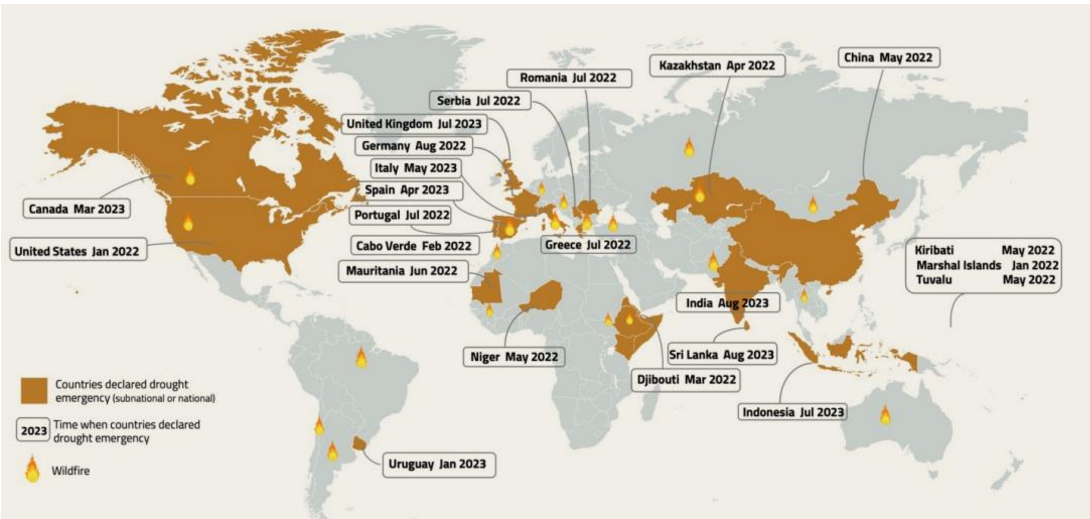


Figure 6. Countries Declaring Drought Emergencies in 2022-2023 Years (United Nations Convention to Combat Desertification, 2023)

The use of plastics in agricultural production poses significant threats to the environment and human health. The production of plastics from petroleum and the emission of CO_2 and other greenhouse gases from burning plastics are major contributors to global warming. Research conducted in 2012 determined that plastic production resulted in an increase of 400 million tons of greenhouse gases, constituting 1% of the global total (Economic Development Foundation, 2020). Activities that increase carbon emissions in agriculture are categorized into three main areas: Livestock, Paddy Fields, and Other Activities. Other activities include practices such as agricultural stubble burning (burning post-harvest crop waste), using nitrogen (N) fertilizers, and biomass burning. There is a need to raise awareness of producers about stubble or biomass burning and to prevent these wrong practices with deterrent policies to be implemented (IPCC, 2023). A study conducted as part of the project "Evaluation of Microplastic Levels in Different Land Use Conditions of Turkish Soils," which received national funding support, found 300 pieces of plastic in 1 kilogram of soil in the Mediterranean Region, 180 pieces in the Aegean Region, and 160 pieces in the Marmara Region. Plastics are ubiquitous and found in environments ranging from oceans to the atmosphere, and microplastics have even been detected in human organs such as the heart and lungs (Akca et al., 2024).

Over the past 15 years, the food supply has been increasingly threatened by extreme weather events, changing environmental conditions, and the accompanying damage and disease. To mitigate the impacts of these problems, sustainable practices and materials must be used and promoted. These measures are essential to prevent future famines and enable nations to adopt more sustainable agricultural practices. Sustainable agricultural solutions are expected to ensure efficient water use and maintain or increase the amount of organic matter in the soil (FAO, 2009). Given these circumstances, developing environmental solutions that enhance productivity, provide economic benefits, and reduce the impact of global climate change has become essential and of strategic importance for the sustainability of agriculture (IPCC, 2023).

The scope and purpose of this review are to outline more environmentally friendly and sustainable plastic soil cover (biodegradable mulch) materials that can provide the same benefits as petroleum-based plastic soil covers (mulches) used in agricultural applications. This study aims to contribute to the literature for future research. The study analyzes and discusses the terminology of biodegradable mulch film materials, existing research, trials and results, and the parameters affecting properties.

2. LITERATURE REVIEW

2.1. Terminology of Plastics

Plastics, which have become integral to human life since the 1950s, are polymeric materials produced from petroleum (Brydson, 1999). Plastics are favored due to their advantageous properties, such as lightness, lipophilicity (tendency to combine with or dissolve in lipids or fats), resistance to most chemicals, buoyancy in water, high durability with additives, and ability to absorb toxic chemicals. These characteristics make plastics particularly suitable for disposable products, which are widely used today. Commonly used plastics include polypropylene (PP), polystyrene (PS), polyethylene (PE), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) (Muneer et al., 2021).

The production and post-use waste processes of plastics made from petroleum-based materials negatively impact humans, living organisms, and the environment. Plastic production increases carbon emissions, and plastics can persist in nature for many years without decomposing naturally. Even when they do decompose, the small plastic fragments that mix into water and soil pose carcinogenic and toxic risks to living beings and the environment. Despite these harmful effects, the production and use of plastics continue to rise globally due to their beneficial properties, ease of production, and wide range of applications. The advantages of petroleum-based plastics and their associated disadvantages, which suggest the need for their gradual phase-out, are summarized in Table 1 (Gironi & Piemonte, 2011).

Table 1. Advantages and Disadvantages of Petroleum-Based Plastics

Advantages of Petroleum - Based Plastics	Disadvantages of Petroleum - Based Plastics
Ease of production	Emit carbon dioxide
Wide range of applications	High carbon footprint
Lightweight	Dependence on oil as a raw material
Lipophilic properties	Non-degradable and generate waste
Resistance to most chemicals	Carcinogenic properties
Buoyant in water	Toxicity
High-temperature resistance (with additives)	Environmental pollutants
Ability to absorb toxic chemicals	Harm plants, animals, water resources, and soil
Ultraviolet (UV) resistance	Significant contribution to greenhouse gas emissions

Synthetic plastics, produced from non-natural materials, create waste in the environment after use because they are not degraded and eliminated by bacteria in natural settings (Muneer et al., 2021). Even when plastics do degrade, their decomposition periods are extremely long. For instance, wet wipes take 100 years to degrade, PET bottles take 450 years, plastic plates 500 years, and plastics, in general, take up to 1000 years. Even the fastest-degrading plastic bags take 20 years. Additionally, as plastics begin to degrade in the environment, they release harmful chemicals that pollute our limited water resources and cause significant harm to living organisms by entering the food chain. Moreover, since plastics cannot break down naturally, prolonged exposure to ultraviolet radiation releases harmful gases, polluting the air, soil, and water (Zhang et al., 2021). As shown in Figure 7, plastics gradually fragment into small pieces over time, dispersing into soil and water in natural environments (FAO, 2021).

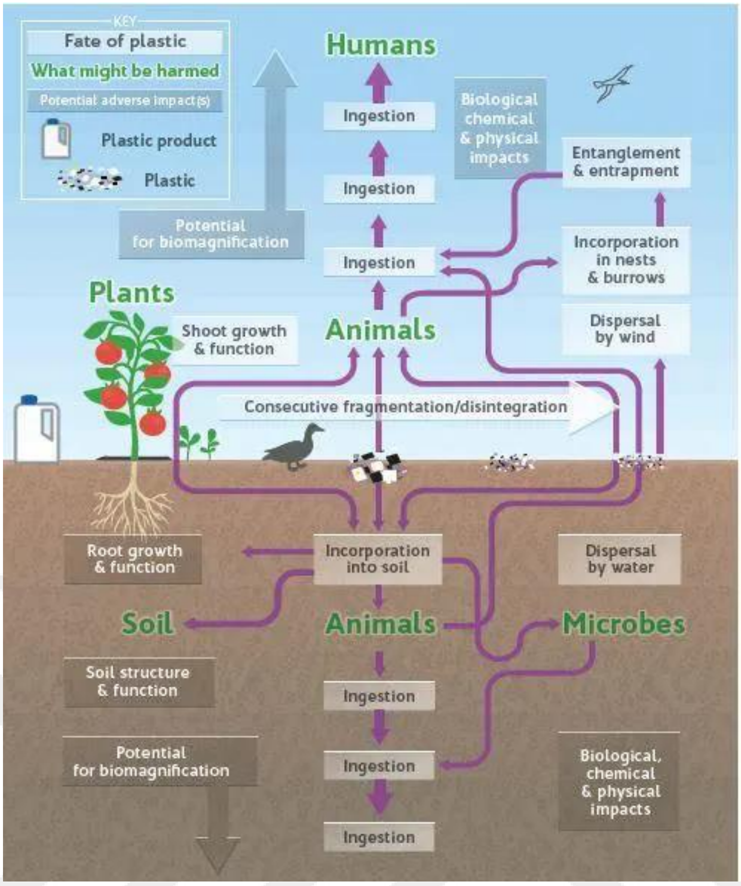


Figure 7. Illustration of the Movement of Plastics in Soil and the Environment (FAO, 2021)

Plastic fragments smaller than 5 millimeters in length are termed microplastics. Due to the detrimental effects of microplastics, their production was prohibited in the United States of America (USA) in 2017. Microplastics are categorized into two classes:

- Primary microplastics: These are microplastics measuring under 5 mm in size, with microbeads commonly utilized in cosmetics belonging to this category.
- Secondary microplastics: Micro-nano pollutants formed due to the degradation and fragmentation of plastic materials are termed secondary microplastics. This group includes textile fibers, vehicle tire components, and other plastic debris (Tirkey & Upadhyay, 2021).

Since the 1950s, an estimated 8.3 billion tons of plastic has been produced, which is projected to reach 33 billion tons by 2050. Despite claims of recycling efforts, only 10% of the plastic produced since the 1950s has been recycled (Gautam et al., 2024). In 2018, it was reported that

8 million tons of plastic waste are discarded into the oceans annually, with Turkey contributing 50 million tons of this waste. Studies conducted in various countries have found microplastics in drinking water and in table salt from 16 different brands in the Turkish market (Önder et al., 2020).

Research indicates that household washing machines can release 1900 microplastic fibers into wastewater from a single garment during each wash. To combat microbead pollution, which is prevalent in cosmetics, Canada, Australia, and the UK banned their use following the US ban in 2017. Since 2018, this ban has been adopted by many countries (Onyena et al., 2021). Algae, a major source of global oxygen production through photosynthesis, are adversely affected by microplastics, which reduce chlorophyll concentrations and hinder photosynthesis, posing a threat to all living organisms. Studies have also revealed that microplastics are present in the human body due to plastic food packaging, plastic water bottles, and microplastics entering the food chain. Ongoing scientific research aims to understand the impacts of these plastics on human health (Sana et al., 2020).

Plastic waste remains one of the most critical issues for achieving a sustainable world. As depicted in Figure 8, waste management methods are prioritized as follows; prevention, reuse, recycling, recovery, and disposal. In Turkey, disposal is the predominant method used for managing waste (Chamber of Environmental Engineers, 2018).

Figure 8. Waste Hierarchy (Zero Waste Europe, 2019)

Three primary methods are generally used to manage plastic waste: recycling, incineration, and landfilling. Globally, 34 million tons of plastic waste are released into the environment annually, with approximately 90% of this waste ending up in oceans and landfills (Kosior & Crescenzi, 2020). In Turkey, 67.2% of the collected plastic waste is disposed of in licensed landfills under appropriate conditions. However, 20.2% is disposed of in landfills that do not meet technical requirements and are harmful to the environment (Turkish Statistical Institute, 2020). Developed countries typically do not prioritize plastic recycling and instead export their plastic waste to developing countries. These developing countries often do not recycle plastic waste effectively, resulting in most of it being left in the natural environment. Although some European Union (EU) member countries have implemented measures like bans on plastic waste storage, about 50% of plastic waste still ends up in landfills. Countries like Sweden, Germany, Denmark, the Netherlands, and Austria have achieved recovery rates between 80% and 100%, but the recovery rate in other EU countries remains at 28% (European Commission, 2013). Turkey imports plastic waste from various countries. In 2020, Turkey imported the largest amount of plastic waste from Europe, with plastic waste imports reaching approximately 660,000 tons, as shown in Figure 9 (Greenpeace, 2021).

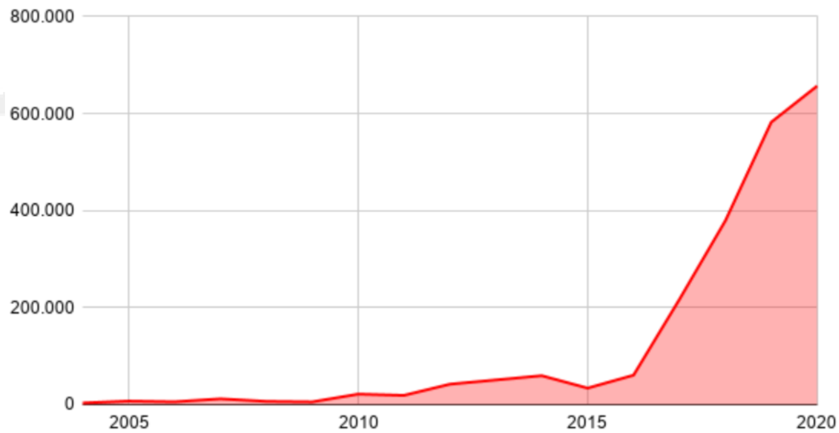


Figure 9. Turkey Plastic Waste Imports (Greenpeace, 2021)

The adverse effects of petroleum-based synthetic polymer plastics on the environment and the health of living organisms have driven the search for environmentally friendly, biodegradable plastic materials. As alternatives to petroleum-based plastics, bioplastics or biodegradable plastics have gained prominence. These bioplastics, which utilize natural resources such as starch, cellulose, sugar, and wood instead of fossil resources like oil and coal, contribute to a sustainable economy by reducing carbon emissions (Gironi & Piemonte, 2011).

Definitions of common terms used to bioplastics and released words:

Polymer: High molecular weight compounds formed by the chemical bonding of numerous repeating small molecules called monomers. These long chains constitute the structure of both natural and synthetic materials such as plastic, protein, rubber, and nylon. Polymers are classified as organic or inorganic based on their chemical structure.

Plastic: Polymeric materials consisting of synthetic or semi-synthetic macromolecules. Plastics are carbon-based and may contain elements such as oxygen, nitrogen, hydrogen, and other organic or inorganic elements. Based on their chemical structure, they are classified as elastomers, thermoplastics, and thermosetting plastics.

Biobased: Materials derived from biological sources, including plant, marine, and forest raw materials.

Bio-Based Plastic: Biodegradable plastics produced from plant-derived raw materials such as corn, sugar cane, and soy.

Biodegradable Plastic: Plastics that can be broken down by microorganisms over time. These plastics can degrade under specific conditions in industrial composting facilities but may remain undegraded for extended periods without these conditions.

Bioplastics: Environmentally friendly plastics that are either bio-based, biodegradable, or both.

Biodegradation: The process by which microorganisms such as bacteria or fungi consume the plastic content for nutrition, converting the material into basic substances like carbon dioxide, water, and methane.

Biodegradability: The capacity of a substance to be broken down into carbon dioxide, methane, water, inorganic compounds, and biomass through enzymatic processes by microorganisms.

Composting: A method where CO_2, water, and inorganic compounds are formed through the natural decomposition of organic waste by microorganisms in controlled environments with specific conditions such as adequate air, humidity, and carbon-nitrogen ratio. This process yields fertilizer content from organic material to enhance soil and plant growth.

Biodegradable: When microorganisms such as bacteria or fungi consume the plastic content, converting it into basic substances like carbon dioxide, water, and methane. Unlike composting, biodegradation is considered a natural process, and not all biodegradable materials are compostable (Anunciado & Hayes, 2019).

Natural polymers exist in various forms, including starches, cellulose, lignin, chitin, proteins, and nucleic acids, and they generally biodegrade in nature (Siegenthaler et al., 2012). Human-produced biodegradable polymers can be categorized based on their sourcing as derived from petrochemical or renewable sources, as illustrated in Figure 10. Biopolymers can also be classified according to their synthesis approach: from biomass, microorganisms, and biotechnology.

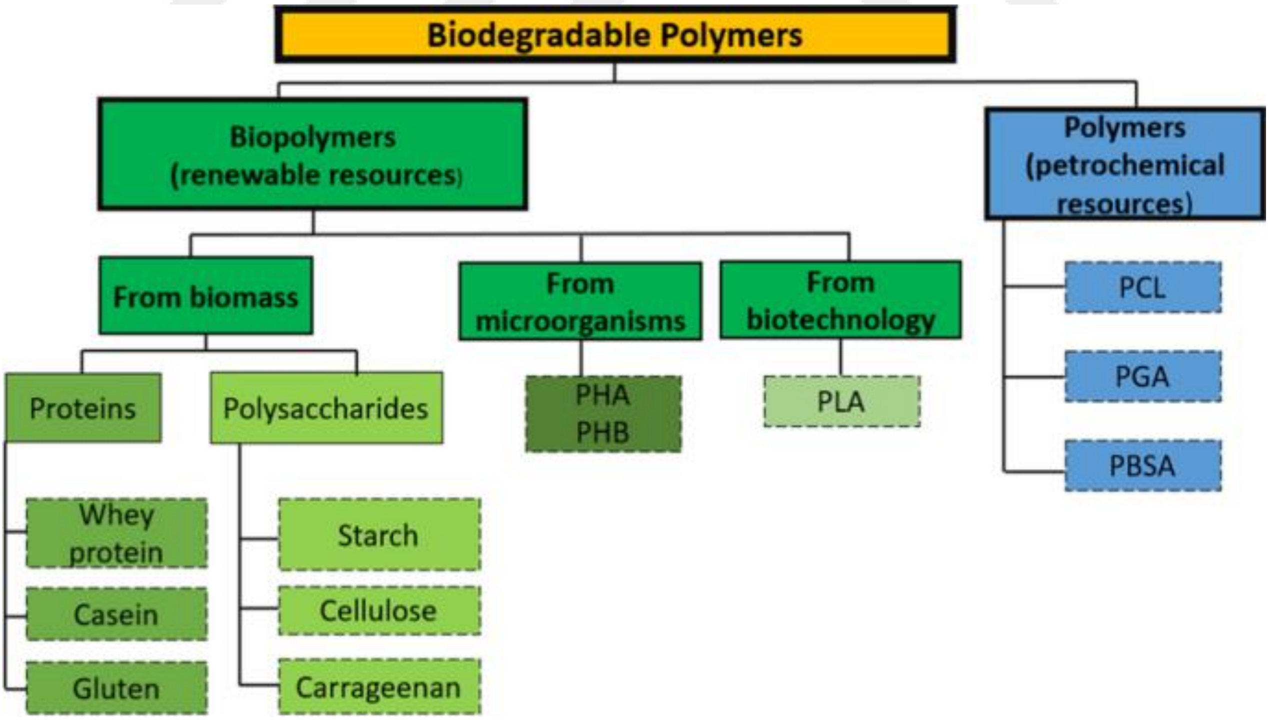


Figure 10. Biodegradable Polymer Types (Zhong et al., 2020)

Other studies classify bioplastics into three groups based on the raw material source:

- **Bioplastics of Plant Origin:** Polysaccharides like cellulose, starch, alginate, agar, carrageenan, various gums, and pectin.
- **Bioplastics of Animal Origin:** Chitin, chitosan, hyaluronates of polysaccharide origin, and proteins such as collagen, albumin, fibrinogen, casein, resilin, silk, and elastin.
- **Bioplastics of Microbial Origin:** Bacterial polyesters and hyaluronates of polysaccharide origin (Hazer, 2012).

Although these terms are often perceived as interchangeable and even used incorrectly, they are distinct. Specifically, the term "bioplastic" refers to plastics that are either bio-based (derived from biological sources) and/or biodegradable (capable of being decomposed by biological processes). In contrast, "biodegradable plastic" refers exclusively to plastics that can be broken down by microorganisms under specific conditions. Thus, not all bioplastics are biodegradable, and not all biodegradable plastics are bio-based. Bio-based plastics are produced from raw materials derived from plant sources, while biodegradable plastics possess chemical structures that enable biological decomposition. Therefore, understanding the difference between these terms is crucial for developing effective environmental sustainability and waste management strategies (Lambert & Wagner, 2017).

Due to their high molecular weight, three-dimensional structure, and hydrophobic properties, polymers are generally not biodegradable, posing significant environmental challenges (Bilck et al., 2010). Synthetic polymers, which are petroleum-based, are unsustainable because they cannot be degraded by microorganisms, leading to solid waste problems (Schneiderman & Hillmyer, 2017). Importantly, the natural origin of a polymer does not guarantee its biodegradability; this characteristic depends on the chemical structure of the molecule. Synthetic, man-made polymers can be biodegradable if their chemical structure allows for microbial degradation. Conversely, even fossil-based polymers can biodegrade if microorganisms can metabolize them, breaking them down into biomass, water, and carbon dioxide. In summary, biopolymers include both biodegradable and non-biodegradable polymers derived from plants, and not all biopolymers are biodegradable (Siegenthaler et al., 2012).

According to American Society for Testing and Materials (ASTM International), biodegradable polymers are defined as “polymers that exist in nature, such as bacteria, algae, fungi, yeast, and other microorganisms that can dissolve without being ecotoxic.” Standards such as ASTM D6400 and EN 13432 have been established to determine biodegradability. It is also important to consider the conditions under which bioplastics marketed as biodegradable can actually fully decompose. The terms 'biodegradable' and 'compostable' do not imply that bioplastics will spontaneously dissolve in nature; appropriate waste management practices must be implemented. Biodegradable plastics can be derived from various renewable agricultural resources such as plant polysaccharides, proteins, lipids, and polyester. Polysaccharides, which are abundant in nature as cellulose and starch, play a crucial role in bioplastic production. The prominent features of plant-based bioplastics are their biodegradability and compostability. Polylactic acid (PLA), produced from starch-based plants such as corn, sugar cane, and wheat, is a thermoplastic polymer in the aliphatic group consisting of repeating lactic acid units (Havstad, 2020). PLA is an environmentally friendly polymer that loses 90% of its weight when buried for a period of 90 days, without causing any damage to the soil or the environment (Boonmee et al., 2016).

The production of plastics using oil and coal results in the emission of carbon dioxide into the atmosphere. Despite the advantageous properties of plastics, their contribution to carbon emissions and climate change necessitates the investigation of alternatives to petroleum-based plastics. Bioplastics have important advantages and disadvantages as listed in Table 2 (Gironi & Piemonte, 2011). With increasing market demand for bioplastics driven by environmental and sustainability concerns, the United States and EU countries have mandated the production of biodegradable materials in packaging (European Commission, 2013). In January 2018, the European Commission announced a "Plastic Waste Management Strategy" aimed at making all plastic packaging sold in EU member states recyclable by 2030. Among its top priorities are reducing the use of single-use plastics and minimizing the amount of primary microplastics used in production (European Commission, 2018).

Table 2. Advantages and Disadvantages of Bioplastics

Advantages of Bioplastics	Disadvantages of Bioplastics
Use of renewable raw materials	Insufficient market demand yet
Reducing the use of oil	High cost of production
Reduced carbon emissions	Recycling problems
Sustainability	Raw material competition with the food sector
Not-toxicity	Thermal instability
Some varieties are biodegradable	Accelerating of complete degradation in nature
High energy efficiency	Consumer awareness raising
Environmentally friendly	Improvement of mechanical and physical properties
Faster decomposition	

2.2. Uses Area of Plastic in Agriculture

Plastics are widely used in agriculture. The reason for its widespread use is that it contributes to efficient use of water and fertiliser, fewer weed problems, less herbicide and pesticide use, earlier harvesting and more efficient production due to its existing properties. In agricultural applications, plastics are mainly used for greenhouse covers, mulching films (soil cover), tunnel and garden cover materials, irrigation equipment such as irrigation pipes, drippers, water tanks, packaging materials such as pesticide boxes, fertiliser bags, crates, shade nets, silage film, as shown in Figure 11 (Malinconico, 2017).

Figure 11. Plastics and Materials Used in Agricultural Crop Production (FAO, 2021)

Commonly used plastics in agriculture, such as PE, PP, PS, PVC, PET, have significant negative impacts on the environment (Liu et al., 2010). The widespread use of PE in agricultural applications generates substantial amounts of plastic waste, which poses a considerable environmental challenge. This plastic waste accumulation profoundly affects farmed environments, leading to soil contamination and ecosystem disruption. Research estimates that the total amount of plastic waste released into terrestrial systems is 4 to 23 times greater than the amount released into marine environments (Di Mola et al., 2023). This stark difference underscores the urgent need to address plastic waste management in agricultural settings to mitigate its adverse environmental effects.

Plastic wastes used in agriculture are left in the fields by farmers, thrown in the garbage or burned uncontrollably (Briassoulis et al., 2016). Disposal of these plastics is not carried out due to high labor costs and related economic reasons, and plastics are left to nature (Bilck et al., 2010). Pieces of plastic left on fields blend into the soil and water, as can be seen in Figure 12.

Figure 12. Pieces of Plastic Mixed with Soil in the Field (Örüç,V. , 2022)

This study covers the topics of mulch material, which is a common soil cover used in agriculture. Therefore, the following sections of the study review issues such as the definition of plastic and biodegradable mulch, advantages and disadvantages, sources, brands on the market, market size, research and studies on these issues.

2.3. Definition, Benefits, and Disadvantages of Mulch

Ensuring effective and sustainable agriculture to meet the nutritional needs of a growing human population is a major challenge, especially given the limited amount of arable land. Limited water and nutrient availability, particularly in arid and semi-arid regions, severely reduces global crop production. Various methods have been employed to increase crop yields and meet the growing food demand, including no-tillage, plastic mulching, and straw mulching (You et al., 2021). Mulch films, used in the mulching method in agriculture, serve as a covering to protect soil moisture, prevent weed growth, and encourage plant growth and development, as shown in Figure 13 (a) and (b). The most commonly used mulch materials include plastic, bio-plastic, paper, and straw layers (Serrano-Ruiz et al., 2021).

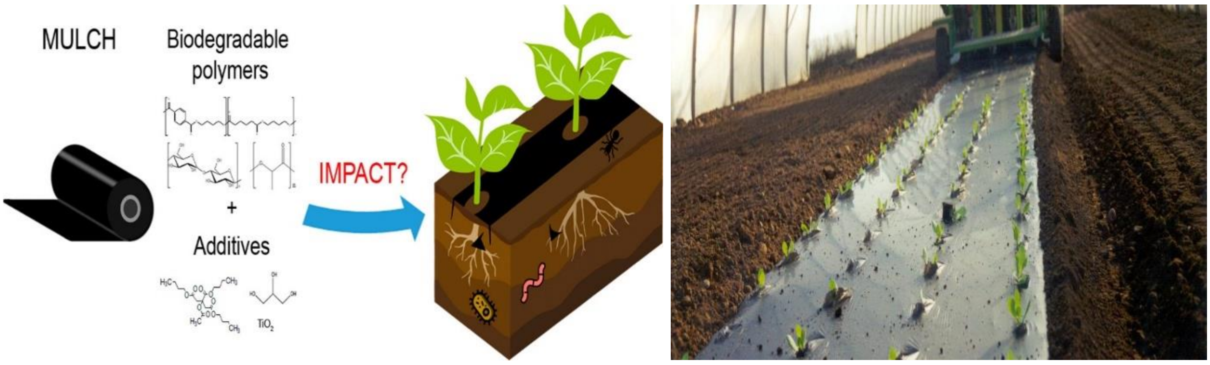


Figure 13. (a) Graphical Image about Mulch Films (Serrano-Ruiz et al., 2021), (b) Bioplastic Mulch Film in the Field (Novamont, 2018)

Since the early 1970s, mulching of fruit and vegetable crops has been a common practice. Nowadays, mulching is used year-round and across various soils for different fruits and vegetables, including watermelon, bell pepper, tomato, melon, eggplant, cucumber, maize, peanut, cotton (Scaringelli et al., 2016), as well as pumpkin, strawberry, raspberry (Zawiska & Siwek, 2014; Siwek & Libik, 2012), ornamental plants, fruit trees, and other trees. Mulching, which blocks sunlight by covering the soil surface, is increasingly used to improve water efficiency in agriculture. Over time, the use of plastic mulch in agriculture has steadily increased worldwide. The use of petroleum-based mulches in agriculture is quite common; in fact, more than 10% of the 6.5 million tons of plastics used globally in agriculture are plastic mulch materials (Liu et al., 2010). In the USA, plastic mulch is used on 162 thousand hectares (Li et al., 2014). Research indicates that by 2017, over 20 million hectares in China were covered with film, producing more than 50 crops, and about 1.2 million tons of mulch, primarily PE, were used annually (Jia et al., 2020). Mulch offers several agricultural advantages, such as suppressing weeds, conserving soil moisture, reducing soil erosion, raising soil temperature, protecting crops from pests and diseases, and improving crop quality and yield (Tofanelli & Wortman, 2020). Soil mulching, which controls soil temperature, conserves soil moisture, and reduces soil evaporation, is a popular method for modifying the crop growing environment and increasing profitability. Additionally, Nitrogen Use Efficiency (NUE) and Water Use Efficiency (WUE), which are critical parameters in agricultural production, are enhanced by soil mulching (Kader et al., 2017; Kasirajan & Ngouajio, 2012). Mulches also provide adequate soil aeration by preventing soil compaction, significantly impacting plant growth rates (Zawiska & Siwek, 2014; Streck et al., 1995).

The main benefits of mulching can be summarized as follows:

- Limiting water losses,
- Improving the soil microclimate,
- Increasing soil temperatures,
- Suppressing weeds,
- Accelerating crop growth,
- Enhancing yield,
- Increasing water and nutrient efficiency by reducing water and fertilizer requirements (Di Mola et al., 2023).

First used in the mid-20th century, petroleum-based polyethylene mulch (PEM) film has significantly impacted the production of many commercial vegetables. PEM film is widely used due to its affordability, accessibility, and physical properties (e.g., flexibility and durability) that facilitate its mechanical application on a commercial scale (Tofanelli & Wortman, 2020). Despite its many benefits, PEM film also poses several hazards and disadvantages (Table 3). For example, a significant proportion of PEM film mulch residues are burned in the field or disposed of by farmers, releasing toxic substances harmful to the environment and human health. This is because most mulch residues are not degradable, damaging soil structure and hindering crop growth. During the summer growing season, mulch helps conserve soil moisture, but the stress of high temperatures from plastic film mulch inhibits root growth (You et al., 2021). Currently, only 3.6% of mulch films in use are biodegradable, with the remainder consisting mainly of plastic materials, typically PE, which presents significant disposal challenges (Sekara et al., 2019). After harvesting, mulching films are often left buried in the fields without being collected, negatively impacting soil quality. Disposing of these petrochemical plastic wastes by incineration or landfilling is illegal in the EU and the USA (Briassoulis et al., 2016). Studies have found that plastic film used in agriculture and left in the soil reduces crop yields when it reaches 58.5 kg per hectare (Li et al., 2014). Although synthetic mulches provide fewer weed problems and higher yields, they take a long time to degrade in nature, break down into pieces containing plastic, and leave harmful chemicals in the soil during the degradation process (SK et al., 2020). These plastic pieces contain harmful toxins and negatively affect the ecosystem in both land and aquatic environments (Li et al., 2014). These chemicals, which mix into soil and water resources, also negatively impact the health of living organisms by entering the food chain (Tirkey & Upadhyay, 2021).

Table 3. Advantages and Disadvantages of Petroleum-Based Polyethylene Mulch(PEM)

Advantages of PEM	**Disadvantages of PEM**
Weed suppression	Labor requirement for collection and processing
Water loss reduction and Water Use Efficiency (WUE) enhancement	Disposal challenges
Soil microclimate enhancement	Labor costs incurred
Effective fertilizer utilization with Nitrogen Use Efficiency (NUE)	Carbon emissions from incineration
Yield enhancement	Toxicity concerns from waste
Plant growth promotion	Negative impact on soil quality and crop growth
Early yield stimulation	Lack of environmental friendliness and sustainability
Fruit quality enhancement	

Agriculture in the EU generates between 0.4 and 0.6 million tons of plastic waste annually despite the lack of specific data on the use of mulching films. This waste includes 0.2 million tons from pipes and fittings and 0.079 million tons from agricultural packaging. In 2008, a total of 1.243 million tons of agricultural plastic waste was produced in Norway, Switzerland, and the 27 EU Member States. According to the European Commission's 2011 report, 53.6% of this total was disposed of, while only 46.4% was recovered (Scaringelli et al., 2016).

Although machines are available to manage plastic waste in agriculture, extracting plastic still requires significant manual labor and takes around 16 hours per hectare. Additionally, farmers often find in-situ burning more economically advantageous due to the high costs associated with landfill fees and transportation (Scaringelli et al., 2016). However, the incineration process preferred by farmers releases CO_2 into the atmosphere and produces hazardous toxic ash and slag. Since farmers are prohibited from openly burning plastics in their fields, switching to compostable products could significantly enhance the environmental sustainability of the agricultural industry (Kader et al., 2017).

2.4. History of Mulch

The first use of mulching with organic materials dates back to 500 BC (Mansoor et al., 2022). In the 16th century, materials such as volcanic ash, stone, and gravel were used as mulch, while straw was used in the 19th century. In the 20th century, the use of paper mulch began, followed by plastic mulch in the 1950s, marking significant advancements. The use of plastic mulches became widespread and had effective results. However, within 30 years, the negative effects of petroleum-based plastic mulches on the environment began to emerge. Although photo-degradable and oxo-degradable plastics were introduced in the 1980s as alternatives to petroleum-based mulches, it was found that these materials do not naturally degrade and form microplastics harmful to the environment, human health and wildlife (Steinmetz et al., 2016). In the 21st century, biodegradable plastic mulch film was first commercialized in 2006, and since then, various companies in many countries have started producing biodegradable plastic mulch films. In late 2021, the FAO recommended using biobased and biodegradable mulches instead of plastic mulches (Mansoor et al., 2022).

2.5. Biodegredable Mulch Films

Biodegradable polymers are a desirable alternative to petroleum-based plastics as mulch materials in agriculture, retaining the beneficial properties of petroleum-based mulches (Li et al., 2014; Auras et al., 2010). Biodegradable mulches, generally made from renewable resources such as plants, are more favorable to the environment (Anunciado & Hayes, 2019). Biodegradable Mulch (BDM) films can be left in the soil after harvest and naturally degraded by microorganisms. This provides both environmental and economic advantages (Liu et al., 2010).

BDM films are designed to biodegrade in a typical soil environment naturally. These films can be produced from bio-based or synthetic polymers and often from a combination of both

(Tofanelli & Wortman, 2020). In Figure 14, the green curves represent biodegradable bio-based mulches, while the brown curves represent the life cycle of petroleum-based mulches. Despite using different raw material sources, both types of mulches undergo the same stages in the cycle, eventually some of them decompose into carbon dioxide and, some of them into biomass (Anunciado & Hayes, 2019).

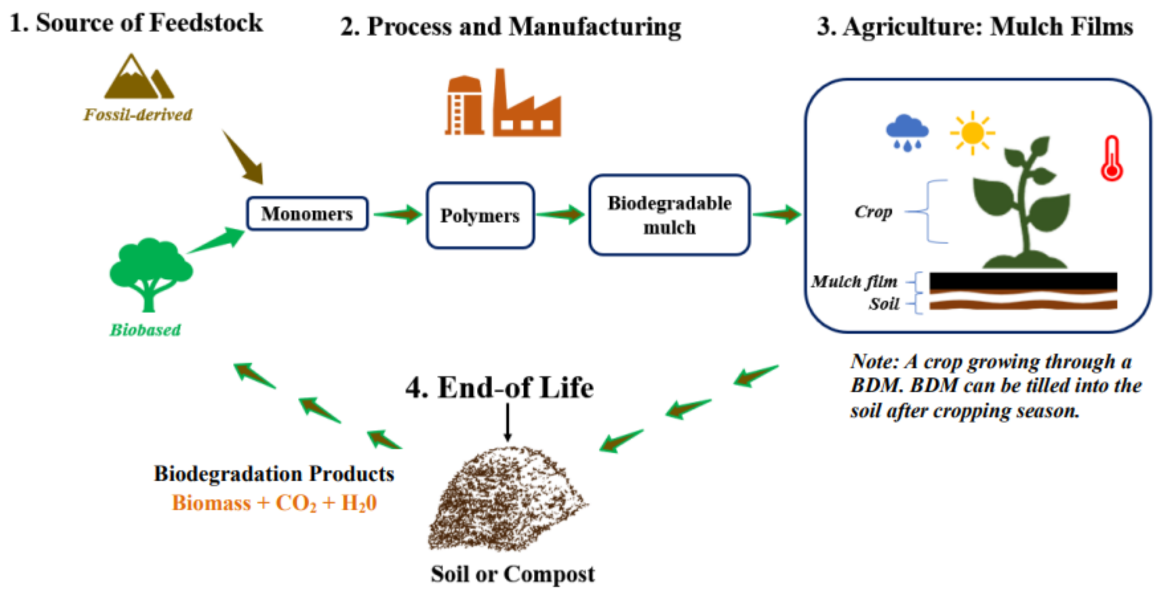


Figure 14. Biodegradable and Fossil-Derived Mulches Life Cycle (Anunciado & Hayes, 2019)

The biodegradable mulching film is produced using sustainable resources such as soybean protein, chitin, cellulose, and starch. These materials can break down into water, carbon dioxide, methane, and minerals, posing no environmental toxicity or harm. Biodegradable films can be degraded by light or microorganisms, effectively controlling soil temperature and moisture, improving soil microbial communities, increasing soil enzyme activity, and boosting yields. Regarding disease infestation and the concentration of toxic substances in crops, biodegradable film significantly outperforms plastic film, enhancing crop quality (You et al., 2021).

Numerous companies are actively engaged in production within this field. These firms focus on developing innovative solutions to meet the growing demand for sustainable and biodegradable materials. Their efforts contribute significantly to advancements in environmental sustainability and agricultural efficiency. The use of these products inevitably requires adherence to specific standards and certain restrictions. Establishing such regulations ensures the safety, efficacy, and environmental sustainability of biodegradable materials. These standards are critical for maintaining product quality and for minimizing any potential adverse impacts on both agriculture and the environment. Such as before being used on United States Department of Agriculture (USDA)-certified organic farms, BDM films must meet several requirements:

- Under normal field conditions, the film must be 90% biodegradable by microorganisms in the soil through biodegradation, bioassimilation, or mineralization to microcrystalline cellulose.
- The film must be produced from 100% biobased materials, excluding the use of petroleum-based or synthetic polymers.
- Genetically modified microorganisms must not be used as a source (Tofanelli & Wortman, 2020).

Biodegradable polymers replace traditional non-biodegradable materials, for which recycling is often impractical or financially unfeasible (Sekara et al., 2019). Many BDM films today can increase crop yields with performance close to that of PEM films (Di Mola et al., 2023). The rate of biodegradation is crucial; for example, Mater-Bi, produced by Novamont, is a biopolymer derived from starch that exhibits properties similar to conventional plastics, with a biodegradation rate akin to cellulose film. Mater-Bi soil mulch has proven to be a good alternative to PE in organic production in the Mediterranean continental climate (Sekara et al., 2019).

In the table 4 below, the manufacturers and raw material sources of the most widely used brands of biodegradable mulching films are presented.

Table 4. Biodegradable Mulch Brands and Feedstocks

Trade Brand	Producer Company	Feedstock	Reference
BioAgri® Ag-Film	BASF	Mater-Bi® (Starch + PCL) + PBAT	Miles et al., 2017
Biopar	BIOP (Germany)	Starch + aliphatic co-polyester	Menossi et al., 2021
Bio360	BioBag	Mater-Bi® (Starch + PCL) + PBAT	Miles et al., 2017
Biocycle®	Organix Solutions	Sucrose / PHA blend	Miles et al., 2017
Biofilm®	Novamont S.p.A	Modified starch	Scaringelli et al., 2016
Bioflex®	KERAKOLL S.p.A.	PLA / copolyester	Miles et al., 2017
Biomax® TPS	DuPont	TPS + Starch	Mansoor et al., 2022
Biomer L™	BASF	PBS	Miles et al., 2017
Bionolle	Showa Denko Europe	TPS + PLA + (PBS or PBSA)	Mansoor et al., 2022
Bioplast®	Group Sphere Ibérica Biotech	TPS + PBAT	Menossi et al., 2021
Biosafe™	Xinfu Pharmaceutical	Starch + PBAT	Menossi et al., 2021
BioTelo Agri	BioTelo Agri	Starch based(Mater-Bi®)	Li et al., 2014
Cellgreen	Daicel Chemical Industries	Cellulose based	Sudesh & Iwata, 2008
Cornpol®	Japan Corn Starch	Starch based	Sudesh & Iwata, 2008
Easter Bio™	Novamont S.p.A	Starch + PBAT	Menossi et al., 2021
EcoFilm™	Organix Solutions	Unspecified plastic	Miles et al., 2017
Ecoflex®	BASF	Starch + PBAT	Mansoor et al., 2022
Ecovio®	BASF	TPS + PBAT + PLA	Mansoor et al., 2022
EcoWorks	Cortec Corporation	TPS + PBAT	Mansoor et al., 2022
EnPol®	AGRICHEMA GmbH	PBS	Miles et al., 2017
Envio	BASF	PBAT + PLA + Starch Blend	Miles et al., 2017
GreenBio®	BioBag	PHA	Miles et al., 2017
Ingeo®	Nature Works	Starch + PLA	Mansoor et al., 2022
Mater-Bi®	Novamont S.p.A	TPS + PCL	Mansoor et al., 2022
Mimgreen Paper®	MimGroup	Cellulose-based (paper mulch)	Scaringelli et al., 2016
Mirel™	Metabolix	PHA	Miles et al., 2017
Naturecycle	Custom Bioplastics	Starch + Polyester	Mansoor et al., 2022
Paragon	Avebe	TPS + Starch	Menossi et al., 2021
ReNew	Loop Industries	PHA	Miles et al., 2017
Skygreen®	BASF	Terephthalic acid copolyester	Miles et al., 2017
Solanyl®	Rodenburg	Starch based	Sudesh & Iwata, 2008
WeedGuardPlus	Sunshine Paper	Cellulose based	Li et al., 2014

* Polybutylene Adipate Terephthalate(PBAT), Polybutadiene Succinate(PBS), Poly(butylene succinate-co-butylene adipate)(PBSA), Polycaprolactone(PCL), Thermoplastic Starch(TPS)

Commonly used plastics are generally petroleum-based materials. Alternatives to PEM include biodegradable or biobased and often paper-based BDM and BDM mulch films, as well as polyhydroxyalkanoate (PHA), polyhydroxybutyrate (PHB), are fabrics derived from biodegradable polyesters, including (but not limited to) PLA, polybutylene adipate terephthalate (PBAT), and starch-polyester blends such as Mater-Bi (Tofanelli & Wortman, 2020).

Some research identifying the benefits of mulching;

Several studies have highlighted the benefits of mulching. Simms et al. (2005) reported 63.4% and 71.4% higher yields in cucumbers and bell peppers, respectively, when grown with transparent film compared to unmulched plants. Gordon et al. (2008) observed improved root growth in the soil microclimate created by mulches, while Rohwer & Fritz (2016) found that mulching accelerated root growth in tomato plants immediately after planting. Black PE film is particularly popular in vegetable gardening due to its excellent qualities and affordability (Adamczewska-Sowinska & Turczuk, 2018). Research shows significant yield increases with the use of PE or PP non-woven mulches (Adamczewska-Sowińska et al., 2018; Robledo Torres et al., 2010). Rohwer & Fritz (2016) found that tomato fruits treated with black PE film had a 24% higher early yield than those without mulch. Thomas et al. (2009) reported higher marketable yields of tomatoes grown on black film mulch than those with other colored materials. Rajablariani et al. (2012) observed that tomato yields increased by 50% and 65% with black or silver-black PE film, respectively, compared to unmulched plots (Rajablariani et al., 2012).

Zawiska & Siwek (2014) conducted a study comparing the effects of conventional PP and non-woven biodegradable fabric PLA mulches on tomato yield and quality. They found that non-woven PP mulch, with its high radiation absorption rate, was more effective in warming the soil, resulting in higher levels of L-ascorbic acid, also known as Vitamin C, in the fruits. Consumers prefer tomatoes with higher Vitamin C content due to its essential health benefits and its ability to extend shelf life. Furthermore, tomatoes grown with non-woven biodegradable PLA mulch exhibited higher soluble sugar and dry matter content, and lower nitrate ion concentrations compared to control plots without mulch (Ochmian et al., 2022).

Dry matter content is a crucial quality parameter in tomatoes, representing the total solid components excluding water. Tomatoes with higher dry matter content generally have a richer flavor, longer shelf life, and better processing qualities, making them desirable for suppliers, especially for processing into products like tomato paste. Soluble sugars, such as fructose, glucose, and sucrose, are subcomponents of dry matter and significantly influence flavor; a moderate level of soluble sugars is preferred to enhance taste (Sinha et al., 2019).

Nitrate content is important for plant growth, must be carefully managed as excessively high levels in fruits can pose health risks. Therefore, the application of nitrogen should be balanced to meet the plant's needs without exceeding legal limits in the fruits. Similarly, nitrogen mineralization is vital for plant growth and yield, but excessive amounts can be harmful to human health. These findings emphasize the importance of selecting appropriate mulch types to optimize tomato quality and yield, considering factors like Vitamin C content, dry matter, soluble sugars, and nitrate levels (Ghorbani et al., 2012).

Liu et al. (2010) compared the biodegradability of three different starch-based BDM films through soil embedding and microorganism culture tests. The study assessed the films' critical properties before and after degradation against commonly used plastics. Results showed that all three mulching films were biodegradable, while no changes were observed in the conventional PE film. The degradation process of BDM films was found to be complex and influenced by various factors such as plastic components, chemical structures, soil pH, temperature, moisture, and microorganisms. Liu et al. (2010) emphasized the need for more field-based studies to better understand the degradation effects of mulches, highlighting that real environment trials across diverse soils are essential.

Tofanelli & Wortman (2020) conducted a qualitative analysis comparing the agronomic performance of BDM and PE films due to the lack of documented studies in this area. Their meta-analysis, based on data from 66 research articles, found that mulch type, color, weed suppression, soil moisture, and temperature significantly influenced the results, while factors such as growing region, medium, or crop type did not. The analysis revealed that BDM and PE films conserved soil moisture equally well and that paper-based BDM suppressed weeds more effectively than PE, although it did not reduce soil temperature.

Dentzman & Goldberger (2020) identified the primary barriers to farmers adopting BDM films as a lack of information, higher costs, and unpredictable decomposition times.

Thompson et al. (2019) showed the benefits of incorporating raw soybean and alfalfa meal particles into a BDM matrix, which enhanced biodegradation and provided additional nutrients to crops.

Jia et al. (2020) found that BDM film provided similar moisture retention to conventional PE film during the early stages of tomato growth. However, from flowering to maturity, PE film increased soil moisture more effectively. While BDM film resulted in lower WUE compared to PE film, it also maintained lower soil temperatures. Although BDM film has a slightly lower average fruit yield and higher input costs, it is worth using environmentally friendly degradable mulch instead of traditional mulch in tomato production.

Studies on the quality and yield of crops have shown promising results for BDM films. Adamczewska-Sowińska and Turczuk (2018) found that the marketable yield of crops with black biodegradable film (59.61 t/ha) was similar to that with PE film mulch (60.63 t/ha), with early marketable yields also comparable. The quality of fruit yields from BDM-treated crops accounted for 68.2% of the total yield, affirming their effectiveness.

Research by Anzalone et al. (2010) and Moreno & Moreno (2008) indicated that the quality of tomatoes grown with PE and BDM films was equivalent. In the context of organic farming, which often suffers from low yields due to N deficiency, Han et al. (2020) explored the impact of BDM film on crop yield and soil mineralization. Over two years, their study demonstrated that combining fertilizer and BDM improved soil temperature, moisture content, and N mineralization, increasing tomato yields.

Sekara et al. (2019) highlighted the need for a cost assessment of BDM films, particularly regarding their impact on tomato yield, fruit quality, and the potential for residual biomass energy production. They conducted a study in Southern Italy comparing different biodegradable covers with conventional low-density polyethylene (LDPE) for two tomato varieties. The study used:

- Black BDM film (15 µm thick, branded MB N2/12 of MaterBi products) produced by Novamont S.p.A. from corn starch
- Black BDM film (12 µm thick, branded MB N8 of MaterBi products) produced by Novamont S.p.A. from corn starch
- 50 µm thick black PEM film from LDPE

The results indicated that BDM films outperformed PEM films in fruit yield and quality and offered benefits for converting plant residue biomass into biofuel. BDM films also increased soil temperature without exceeding optimal levels and did not require manual labor for removal, unlike PEM films. This study underscores the environmental and practical advantages of BDM films in agriculture (Sekara et al., 2019).

Researches revealing the effect of other factors on mulching applications;

Research on the factors affecting mulching applications has identified temperature, polymer type, and crop species as key influences on the degradation rate of BDM films. Serrano-Ruiz et al. (2023) demonstrated that different crop varieties exhibit varying sensitivity to BDM fragments, with lettuce being more sensitive than tomatoes, making it a better indicator of potential BDM ecotoxicity. This underscores the need to assess BDM effects across diverse crops to develop environmentally friendly formulations.

Greer & Dole (2003) state that the weathering process of mulch films is slower in temperate regions due to lower levels of solar radiation. Additionally, rapid growth of crops like tomatoes or pumpkins can further slow film degradation by covering the soil surface. Kijchavengkul et al. (2008) found that film color significantly impacts degradation rates, with white biodegradable film breaking down faster than black film. Despite the black biodegradable film not warming the soil as much as black PE film, Moreno & Moreno (2008) and Ngouajio et al. (2008) reported similar plant yields with both materials. This finding was supported by Anzalone et al. (2010).

Studies have shown that mulching films do not alter the chemical composition of tomatoes, although the tomato variety influences the mineral content of the fruit (Adamczewska-

Sowińska & Turczuk, 2018). Plant morphology and physiological metabolism are also affected by light. You et al. (2021) found that the right color of the mulching film can promote dry matter accumulation, enhance crop yield, and increase photosynthetic intensity. Red and blue films improved maize yield, with blue film also increasing plant height. Yellow film enhanced oleic and linoleic acid content in peanuts and their yields, while red light boosted invertase activity and starch accumulation, benefiting from a combination of red and blue light (You et al., 2021)

2.6. Market Growth

Despite the growing trend towards bioplastics, their production remains significantly lower than that of petroleum-based plastics. In 2014, only 5 million tons of bioplastics were produced, compared to 325 million tons of petroleum-based plastics, a difference of 65 times (PAGEV, 2021). According to European Bioplastics Market Data, as seen in Figure 15, global bioplastic production was 1.813 million tons in 2022, with projections suggesting an increase to 7.432 million tons by 2028. Additionally, the production of biodegradable plastics, estimated at 2.18 million tons in 2023, is expected to reach 7.43 million tons by 2028, marking a 241% increase (European Bioplastics, 2023).

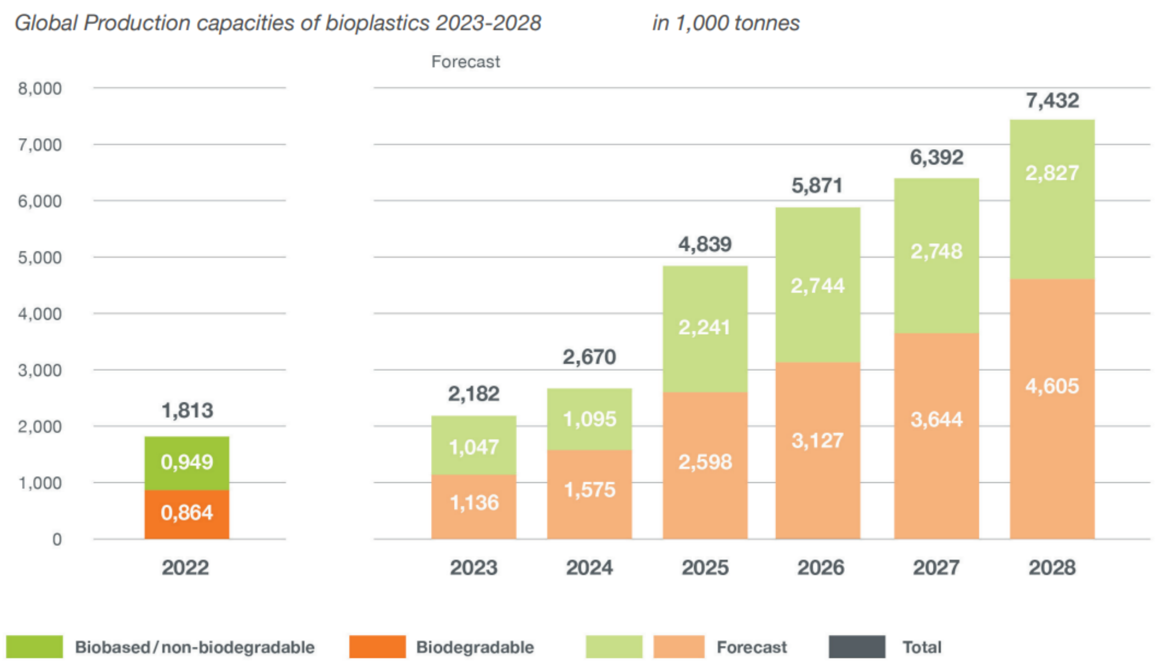


Figure 15. Global Production of Bioplastics (European Bioplastics, 2023)

The size of the Turkish plastics market reached 8.3 million tons in 2021, with 5% of the plastic produced being used in the agricultural sector (PAGEV, 2021).

2.7. Biodegradable Mulch Film Production Methods

Biodegradable polymeric mulch films can be produced through various methods, including extrusion, casting, blow molding, and other techniques, as illustrated in Figure 16-17.

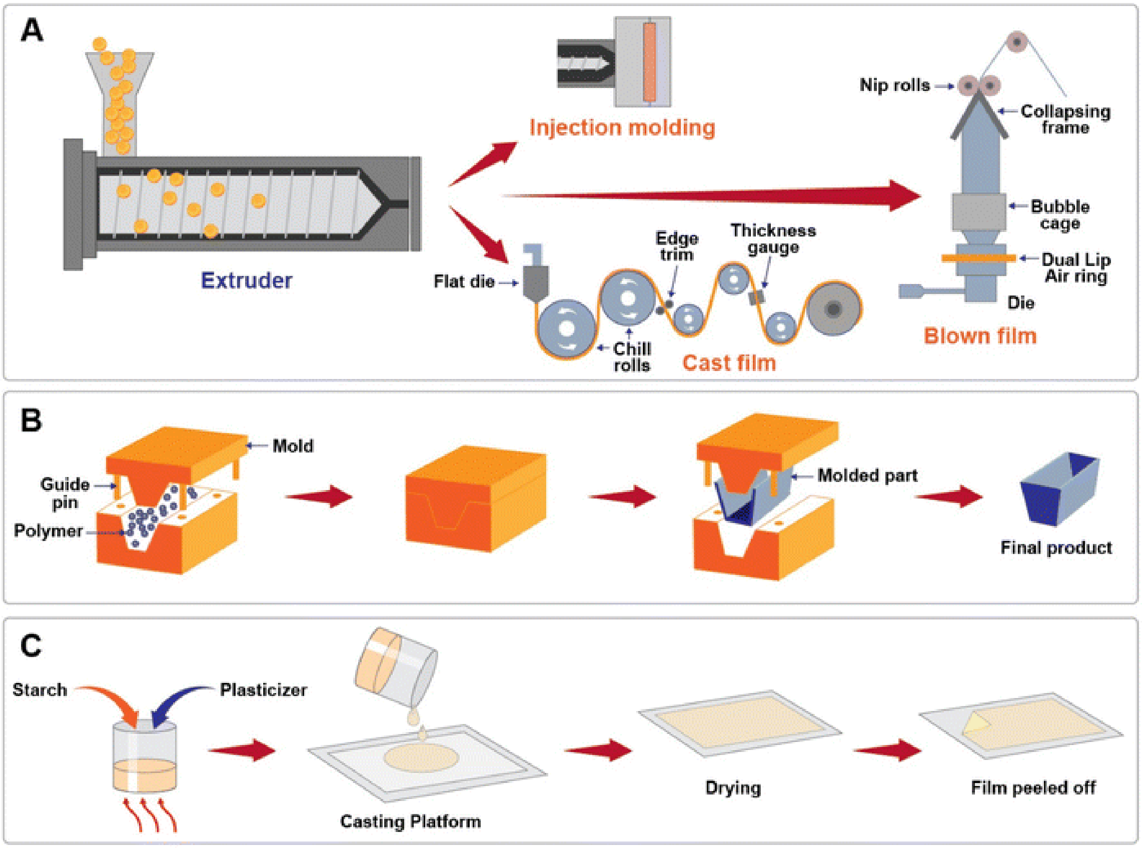


Figure 16. Production Methods of Biodegradable Mulch Films (A) Extrusion (B) Moulding and (C) Casting (Surendren et al., 2022)

Extrusion Method: Extrusion is a core production method in polymer manufacturing involving processing polymer material into a specific form using an extrusion machine.
The general stages of biopolymer production by the extrusion method are as follows:

Raw Material Preparation: Granular or powdered polymer is typically used as raw material. The raw material is melted to make it suitable for extrusion if necessary.

Mixing: Biocomposite is produced by mixing other additives or colorants into the polymer matrix to impart different properties to the polymer material.

Melting: The polymer material is melted at high temperatures for better material processing.
Loading to Extrusion Machine: The melted material is loaded into the feeding unit of the extrusion machine.

Extrusion: The melted and loaded material is pushed through the extrusion machine with the help of a screw mechanism, initiating the extrusion process. The material is then shaped and sized as desired.

Cooling and Solidification: After the material is shaped, it is cooled and solidified.
Cutting and Shaping: The cooled material is cut and shaped according to the desired final product specifications.

Thermoplastic Starch (TPS) blends and composites are primarily prepared through primary and secondary extrusion processes:

Primary Extrusion Process: Plasticizers and/or hardened polymers or additives are added to the raw material to facilitate processing and shaping, obtain a more homogeneous and uniform product, and improve the mixture's properties. The mixture is then melted and blended.

Secondary Extrusion Process: The material is passed through different molds to achieve the desired final shape. During this stage, the molten mixture is passed through a slit mold and rapidly quenched on polished cold rolls, thereby maintaining the film's clarity and mechanical properties. Different rollers are used to adjust the film thickness.

Blown Film Extrusion Technique: The extruded molten material is passed between a pair of rotating rollers with airflow support, forming the material into a thin film.

Molding Method: The compression molding method is frequently preferred in biopolymer mulch film production, where the material is heated at high temperatures and pressure with low humidity and short dwell time (Figure 15.A).

The general stages of biopolymer mulch film production by the compression molding method are as follows:

Raw Material Preparation: Polymer raw material is prepared in granule or powder form.

Mixture Preparation: Plasticizers or fillers are added to improve the properties of the mulch material.

Heat Treatment: The prepared mixture is melted into a homogeneous paste through an extrusion process.

Molding: The dough-like material is transferred to the compression molding machine, where it is brought to the desired thickness using a heated mold, and the shaping process is performed.

Cooling and Solidification: Cooling and solidification processes are conducted to adjust the thickness of the molded film and achieve the desired mechanical properties. Flexible thickness optimization and forming processes, especially in small-scale production, increase the preference for this method.

Cutting and Packaging: The solidified film is cut to the desired final product size and then packaged.

Casting Method: The casting method involves shaping the biopolymer mixture by pouring it into a casting mold (Figure 16. B and C). This method comprises several key stages, detailed as follows:

Raw Material Preparation: Biodegradable mulch production commonly utilizes plant-based raw materials. The selected polymers are typically in granule or powder form.

Gelatinization & Plasticization or Homogenization: The processing temperature and duration of the gelatinization and plasticization process vary based on the raw material source and plasticizer content.

Casting: The homogenized mixture is poured onto a casting reel or into a casting mold. The thickness of the film is determined by the shape of the casting mold or reel.

Drying: The cast film undergoes drying to achieve the desired mechanical properties and thickness.

Cutting, Shaping, and Wrapping: The cooled film is cut and wrapped according to the specifications of the final product size.

In starch-based films, which are frequently produced using the casting method, factors such as plasticizer content, drying and storage temperature, and humidity significantly influence the crystallinity of the films (Surendren et al., 2022).

Hot Pressing Method: Beyond the commonly preferred production methods, the hot pressing method can be employed to produce thicker and more durable films. This method involves several key stages similar to other production techniques.

The raw material is initially prepared, and the mixture is formulated by adding necessary additives to enhance film properties. The prepared material is then subjected to high temperature and pressure in a plate press. Heat treatment is applied to melt the mixture during this process, ensuring the material attains the desired thickness and density. Following this stage, the material undergoes cooling, solidification, cutting, and shaping, akin to other production methods. The hot pressing method is particularly suitable for manufacturing thick biocomposite films (Jahangiri et al., 2024).

Spray Method: The application of mulch films in spray form is a preferred method due to its efficiency and ease of use. This process comprises several fundamental steps, outlined below (Figure 17. a, b):

Raw Material Preparation: Sprayable, biodegradable mulch film is typically composed of biodegradable polymers or natural materials.

Solution Preparation: The chosen mulch film materials are mixed with water or an appropriate solvent to create a solution or suspension. This mixture is stirred until it becomes homogeneous.

Application: The prepared solution is then applied to the soil surface and around the plants using a spray gun.

Drying and Film Formation: The sprayed solution is allowed to dry, forming a thin layer on the soil surface. The mulch application is considered complete once the solution has dried (Malinconico et al., 2008).

This method efficiently applies biodegradable mulch films, ensuring even coverage and effective soil protection.

Figure 17. (a) Biodegradable Water-Based Spray Mulch Coating Application to Plants in Pots, (B) Soil Mulch Application by Spraying Method (Malinconico et al., 2008)

Literature research highlights the importance of the specific properties of biodegradable mulch films in delivering the expected benefits. Table 5 summarizes information from various references on biodegradable mulch films, including details on matrix composition, content of additives and their amount(%), thickness(μm), Young's modulus(MPa), tensile strength(MPa), elongation at break (%), water vapor permeability, and production methods. It is important to note that not all authors or research groups provided data for every parameter in their publications. The data have been compiled and presented using a taxonomy method to offer a comprehensive overview and facilitate general insights. Various characterization and standard control tests are employed to determine the physical, chemical, microstructural, and mechanical properties of both commercially available and newly developed mulching films. The results of these tests are presented in the Results and Discussion section provides detailed results and discussions on these findings.

2.8. Taxonomy

Table 5 below summarizes properties of BDM films with different materials.

Table 5. Taxonomy of the study

Ref.	Matrix &Mark	Filler	Filler Content (wt%)	Thickness (µm)	Young's Modulus (YM, MPa)	Tensile Strenght (TS, MPa)	Elongation at Break (EAB, %)	Water Vapor Permeability (WVP)	Production Method
Ayu et al., 2020	PBS/Modified tapioca starch	No filler	0	650 ±1	3216	16.12	NM	5.71 ± 1.32 × (10^{-8} g mm kPa^{-1} s^{-1} m^{-2})	NM
	PBS/Modified tapioca starch	Empty fruit brunch fibers	30	620 ±1	3177	15.16	NM	6.21 ± 1.47 × (10^{-8} g kPa^{-1} s^{-1} m^{-2})	NM
	PBS/Modified tapioca starch	Empty fruit brunch fibers	40	610 ±1	2803	13.25	NM	6.36 ± 0.26 × (10^{-8} g kPa^{-1} s^{-1} m^{-2})	NM
	PBS/Modified tapioca starch	Empty fruit brunch fibers	50	660 ±1	2318	10.13	NM	7.02 ± 1.51 × (10^{-8} g kPa^{-1} s^{-1} m^{-2})	NM
Bilck et al., 2010	TPS/PBAT (30/70) [White]	No filler	0	123 ±12	48.6^{a} ±4.0	8.4^{b} ±1.1	537^{a} ±89	$2.29^{a,C}$ ± 0.46 × (10^{-6} g/m·Pa·day) under 0-33% RH gradient, $4.22^{a,C}$ ± 0.23 × (10^{-6} g/m·Pa·day) under 33-64% RH gradient, $7.92^{a,A}$ ± 0.23 × (10^{-6} g/m·Pa·day) under 64-97% RH gradient	Extrusion

Ref.	Matrix &Mark	Filler	Filler Content (wt%)	Thickness (µm)	Young's Modulus (YM, MPa)	Tensile Strenght (TS, MPa)	Elongation at Break (EAB, %)	Water Vapor Permeability (WVP)	Production Method
	TPS/PBAT/Pigment (30/70/2) [Black]	No filler	0	218 ±22	40.1[a] ±5.8	6.1[b] (±1.6)	530[a] ±102	2.50[a,C] ± 0.11 × (10^{-6} g/m·Pa·day) under 0-33% RH gradient, 4.72[a,B] ± 0.20 × (10^{-6} g/m·Pa·day) under 33-64% RH gradient, 8.36[a,A] ± 0.41 × (10^{-6} g/m·Pa·day) under 64-97% RH gradient	Extrusion
	PE	No filler	0	25 ±1	10.9[b] ±0.4	25.8[a] ±8.4	336[b] ±159	0.01049[a,D] ± 0.012 × (10^{-6} g/m·Pa·day) under 0-33% RH gradient, 0.02125 [a,D] ± 0.002 × (10^{-6} g/m·Pa·day) under 33-64% RH gradient, 0.07633 [a,D] ± 0.020 × (10^{-6} g/m·Pa·day) under 64-97% RH gradient	Extrusion
Bodirlau et al., 2013	Chemically modified starch / starch	No filler	0	200	1169	12.8	8.3	NM	Casting
	Chemically modified starch / starch	Keratin fibers	4	200	1645	25.3	4.5	NM	Casting
	Chemically modified starch / starch	Lignin fibers	4	200	1084	16.5	5.2	NM	Casting
	Chemically modified starch / starch	Cellulose fibers	4	200	1236	19.3	6.5	NM	Casting
Chiellini et al., 2001a	Gelatin	No filler	0	NM	33 ± 1	10 ± 1.6	146 ± 16	NM	Casting

Ref.	Matrix &Mark	Filler	Filler Content (wt%)	Thickness (µm)	Young's Modulus (YM, MPa)	Tensile Strenght (TS, MPa)	Elongation at Break (EAB, %)	Water Vapor Permeability (WVP)	Production Method
	Gelatin	Sugarcane	20	NM	283 ± 2.1	11 ± 2.6	14 ± 2.6	NM	Casting
Chiellini et al., 2001b	PVA	Sugarcane fibers	0	NM	NM	0.8	11.1	NM	Casting
	PVA	Sugarcane fibers + starch	8	NM	NM	0.9	11.8	NM	Casting
	PVA	Sugarcane fibers + starch	14	NM	NM	1.6	15.4	NM	Casting
	PVA	Sugarcane fibers + starch	25	NM	NM	1.8	13.6	NM	Casting
	PVA	Orange pomace fibers	0	NM	NM	2.7	105.4	NM	Casting
	PVA	Orange pomace fibers/starch	8	NM	NM	3.0	76.1	NM	Casting
	PVA	Orange pomace fibers/starch	14	NM	NM	3.1	45.0	NM	Casting
	PVA	Orange pomace fibers/starch	25	NM	NM	3.1	29.6	NM	Casting
	PVA	Apple pomace fibers	0	NM	NM	2.7	149.7	NM	Casting
	PVA	Apple pomace fibers/starch	8	NM	NM	2.4	67.5	NM	Casting

Ref.	Matrix &Mark	Filler	Filler Content (wt%)	Thickness (µm)	Young's Modulus (YM, MPa)	Tensile Strenght (TS, MPa)	Elongation at Break (EAB, %)	Water Vapor Permeability (WVP)	Production Method
	PVA	Apple pomace fibers/starch	14	NM	NM	2.7	60.4	NM	Casting
	PVA	Apple pomace fibers/starch	25	NM	NM	2.7	65.0	NM	Casting
Chong et al., 2019	Seaweed-based (Control)	No Filler	0	58.20 ± 25.03 ^{b}	182.87 ± 35.88 ^{c}	38.32 ± 2.99 ^{c}	23.26 ± 2.77 ^{c}	3.87 ± 0.05^{c} (x10^{-10} g·m/m^{2}·s·Pa)	Casting
	Seaweed-based	Commercial $CaCO_3$	0.1	61.20 ± 24.63 ^{d}	351.89 ± 12.71 ^{c}	69.31 ± 0.74 ^{d}	25.22 ± 1.08 ^{bc}	2.45 ± 0.05 ^{b} (x10^{-10} g·m/m^{2}·s·Pa)	Casting
	Seaweed-based	Microbially Induced $CaCO_3$	0.15	60.00 ± 24.37 ^{c}	286.79 ± 39.92 ^{b}	58.50 ± 5.95 ^{c}	29.1 ± 1.88 ^{c}	2.05 ± 1.06 ^{a} (x10^{-10} g·m/m^{2}·s·Pa)	Casting
	PLA	No Filler	0	13.4 ±1.14 ^{a}	159.30 ± 17.86 ^{c}	10.45 ± 1.49 ^{c}	15.66 ± 3.72 ^{c}	2.68 ± 0.35^{c} (x10^{-10} g·m/m^{2}·s·Pa)	
Finkenstadt & Tisserat, 2010	PLA	No filler	0	NM	575	57.3	18.6	NM	Extrusion
	PLA	Osage orange wood fibers	10	0.4	567±9	48.1	11.3 ± 3.2	NM	Extrusion
	PLA	Osage orange wood fibers	25	0.4	578±11	36.6	8 ± 3.2	NM	Extrusion
	PLA	Osage orange wood fibers	10	0.2	428±37	31.3	9.4 ± 0.3	NM	Extrusion
	PLA	Osage orange wood fibers	25	0.2	643±24	40.4	8.2 ± 0.6	NM	Extrusion
	PLA	Osage orange wood fibers	10	0.14	451±12	30	9.9 ± 0.4	NM	Extrusion

Ref.	Matrix &Mark	Filler	Filler Content (wt%)	Thickness (µm)	Young's Modulus (YM, MPa)	Tensile Strenght (TS, MPa)	Elongation at Break (EAB, %)	Water Vapor Permeability (WVP)	Production Method
	PLA	Osage orange wood fibers	25	0.14	610±28	38	8.2 ± 2.7	NM	Extrusion
Flores et al., 2009	PBS	No filler	0	500	NM	37.2	27.6	NM	Hot pressing
	PBS	Corn starch	20	500	NM	25.1	49.4	NM	Hot pressing
	PBS	Corn starch	40	500	NM	11.6	25.5	NM	Hot pressing
	PBS	Corn starch	60	500	NM	5.7	9.5	NM	Hot pressing
	PBS	Cellulose fibers	20	500	NM	23.9	47.2	NM	Hot pressing
	PBS	Cellulose fibers	40	500	NM	14.7	50.5	NM	Hot pressing
	PBS	Cellulose fibers	60	500	NM	7.8	41.7	NM	Hot pressing
França et al., 2018	PBAT/PLA	No filler	0	100	450 ± 41	12.2 ± 0.7	18.0 ± 0.1	NM	Casting
	PBAT/PLA	Babassu	10	100	480 ± 13	12.0 ± 1.0	10.7 ± 1.4	NM	Casting
	PBAT/PLA	Babassu	20	100	470 ± 43	9.5 ± 1.2	7.1 ± 1.7	NM	Casting
	PBAT/PLA	Babassu	30	100	600 ± 69	7.1 ± 0.4	4.0 ± 0.9	NM	Casting
	PBAT/PLA	Babassu	50	100	650 ± 42	4.4 ± 0.1	1.6 ± 0.1	NM	Casting
Hoffmann et al., 2019	PBAT/PHB (25/75)	No filler	0	100	577 ± 127	11.3 ± 2.2	2.9 ± 0.1	NM	Extrusion
	PBAT/PHB (25/75)	Babassu	1	100	505 ± 158	9.8 ± 1.5	2.2 ± 0.4	NM	Extrusion
	PBAT/PHB (25/75)	Babassu	3	100	510 ± 79	9.8 ± 1.3	2.6 ± 0.5	NM	Extrusion
	PBAT/PHB (50/50)	No filler	0	100	536 ± 49	13.4 ± 1.4	3.4 ± 0.4	NM	Extrusion
	PBAT/PHB (50/50)	Babassu	1	100	475 ± 63	10.0 ± 1.5	2.4 ± 0.1	NM	Extrusion

Ref.	Matrix &Mark	Filler	Filler Content (wt%)	Thickness (µm)	Young's Modulus (YM, MPa)	Tensile Strenght (TS, MPa)	Elongation at Break (EAB, %)	Water Vapor Permeability (WVP)	Production Method
	PBAT/PHB (50/50)	Babassu	3	100	465 ± 43	10.1 ± 1.2	2.6 ± 0.3	NM	Extrusion
	PBAT/PHB (75/25)	No filler	0	100	326 ± 23	16.4 ± 1.5	700 ± 113.0	NM	Extrusion
	PBAT/PHB (75/25)	Babassu	1	100	340 ± 22	12.5 ± 0.9	640.0 ± 46.0	NM	Extrusion
	PBAT/PHB (75/25)	Babassu	3	100	285 ± 29	12.1 ± 1.1	655.0 ± 2.0	NM	Extrusion
Kumar et al., 2018	Cellulose	No filler	0	NM	NM	107.9 ± 6.5	7.8 ± 0.42	NM	NM
	Cellulose	Cellulose fibers	5	NM	NM	76.8 ± 3.8	8.6 ± 0.22	NM	NM
	Cellulose	Cellulose fibers	10	NM	NM	66.8 ± 4.0	9.5 ± 0.29	NM	NM
	Cellulose	Cellulose fibers	15	NM	NM	57.9 ± 4.0	10.2 ± 0.47	NM	NM
	Cellulose	Cellulose fibers	20	NM	NM	56.9± 4.5	11.6 ± 0.38	NM	NM
	Cellulose	Cellulose fibers	25	NM	NM	49.7 ± 3.5	12.7 ± 0.31	NM	NM
Lyu & Han, 2023	Heulgro	-		NM	130.03 ± 15.98[a]	21.82 ± 3.11[a]	198.00 ± 23.65[b]	1,82 (g mm/m^2·day·kPa)	NM
	Ecovio®	-		NM	229.51 ± 34.65[b]	23.86 ± 1.93[a]	152.84 ± 22.33[a]	1,52 (g mm/m^2·day·kPa)	NM
	PBAT (Pure)	No Filler	0	NM	91.125 ± 7.7 0[a]	16.42 ±0.6 4[a]	600 > [d]	5,08 (g mm/m^2·day·kPa)	Extrusion
	PLA (Pure)	No Filler	0	NM	2184.4 ± 83.43[g]	49.83 ±2.3 8[e]	3.80 ± 0.32[a]	2,69 (g mm/m^2·day·kPa)	Extrusion
	PBAT/PLA/CE (80/20)	No Filler	0	30 ± 1	142.57 ± 19.22[c]	16.40 ± 1.53[a]	594.52 ± 9.36[d]	NM	Extrusion
	PBAT/PLA/CE (80/20/1)	Chain Extender (CE)	1	30 ± 1	149.51 ± 13.17[d]	21.12 ± 1.26[d]	600 >d	0.83 ± 0.09 (g mm/m^2·day·kPa)	Extrusion

Ref.	Matrix &Mark	Filler	Filler Content (wt%)	Thickness (µm)	Young's Modulus (YM, MPa)	Tensile Strenght (TS, MPa)	Elongation at Break (EAB, %)	Water Vapor Permeability (WVP)	Production Method
Mariniello et al.,2007	Fennel waste-based	No filler	0	250.8 ± 7	NM	1.9 ± 0.1	7.3 ± 0.58	68.45 ± 1.1 (cm^3 mm m^{-2} day^{-1} kPa^{-1})	Casting
	Fennel waste-based	Phaseolin	NM	303.4 ± 22	NM	3.3 ± 0.3	8.0 ± 1.43	55.24 ± 2.3 (cm^3 mm m^{-2} day^{-1} kPa^{-1})	Casting
	Fennel waste-based	Phaseolin and TG	NM	318.8 ± 19	NM	4.0 ± 0.5	9.0 ± 1.64	48.20 ± 2.1 (cm^3 mm m^{-2} day^{-1} kPa^{-1})	Casting
	Ecoflex	-		NM	NM	30.3[a]	820[d]	0.14 ± 0.03[c] (cm^3 mm m^{-2} day^{-1} kPa^{-1})	Extrusion
	Starch based & Mater- Bi- Z	-		NM	NM	20-50[b]	200-600[b]	33.33[b] (cm^3 mm m^{-2} day^{-1} kPa^{-1})	NM
	LDPE	No filler	0	NM	NM	8-10[d]	15-600[d]	0.5[b] (cm^3 mm m^{-2} day^{-1} kPa^{-1})	NM
Merino & Alvanez, 2020	Starch/chitosan	No filler	0	NM	1.9 ± 0.06	1.5 ± 0.1	70.5 ± 5.2	NM	NM
	Starch/chitosan	Alginate	0.5	NM	1.8 ± 0.23	2.4 ± 0.2	162.0 ± 28.9	NM	NM
	Starch/chitosan	Alginate	1	NM	1.9 ± 0.26	2.9 ± 0.4	125.4 ± 8.8	NM	NM
	Starch/chitosan	Alginate	2	NM	2.2 ± 0.36	2.6 ± 0.3	165.2 ± 21.9	NM	NM
	Starch/chitosan	Alginate	10	NM	2.1 ± 0.24	1.3 ± 0.1	82.4 ± 18.8	NM	NM
Amalini et al., 2019	Cellulose	Microcrystal line cellulose	6.5	30 ± 5	NM	13.03 ± 0.56	NM	1.3 ± 0.05 ($\times 10^{-10}$ g H_2O Pa^{-1} s^{-1} m^{-1})	NM
Ao et al., 2013	Citric acid fermentation wastes	No filler	0	NM	173.1 ± 10.4[a]	5.4 ± 0.3[a]	9.2 ± 0.5[c]	3.10 ± 0.01 ($\times 10^{-10}$ g H_2O Pa^{-1} s^{-1} m^{-1})	NM
Briassoulis & Giannoulis, 2018	LLDPE	-		50 ± 5		33.6 ± 5.3	NM	NM	NM

Ref.	Matrix &Mark	Filler	Filler Content (wt%)	Thickness (µm)	Young's Modulus (YM, MPa)	Tensile Strenght (TS, MPa)	Elongation at Break (EAB, %)	Water Vapor Permeability (WVP)	Production Method
Liling et al., 2016	Sodium alginate / Calcium chloride			125 ± 15		134.58 ± 10	NM	0.603 ± 0.1 ($\times 10^{-10}$ g H_2O Pa^{-1} s^{-1} m^{-1})	NM
Ma et al., 2016	Citric acid fermentation wastes / PVA(polyvinyl alcohol)	No filler	0	60 ± 10		16.43 ± 0.5	NM	1.23 ± 0.01 ($\times 10^{-10}$ g H_2O Pa^{-1} s^{-1} m^{-1})	NM
Ning et al.,2021	Cellulose/ Humic acid (3.5/1.5)	Chitosan/ Neferin/ Glycerol	2/0.75/6	90 ± 0.04[b]		57.98 ± 0.6[a]	NM	0.87 ± 0.02[a] ($\times 10^{-10}$ g H_2O Pa^{-1} s^{-1} m^{-1})	Casting
Patil & Netravali, 2016	Starch(Mango seed)	No filler	0	200 ± 100	1347 ± 324	16.24 ± 1.98	1.54 ± 0.56	NM	Casting
	Starch(Mango seed)	Micro fibrillated cellulose	20	200 ± 100	1667 ± 275	31.17 ± 7.01	3.80 ± 0.72	NM	Casting
	Starch(Mango seed)	Micro fibrillated cellulose	30	200 ± 100	1780± 221	38.69 ± 3	3.95 ± 0.77	NM	Casting
	Starch(Mango seed)	Micro fibrillated cellulose	40	200 ± 100	2407 ± 63	50.03 ± 1.97	2.65 ± 0.13	NM	Casting
Spiridon et al., 2011	Corn starch/ Chemically modified starch microparticles	No filler	0	200	1162	11.5	7.8	NM	Casting
	Corn starch/ Chemically modified starch microparticles	Beech lignin	4	200	796	13.9	5.5	NM	Casting
	Corn starch/ Chemically modified starch microparticles	Boost lignin	4	200	1074	16.9	4.8	NM	Casting

Ref.	Matrix &Mark	Filler	Filler Content (wt%)	Thickness (µm)	Young's Modulus (YM, MPa)	Tensile Strenght (TS, MPa)	Elongation at Break (EAB, %)	Water Vapor Permeability (WVP)	Production Method
Stasi et al., 2020	Starch(Maize)	No filler	0	NM	27.87 ± 0.91	2.65 ± 0.03	0.66 ± 0.05	NM	NM
	Starch(Maize)	Carbon ashes	7	NM	32.19 ± 0.66	2.27 ± 0.16	0.33 ± 0.03	NM	NM
Touchaleaume et al.,2016	PE	No filler	0	40	178 ± 20	NM	335 ± 20	0.24 ± 0.19 (x 10^{12} mol m^{-1} s^{-1} Pa^{-1})	NM
	PLA/PBAT (30/70) & Bioflex F2110	No Filler	0	40	787 ± 40	NM	269 ± 40	0.81 ± 0.12 (x 10^{12} mol m^{-1} s^{-1} Pa^{-1})	Extrusion
	PPC/PBAT (20/70) & Bioflex F2110	No Filler	0	40	210 ± 15	NM	369 ± 36	1.33 ± 0.07 (x 10^{12} mol m^{-1} s^{-1} Pa^{-1})	Extrusion
	Starch/ PBAT & Mater-Bi® CF04P	No Filler	0	40	217 ± 12	NM	376 ± 59	1.11 ± 0.12 (x 10^{12} mol m^{-1} s^{-1} Pa^{-1})	Extrusion
	Starch/PBATr & Mater-Bi® CF04P	Recycled waste material	10	40	140 ± 10	NM	509 ± 65	1.54 ± 0.13 (x 10^{12} mol m^{-1} s^{-1} Pa^{-1})	Extrusion

Notes:

Values are represented as mean ± standard deviation.

Means in the same rows followed by the same letters denote no significant difference ($p < 0.05$). Different letters (a, b, c, d), in the same column indicates significant differences ($p < 0.05$).

Tapioca is a starch product obtained from the roots of cassava or yucca, a root vegetable with high starch content grown in tropical regions.

The Osage orange, botanically known as Maclura pomifera, is a species of tree native to the central and eastern United States.

Babassu oil is an oil that is extracted from the fruit of the babassu palm, which grows in Brazil.

Chitosan is a natural polysaccharide found in shellfish.

Not Measured or Mentioned (NM)

Linear low-density polyethylene (LLDPE)

3. RESULT AND DISCUSSION

3.1. Characterization Tests and Standards

To replace the widely used synthetic mulch films with biodegradable, environmentally friendly mulch films, it is stated that mulch films should be able to meet the physical, chemical, mechanical, and microstructural properties expected for use in agricultural applications. It is also important to ensure economic viability through the use of synthetic plastic production technologies (Scarascia-Mugnozza et al., 2006).

3.1.1. Mechanical Properties

The mulch films used in agriculture are expected to meet the expected mechanical properties during unrolling, laying and fixing in the soil and also in the face of other factors such as rain (Hegazi, 2000). The internationally recognized ASTM D882 standard primarily addresses the mechanical properties of general plastic films, including mulching materials, by outlining the necessary test methods and requirements. This standard provides recommended value ranges for the mechanical properties of mulch materials. In contrast, the EN 17033 standard, used in EU countries, specifically defines the requirements and test methods for biodegradable mulch films used in agriculture and horticulture, along with the expected values for their properties (Briassoulis & Giannoulis, 2018).

Tensile Strength (TS, MPa): Relevant standards for determining the tensile strength of mulch materials includes,

- ASTM D882 - Standard Test Method for Tensile Properties of Thin Plastic Sheeting
- EN 17033 - Plastics - Biodegradable mulch films for use in agriculture and horticulture - Requirements and test methods (Table 6).

According to the EN 17033 EU Standard, the minimum tensile strength of mulch films should be 12 MPa in the machine direction and 10 MPa in the transverse direction, with an expected value of 16 MPa (Briassoulis & Giannoulis, 2018). For example, in the study by Lyu & Han (2023), the tensile strength of commercially preferred non-biodegradable LDPE mulch film was measured at 38.38 MPa for 15 µm thickness and 25.23 MPa for 20 µm thickness (Lyu & Han, 2023).

Young's Modulus (Elastic Modulus) (YM, MPa): Relevant standards for determining the Young's modulus of mulch materials includes,

- ASTM D882 - Standard Test Method for Tensile Properties of Thin Plastic Sheeting
- EN 17033 - Plastics - Biodegradable mulch films for use in agriculture and horticulture - Requirements and test methods (Table 6).

The EN 17033 EU Standard specifies that the YM value should be between 250-300 MPa. In contrast, the ASTM D882 standard recommends a range of 500-1000 MPa. According to the study by Lyu & Han (2023), the YM value of non-biodegradable LDPE mulch film was 814.88 MPa for 15 µm thickness and 251.01 MPa for 20 µm thickness(Lyu & Han, 2023).

Elongation at Break (EAB, %): While specific standards do not specify exact values for EAB(%), the EN 17033 EU Standard expects a Parallel Elongation at Break value of 150% and a Transverse Elongation at Break value of 300%. In the study by Lyu & Han (2023), the EAB value of non-biodegradable LDPE mulch film was measured at 577% for 15 µm thickness and 461.40% for 20 µm thickness (Lyu & Han, 2023).

Conventional mulch films sold in the market are expected to comply with the European standard in Table 6.

Table 6. Mechanical and Biodegradability Criteria for BDM films According to EN 17033 EU Standard (Scarascia-Mugnozza et al., 2006).

Tensile Strenght [MPa]	**Stress at Yield [MPa]**	**Parallel Elongation at Break (%)**	**Transverse Elongation at Break (%)**	**Biodegradation**
16	9	150	300	≥90 % conversion into CO_2 within 2 years under ambient soil consitions

3.1.2. Water-Resistant Properties

3.1.2.1. Water Vapor Permeability

Water Vapor Permeability (WVP) is defined as the rate at which water vapor passes through a unit area of a material of unit thickness, driven by a unit vapor pressure difference between two surfaces, under specified temperature and humidity conditions (ASTM E96/E96M). In addition to mechanical properties and biodegradability, WVP is a crucial parameter for mulching applications, particularly in arid regions. Low WVP values help retain soil moisture, thereby promoting sustainable water management (Menossi et al., 2021).Minimizing moisture loss by preventing evaporation is especially important in dry and non-irrigated lands, where low WVP is desired (Hegazi, 2000).

In the study of Ayu et al. (2020), WVP value was measured using ASTM E96/E96M standard method. In the study, the WVP value of PBS/Modified tapioca starch mulch film was 0.24 ± 0.19 (x 10^{12} mol m^{-1} s^{-1} Pa^{-1}) , while adding empty fruit brunch fibres to the matrix increased the WVP value. This can be explained by the fact that materials with hydrophilic fibres in nature lose more water because they tend to absorb water molecules (Ayu et al., 2020).

Touchaleaume et al. (2016) also measured WVP values gravimetrically using ASTM E96/E96M method. In the study, before the mulch films were laid on the soil, the WVP value of PE film was 0.24 ± 0.19 (x 10^{12} mol m^{-1} s^{-1} Pa^{-1}), while the WVP values of PLA/PBAT, PPC/PBAT, Starch / PBAT blend mulch films were higher. It was stated that this was expected since most biobased polymers are hydrophilic. In the study of Bilck et al., 2010, the WVP value of biodegradable TPS/PBAT mulch films was higher than PE mulch film. However, similar results were obtained in fruit yield of biodegradable and PE mulch films (Touchaleaume et al., 2016)

Many WVP values are not measured or mentioned in the Table 5. There is a need for further investigation of WVP values of BDM films in future studies (Ayu et al., 2020).

3.1.1.1. Water Contact Angle

The Water Contact Angle (WCA) value, which shows the surface hydrophobicity of the films, is considered hydrophobic if the water contact angle is greater than 90 degrees. Chong's study (2019) indicates that seaweed-based biodegradable film incorporated with MB–$CaCO_3$ and C–$CaCO_3$ exhibited superior wetting resistance compared to the conventional biodegradable mulch film. The film with microbial-induced $CaCO_3$ denoted the highest WCA (100.94◦), while conventional biodegradable mulch film denoted the lowest WCA (90.25◦). (Figure 18) Results verified that the fillers improved the film water contact angle (Chong et al., 2019).

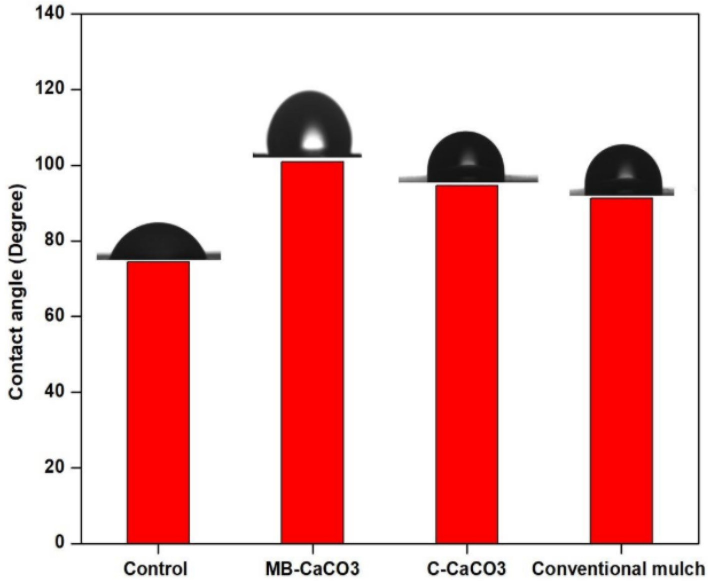


Figure 18. Contact Angle of Control, MB-$CaCO_3$, C-$CaCO_3$ and PEM (Chong, 2019).

3.1.3. Chemical and Microstructural Properties and Analyses

Various analyses performed on mulch films, such as provide structural information by Scanning Electron Microscopy (SEM), bonding information by Fourier Transform Infrared Spectroscopy (FTIR) and crystallinity and amorphous information by X-Ray Diffraction (XRD) analyses.

3.1.3.1. Fourier Transform Infrared Spectroscopy (FTIR) Analysis

FTIR is a powerful analytical technique used to detect the presence or absence of specific peaks, providing critical information about the molecular structure of materials. This method identifies the types of bonds between molecules by analyzing the absorption of infrared light at various wavelengths. Each type of chemical bond absorbs infrared radiation at characteristic frequencies, resulting in distinct peaks in an FTIR spectrum. The presence or absence of these peaks can confirm the existence of particular functional groups within the sample. The absorbance or transmittance spectra of materials is recorded across a range of 400-4000 cm^{-1} For example, the O-H stretching vibrations typically appear as broad peaks around 3200-3600 cm^{-1}, while C=O stretching vibrations usually manifest around 1700 cm^{-1}. By comparing these observed peaks with known reference spectra, one can identify the specific functional groups present in the sample.

In a study by Chong et al. (2019), attenuated total reflectance (ATR) mode FTIR was employed to identify the chemical functional groups in seaweed-based films with added fillers and commercial PLA mulch film before and after a 6-month soil burial test. Prior to FTIR analysis, the films were prepared by drying 2 cm x 2 cm samples in an oven at 60ºC for 24 hours. Due to the hydrophilicity of seaweed, broad and diffuse peaks with hydroxyl groups forming O-H stretching vibrations were observed in the range of 3320 to 3329 cm^{-1} (Khalil et al., 2018). The addition of MB-$CaCO_3$ and C-$CaCO_3$ resulted in decreased peak intensity compared to the control, attributed to the strong interaction between seaweed and C-$CaCO_3$, which improved the mechanical and physical properties of the seaweed-based film. The commercial PLA film did not exhibit functional groups in the O-H stretching vibration region. In seaweed-based films, O-H stretching and symmetrical and asymmetrical stretching of aliphatic C-H were identified between 2924 and 2889 cm^{-1}, and at 2959 cm^{-1} in commercial mulches. Stress vibrations of (C=O) produced absorption peaks between 1643 and 1647 cm^{-1} in seaweed-based films, with the main peak at 1712 cm^{-1} in conventional mulch film assigned to the carbonyl group (Figure 19). Absorption bands due to CH deformation and asymmetry were observed at 1361 and 1386 cm^{-1} in conventional mulch film (Chong et al., 2019).

Beyond identifying functional groups, FTIR spectroscopy also allows for the examination of relative changes in these peaks. Such changes can reveal valuable insights into the material's structure and properties. For instance, variations in peak intensity can indicate changes in the concentration of certain functional groups, suggesting modifications in the chemical composition or interactions within the sample. These relative changes can help elucidate the degree of polymerization, crystallinity, or the presence of additives and impurities (Chong et al., 2019).

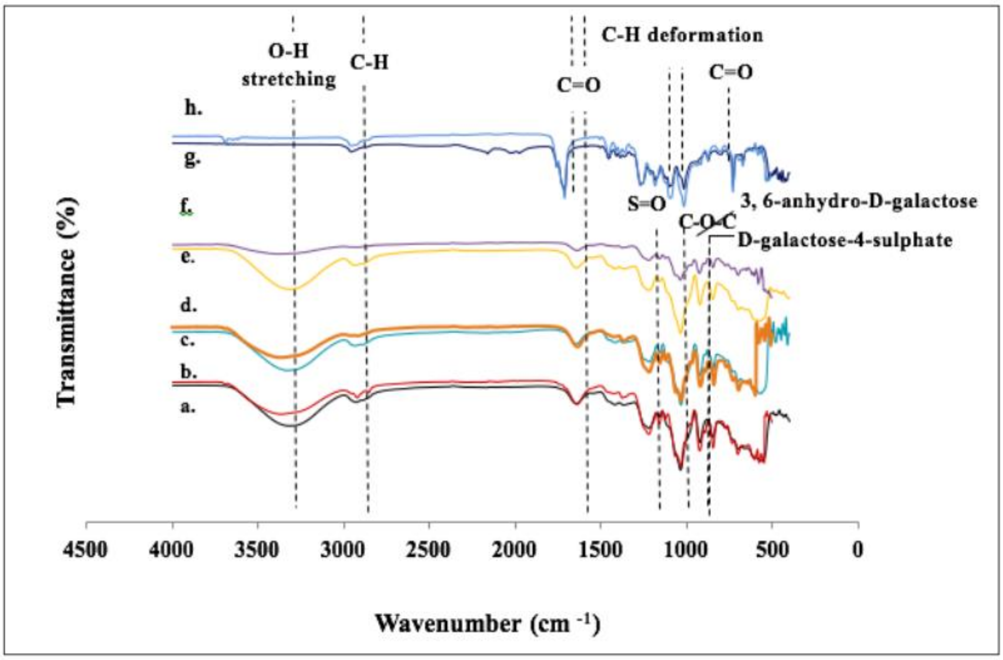


Figure 19. FTIR Spectra of Seaweed-Based Films with Added Fillers and Commercial PLA Mulch Film Before and After 6 Months of Soil Burial Test (Chong et al.,2019)

In addition, shifts in peak positions can provide information about the chemical environment of the functional groups. For example, hydrogen bonding can cause the O-H stretching vibration peak to shift to lower wavenumbers. By analyzing these shifts, researchers can gain insights into the molecular interactions and the overall structural dynamics of the material. FTIR spectroscopy, therefore, not only identifies the types of bonds present in a material but also tracks the relative changes in these bonds under different conditions. The FTIR spectra of seaweed-based and commercial PLA film before and after 6 months of soil burial test, with wavenumbers between 500 and 4000 cm^{-1} are shown in Figure 20 (Chong et al.,2019). This dual capability makes FTIR an indispensable tool in materials science for understanding the chemical composition, structural integrity, and interaction of various components within a sample.

Considering that every material, additive, and process parameter alters the microstructure and chemical bonds of the initial product, and acknowledging that factors such as soil type, planted crop, temperature, humidity, and the presence and diversity of microorganisms and fungi influence degradation characteristics post-burial, it is more appropriate to evaluate studies within the context of their specific parameters. By leveraging both the identification of functional groups and the analysis of their relative changes, FTIR provides a comprehensive understanding of material properties, crucial for applications ranging from quality control to the development of new materials.

Wave Numbers (cm^{-1})			Functional Groups/Bonds/Vibrations
Types of Films	**Before Burial**	**After Burial**	
Control	3329	3325	O–H stretching vibration
	2924	2908	Stretching of aliphatic C–H
	1647	1647	Stretching vibration of C=O
	1219	1219	Sulphate ester group/ stretching vibration of S=O
	1034	1033	Stretching of C–O–C glycosidic bond
	922	922	3, 6-anhydro-D-galactose
	845	845	D-galactose-4-sulphate
MB–$CaCO_3$	3325	3320	O–H stretching vibration
	1646	1616	Stretching vibration of C=O
	1219	1201	Sulphate ester group/ stretching vibration of S=O
	1034	1026	Stretching of C–O–C glycosidic bond
	922	902	3, 6-anhydro-D-galactose
	845	823	D-galactose-4-sulphate
C–$CaCO_3$	3320	3302	O-H stretching vibration
	2889	2873	stretching of aliphatic C–H
	1643	1639	Stretching vibration of C=O
	1219	1253	Sulphate ester group/ stretching vibration of S=O
	1034	1014	Stretching of C–O–C glycosidic bond
	922	925	3, 6-anhydro-D-galactose
	845	848	D-galactose-4-sulphate
Conventional mulch	2959	2927	stretching of aliphatic C–H
	1712	1710	Stretching vibration of C=O
	1386	1386	CH deformation and asymmetric
	1361	1361	CH deformation and asymmetric
	1016	1012	C–O–C asymmetric
	699 to 729	679 to 723	Stretching vibration of C=O

Figure 20. Functional Groups, Bonds, and Vibrations of Seaweed-Based Films and Conventional Mulch (Chong et al.,2019)

In the study of Ghani et al. (2023), it was stated that molecular structure information of samples in solid, liquid or low phase can be determined precisely and with high accuracy by using Michelson interferometer with high resolution.

Figure 21 shows the various functional group compositions of the mulch films in the study, such as O-H, C-H, N-H, C-H, and C-O. The stretching vibration range of the O-H group bond is seen in the 3271 cm^{-1} regions of the absorption spectra and the symmetric and asymmetric stretching vibrations of the C-H bond are seen with the 2930 cm^{-1} spectra. The absorption spectra in the 1552 cm^{-1} region show N-H bending, C-C stretching at 1407 cm^{-1} and C-O stretching range of starch at 1022 cm^{-1} (Ghani et al., 2023).

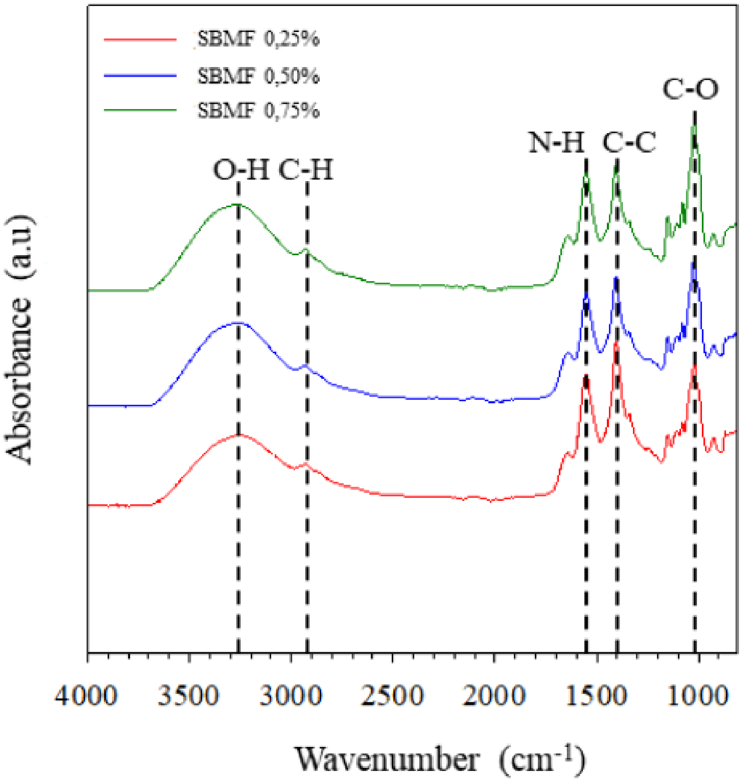


Figure 21. FTIR Test Results from BDM (Ghani et al.,2023)

3.1.3.2. Scanning Electron Microscopy (SEM) Analysis

SEM analyses of mulch materials provide micro and morphological observation. In addition, cracks in the films, homogeneity, and microscopic mixing surface smoothness can be detected by SEM analysis.

In the study of Chong et al. (2019), before SEM analysis, the films were dried in the oven and 1 cm x 1 cm sized tape was prepared as a representative sample. Then, the films were coated with a thin layer of gold with a sputtering coater. The surface of the films and fractured morphologies were examined by SEM by using 500x and 2000x magnification, respectively. (Figure 22) (Chong et al., 2019).

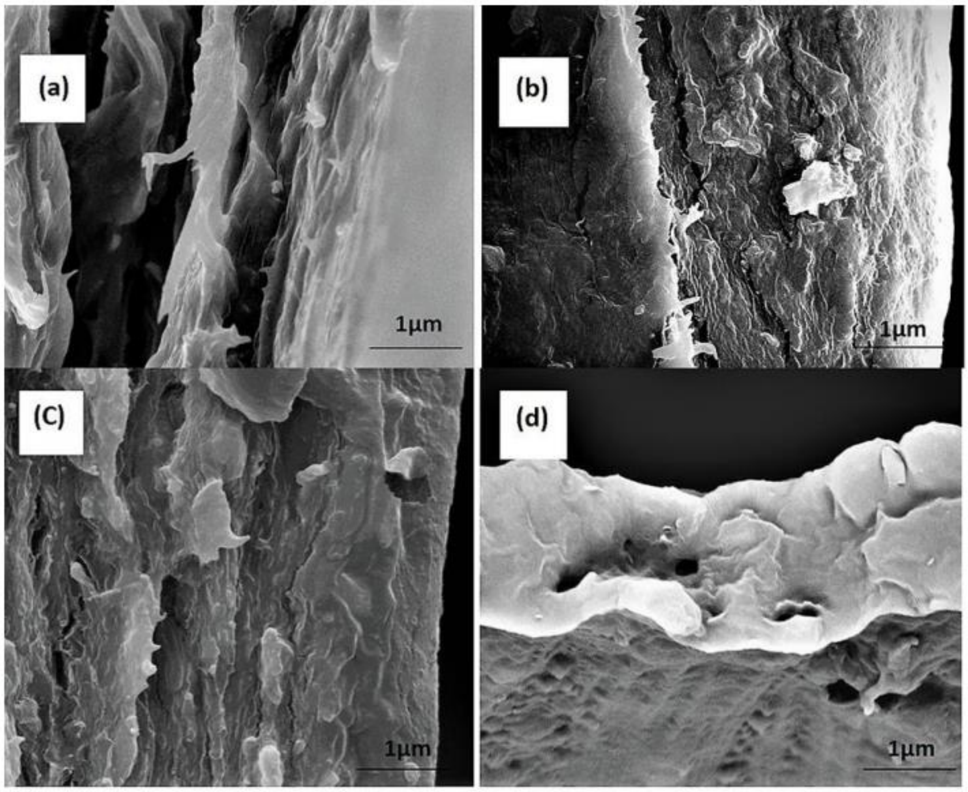
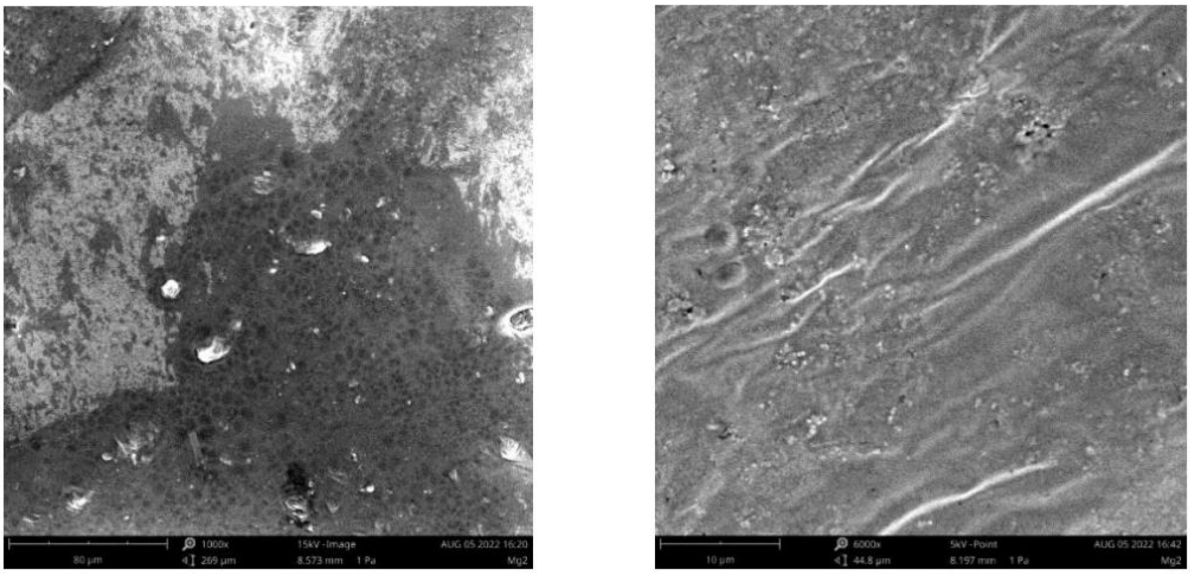


Figure 22. Fractured Morphologies of (a) Control Film and (b) Composite Film Containing 0.1% C-$CaCO_3$; (c) 0.15% MB-$CaCO_3$; and (d) Conventional Mulch Film (Chong et al., 2019).

It was observed that the broken surfaces of MB-$CaCO_3$ and C-$CaCO_3$ added seaweed-based films have a less void ratio and more compact morphological structure compared to the control film. This is due to the strong interaction between the matrix and the filler. This strong interaction provides good interfacial tension, and the material shows better mechanical properties in service life. The presence of some holes in the morphology of the commercial PLA film resulted in it having lower mechanical properties than seaweed-based films. Observing homogeneous distribution in the matrix with the addition of $CaCO_3$ explains the improvement in physical and mechanical properties. The rough and uneven surface appearance with the addition of $CaCO_3$ also shows the strong communication between the matrix and the C-$CaCO_3$ filler. Biocomposite film strength increased with C-$CaCO_3$, which contains higher crystallinity than MB-$CaCO_3$. It was observed that MB-$CaCO_3$ consists of more regular layers with uniform shape and type structure (Chong et al., 2019).

In the study of Ghani et al. (2023), the morphological analysis of 0.75% starch-based BDM film was studied using SEM with 1000 and 6000 times magnification. Figure 23 shows that the ground surface of the film is irregular and fibrous (a), while pores are present (b). According to the authors, the pores were formed due to inhomogeneous solution mixing. It is seen that carbon black is not homogeneously distributed in the polymer matrix. This creates favorable areas for water accumulation. Even if water does not interact with the polymer matrix, it acts as a plasticizer and reduces mechanical values. The roughnesses noticed when the film surface is touched are consistent with the SEM images (Ghani et al., 2023).



(a) (b)

Figure 23. The Morphology of the Biodegradable Mulch Film is (a) 0.75% Sprayable BDM with 1000x Magnification (b) 0.75% Sprayable BDM with 6000x Magnification (Ghani et al., 2023)

3.1.4. X-Ray Diffraction (XRD) Analysis

X-ray diffraction (XRD) analysis is used to ascertain the crystal structure and atomic arrangement within materials. Through this method, material analyzed specified intervals of 2theta. The resulting pattern of X-rays, displaying intensity and angle of diffraction points, yields valuable information about the crystal structure by using computer software analysis.

In the research by Lyu & Han (2023), analyses were conducted on biodegradable mulch (BDM) films utilizing an X-ray diffractometer. The correlation between the internal crystal structure, molecular arrangement of polymers, and their mechanical properties and phase behavior was explored.

Figures 24 a, b, and c depict the crystal structures corresponding to the compositions of PLA, PBAT, PBAT/PLA, and PBAT/PLA/CE, respectively. The presence of five peaks in the PBAT (pure) film indicates a crystalline structure, contrasting with the absence of a peak in the PLA (pure) film, indicative of an amorphous structure. PBAT/PLA films exhibit PBAT-like diffraction peaks rather than PLA, suggesting that only PBAT contributes to the crystalline phase of the composite material. Consistent with prior observations, the determined crystallinity percentages for pure PBAT, PBAT/PLA, and PBAT/PLA/CE were 13.77%, 10.36%, and 10.07%, respectively. The PBAT/PLA matrix demonstrates higher peak density and crystallinity than the CE-added composition, albeit with closely positioned peaks. This observation suggests that adding CE diminishes the crystallinity of BDM films, potentially attributable to reduced polymer mobility resulting from elongation of the polymer chain (Lyu & Han, 2023).

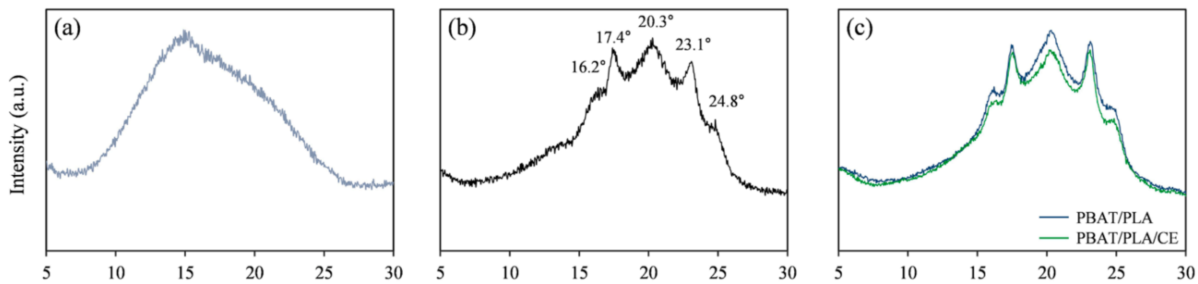


Figure 24. XRD Diffractogram of (a) PLA (b) PBAT, and (c) PBAT/PLA Blend with and without CE (Lyu & Han, 2023)

3.2. Factors Affecting the Biodegredable Mulch Properties

This study evaluated the mechanical properties, water vapor permeability and production methods of biodegradable mulch films made from different materials and fillers. It was found that the mechanical and water vapor resistance properties of mulch materials vary according to different parameters. The factors affecting the properties of biodegradable mulch and a discussion of these factors according to the results of the study are presented below.

3.2.1. Thickness of Mulch

The study observed that the thickness of the films produced with different materials and fillers varied. As an example, the study by Ayu et al. (2020) showed that mulch films made with PBS/Modified tapioca starch had a thickness of 650 µm in films without fillers, and the thickness changed in the range of 620-660 µm with the addition of empty fruit brunch fibers (Ayu et al., 2020)

In another study by Bilck et al. (2010), films without fillers had a thickness of 123 µm, which increased to 218 µm with the addition of 2 wt% pigments.

As the thickness of biopolymer films increases, mechanical and water barrier properties are expected to improve as the resistance of the film increases. Finkenstadt & Tisserat (2010) developed BDM films of different thicknesses by adding wood fibers with different particle sizes containing Osage orange in increasing ratios by weight into the PLA matrix as filler. This study evaluated the effect of thickness and amount of filler material on mechanical properties. For the 0.4 µm BDM film, adding 25 wt% Osage orange resulted in a slight improvement in YM. The thinner (0.2 and 0.14 µm) BDM films containing 25% Osage orange had an increase in YM. Film containing 25% Osage Orange had TS between 36-40 MPa, while EAB did not change. Film containing 10% Osage orange showed a decrease in YM (567-451 MPa) and TS (48-30 MPa) with decreasing thickness, while EAB was not affected. For all BDM films, TS and EAB values decreased with the addition of Osage orange at all thicknesses (Finkenstadt & Tisserat, 2010). In this study, it was obtained that BDM films could not reach the desired EAB value while they were above the preferred TS and YM values according to the EN 17033 standard.

These indicate that the relationship between film thickness and mechanical properties is complex and depends on the specific composition and filler content of the BDM films. While increasing thickness generally improves mechanical properties, the effect can be influenced by factors such as the type and amount of filler used. In some cases, reducing thickness has not had a major effect on mechanical properties, while in other cases, it has led to a decline in TS and EAB values. Therefore, the optimum balance between film thickness and mechanical performance should be determined based on the specific requirements and formulation of the BDM films.

3.2.2. Matrix and Filler Compatibility

The compatibility between the matrix and filler significantly influences the films' mechanical and water vapor permeability properties. Several studies have demonstrated that factors such as chemical compatibility between the matrix and filler, differences in functional groups, non-uniform distribution, and interference bonding play crucial roles in determining these properties.

In a study by Ayu et al. (2020), PBS and modified tapioca starch were utilized as the matrix, while empty fruit bunch fibers were incorporated as filler at varying weight ratios. The authors observed decreased YM and TS values with increasing fiber ratio in the PBS/modified cassava starch matrix. This decline was attributed to poor interface compatibility between the matrix and filler, variations in functional groups, and non-uniform distribution. Additionally, an increase in the water vapor permeability (WVP) value was noted due to the hydrophilicity of fibrous crystals.

Similarly, Spiridon et al. (2011) developed BDM films using the casting method by incorporating lignin derived from two different sources (boost and beech) into a matrix of corn starch and chemically modified starch microparticles at a filler rate of 4 wt%. The study revealed that adding lignin increased the TS value of BDM films while reducing the YM and EAB values. The authors attributed this enhancement in mechanical properties to the formation of strong molecular hydrogen bonds between starch and lignin, resulting in film hardening.

These findings underscore the importance of achieving compatibility between the matrix and filler to optimize biodegradable mulch films' mechanical and water vapor permeability properties.

Bodirlau et al. (2013) employed the casting method to produce BDM films using corn starch and chemically modified starch microparticles as the matrix structure. They added keratin, lignin, and cellulose fibers at a rate of 4% by weight. Interestingly, while adding keratin and cellulose fibers increased the YM value, the incorporation of lignin fibers decreased. Furthermore, adding 4 wt% keratin, lignin, and cellulose fibers increased TS values, with the highest increase observed with keratin fibers. However, all three fillers caused a decrease in the EAB value, with the most significant reduction observed with keratin fibers. The formation of high molecular hydrogen bonds between starch and natural fibers produced more brittle biopolymer composite materials.

In the study by Merino & Alvarez (2020), BDM was developed by adding natural seaweed microparticles to the starch and chitosan matrix at different weight ratios as filler, and its mechanical properties were investigated. The addition of natural seaweed microparticles did not significantly improve the TS, regardless of the weight ratio. However, YM values increased with the increasing weight percentage of alginate, except for the BDM with 10% alginate, where the YM value decreased. Furthermore, the EAB value increased in the BDM film with 0.5% and 2% alginate weight ratios. The authors attributed the improvement in the YM value to the chemical compatibility and integrity between the starch/chitosan matrix and alginate filler. However, discontinuities resulting from particle agglomeration in the composite film containing 10% filler caused a decrease in mechanical properties. Consequently, the BDM films in this study did not meet the preferred TS, YM, and EAB values according to the EN 17033 standard.

In a study by Chong et al. (2019), two different types of calcium carbonate ($CaCO_3$) were added to the seaweed matrix, and the properties of YM, TS, EAB, and WVP were evaluated. WVP of seaweed-based films containing MB-$CaCO_3$ is lower than that of conventional mulch films. The desired low WVP property for mulch films made it advantageous to prefer the MB-$CaCO_3$ film. The hydrophobicity created by adding MB-$CaCO_3$ and C-$CaCO_3$ resulted in lower water vapor permeability than the control film. The TS value of both mulch films with the filler is 16 MPa and above, which is preferred according to the EN 17033 standard. The YM value is at least 250 MPa and above according to the EU standard EN 17033. Seaweed-based films containing MB-$CaCO_3$ and C-$CaCO_3$ showed higher TS, YM and EAB than commercial PLA films. Adding MB-$CaCO_3$ resulted in better results than C-$CaCO_3$ (Chong et al., 2019). According to the study results, adding calcium carbonate improved the properties of the pure seaweed film and showed better mechanical and WVP properties than commercial biodegradable films. Therefore, seaweed-based films are a suitable material candidate as mulch films in agricultural applications.

In the study of Kumar et al. (2018), biopolymer BDM was produced by the regeneration process by adding cellulose fibrils as fillers in cellulose matrix at increasing ratios by weight (0,5%, 10%, 15%, 20%, and 25%) and its mechanical properties were investigated. The increase in cellulose fibrils filler by weight caused a decrease in the amount of TS and an increase in the EAB value. According to the author, the difference in the size of cellulose fibers and their irregular arrangement in the matrix caused a decrease in the TS value (Kumar et al., 2018).

According to these studies, optimizing the composition of the matrix and filler is crucial for achieving the desired properties. Additionally, it is important to ensure that the filler material is appropriately distributed during the application phase.

3.3. Type and amount of filler material

The type and amount of filler material added to the matrix also affected the properties of the biodegradable mulch films. In the study of Patil & Netravali (2016), BDM films were developed and characterized by the casting method by adding microfibril cellulose as filler in the starch matrix at increasing ratios by weight. For BDM, increasing the weight of microfibril cellulose in the starch matrix (0% to 40%) increased YM and TS. The TS value increased almost twice, especially with the addition of 20% microfibril cellulose. Adding 0% to 30% microfibril cellulose increased the EAB value of BDM while adding 40% microfibril cellulose decreased the EAB value. The authors stated that the addition of cellulose to the biopolymer material in which the matrix is starch as a filler up to a certain ratio by providing homogeneous distribution greatly improves the mechanical properties of BDM. The chemical similarities of the matrix and fillers can provide interfacial bonding of BDM films (Patil & Netravali (2016).

The studies of França et al. (2018) and Hoffmann et al. (2019) used babassu filler in different weight ratios, while França et al. (2018) used PBAT/PLA matrix and Hoffmann et al. (2019) used PBAT and PHB (25/75, 50/50, 75/25) matrix. Both studies showed that the babassu-added films achieved the minimum target YM value (250 MPa) according to the EN 17033 standard, but were unable to achieve the minimum target TS value (16 MPa). Regarding the EAB value, in the study by Hoffmann et al. (2019), 640-655% values were achieved with the films using

PBAT/PHB (75/25) matrix. According to the authors, cellulose-based particles showing reinforcement effect supported the hardness increase. This problem is thought to be solved by optimizing the matrix-filler compatibility to increase the TS value of mulch films.

Chiellini et al. (2001b) produced mulch films using the casting method, incorporating starch from sources like sugar cane, apple, and orange wastes into a biodegradable PVA matrix. The gradual addition of sugarcane fibers/starch and orange pomace fibers/starch slightly increased the TS value, while apple pomace fibers/starch had no significant effect. The EAB value significantly decreased with the addition of orange and apple pomace fibers/starch, but only slightly with sugarcane fibers/starch. However, the films did not meet the 16 MPa TS criterion according to the EN 17033 standard.

In the study conducted by Flores et al. in 2009, mulch film was developed by adding gradually increasing amounts of corn starch and cellulose fibres by weight to the biodegradable synthetic polymer PBS (polybutadiene succinate) matrix by hot pressing production method. Increasing the ratio of corn starch and cellulose fibres by weight caused the TS value of BDM to decrease. Except for the addition of 40 wt% cellulose fibres, the addition of corn starch and cellulose fibres decreased the EAB value of BDM. The authors stated that the addition of starch in the mulch film as a filler up to a certain ratio to be distributed homogeneously improved the TS value (Flores et al., 2009).

Stasi et al. (2020) improved the mechanical properties of BDM films with a corn starch matrix by adding 7% carbon ashes from lignocellulosic agricultural wastes. While the addition increased the YM value, it decreased both TS and EAB values (Stasi et al., 2020).

Touchaleaume et al. (2016) added recycled waste material as a filler to a starch/PBAT mulch film, resulting in a lower WVP value but an EAB value of 509%, which was above the target value of 300%. The author noted that the higher WVP value compared to PE might not pose an issue for agricultural applications in warm climates (Touchaleaume et al., 2016).

These findings underscore that the type and percentage of filler material are critical in optimizing the mechanical and physical properties of biodegradable mulch films. The specific composition and distribution of fillers must be carefully controlled to achieve the desired performance characteristics.

3.4. Use of Cross-Linking Substances

Using cross-linking agents in protein-based films reduces the distance and movement between protein chains, resulting in enhanced tensile strength and water vapor permeability (Çağrı-Mehmetoğlu, 2010).

In a study by Mariniello et al. (2007), the goal was to develop new biodegradable products utilizing agricultural wastes. The researchers produced recycled fennel waste-based films (FW films), fennel waste-based films containing bean protein (phaseolin) (FW/Pha films), and fennel waste-based films modified with the transglutaminase (TG) enzyme (FW/Pha/TG films) using the casting method. The morphological, mechanical, water vapor permeability and biodegradability properties of these films were compared with commercial biodegradable films (Ecoflex and Mater-Bi) and non-biodegradable LDPE films. The addition of phaseolin and TG to the fennel waste-based films increased the thickness, tensile strength (TS), and elongation at break (EAB) values, while also improving the water vapor permeability (WVP). The study concluded that FW/Pha/TG films have the potential to be developed as environmentally friendly biodegradable mulch film materials (Mariniello et al., 2007).

In another study by Chiellini et al. (2001a), biodegradable mulch films (BDM) were produced using the casting method by adding 20% sugar cane by weight to a gelatin matrix, and their mechanical properties were investigated. Additionally, glutaraldehyde was used as a cross-linker with pure gelatin. The addition of sugar cane fibers to the gelatin matrix led to significant changes in the Young's modulus (YM), which increased by 758%, and a decrease in the EAB value by 90%, while the TS remained unchanged. The authors noted that the resulting hard and brittle composition was unsuitable for agricultural mulch films (Chiellini et al., 2001a).

These studies indicate that the use of cross-linking agents in BDMs can enhance mechanical and water barrier properties if properly optimized.

3.5. Optimising the composition of the mulch material

Ning et al. (2021) developed a cost-effective, high-strength, and environmentally friendly black biodegradable mulch film (BDM). The researchers used cellulose and humic acid as the matrix, with chitosan, nepheline, and glycerol as fillers. To optimize the BDM composition, samples were prepared at varying concentrations, and their mechanical properties were analyzed. The study evaluated the effects of adding cellulose, humic acid, chitosan, nepheline, and glycerol on the mechanical properties. It was observed that increasing cellulose content beyond 3.52% resulted in decreased mechanical properties. The optimal BDM film exhibited a tensile strength (TS) of 57.98 MPa, surpassing both the compared mulch films and the target TS value according to the EN 17033 standard. Although biodegradable mulch films typically have high water vapor permeability (WVP), the developed BDM film had the second lowest WVP value after the sodium alginate mulch film. According to the authors, the intermolecular forces within the BDM film structure contribute to its reduced WVP. The study determined the optimal BDM composition to be 3.5% cellulose, 1.5% humic acid, 2% chitosan, 0.75% nepheline, and 6% glycerol, concluding that this formulation meets the mechanical, WVP, and other performance expectations for a low-cost, eco-friendly mulch film (Ning et al., 2021).

Lyu & Han (2023) aimed to develop an environmentally friendly biodegradable alternative to traditional mulch films. They prepared various BDM films by adding different concentrations (0.5% and 1%) of a chain extender (CE) to PBAT and PLA matrices using a two-step extrusion method. For comparison, they also included petroleum-based LDPE mulch films (15 μm and 20 μm thick) and commercial biodegradable Ecovio® and Heulgro mulch films. The 15 μm LDPE mulch film exhibited the best mechanical properties (TS, EAB, YM) compared to the 20 μm LDPE film. Pure PBAT film demonstrated lower TS and YM but higher EAB than commercial BDM films, indicating high flexibility. In contrast, pure PLA film had the highest TS and YM but the lowest EAB, making it hard and brittle. The optimal formulation, PBAT80/PLA20/CE1, exhibited a YM of 149.51 MPa, meeting the EN 17033 standard with high TS (21.12 MPa) and EAB values. Additionally, the optimal BDM had a water vapor permeability of 0.83 g mm/m^2·day·kPa and a water contact angle of 93.77 degrees, indicating excellent water barrier properties. The study suggests that with further processing, PBAT80/PLA20/CE1 film could serve as a preferred environmental mulch material (Lyu & Han, 2023).

These studies indicate that optimizing the composition and ratios of matrix and filler materials is crucial for enhancing biodegradable mulch films' mechanical, water barrier, and other properties. These findings contribute significantly to developing high-performance, environmentally friendly biodegradable mulch films.

3.6. Production Methods

In the studies reported in Table 5, casting and extrusion were found to be more preferred methods for BDM film production. The casting method is chosen for its ability to provide a uniform and homogeneous film surface, uniform thickness and structure, flexibility in the use of materials and thickness angles, relatively simple and economical characteristics. The reasons for the widespread use of the extrusion method are that it allows the film to be produced quickly and efficiently at the desired thickness and uniformity.

Chong et al. (2019), Mariniello et al. (2007), Chiellini et al. (2001a, 2001b) and Merino & Alvarez (2020) produced mulch films using the casting method in their studies. Finkenstadt & Tisserat (2010), Lyu & Han (2023), Touchaleaume et al. (2016) and Briassoulis & Giannoulis (2018) produced mulch film by extrusion method. Exclusively Flores et al. (2009) used the hot pressing method in their study. The casting method offers more flexibility in terms of material composition and film thickness, making it suitable for research and development purposes (Rocha et al., 2018) . On the other hand, the extrusion method is more efficient and suitable for large scale production, allowing faster and more uniform film production. The choice between casting and extrusion may depend on the specific requirements of the biodegradable mulch film, such as desired properties, scale of production and availability of equipment (Xiong et al., 2024).

The spray method used in agricultural applications provides significant advantages in terms of the production and application of mulch films. Immirzi et al. (2009) found that the biodegradable mulch film applied by spray method provided similar crop yields to LDPE mulch performance and also had the advantage of biodegradability. The biodegradable mulch they developed maintained its soil-covering effect for 6 months and prevented weed growth. Gu et al. (2021) also reported that the spray mulch film that utilized kitchen waste maintained its soil covering, heat, and moisture preservation effect 6 months after application. In the study of Ghani et al. (2023), a biodegradable mulch film (BDM) containing 0.75 wt% yam Nagara starch was produced by spray method, and the mechanical properties of the produced BDM (tensile strength 0.374 N/mm², elongation value 0.112%) were found to be considerably lower than conventional mulch films. According to the authors, inhomogeneous mixing and high water absorption of the mulch material are the main reasons for the low mechanical properties of BDM.

The hot pressing method can be used effectively to produce biodegradable PBS-based composites. The advantages of the hot pressing method include homogeneous distribution of the components, easy processability, and low cost. However, it also has disadvantages, such as decreased mechanical properties at high fiber ratios, poor interfacial adhesion, and increased water vapor permeability (Ayu et al., 2020). Flores et al. (2009) and Ayu et al. (2020) investigated the change in mechanical properties of hot-pressed PBS composites. Accordingly, the increase in starch or cellulose content caused a decrease in tensile strength, while the EAB value improved at certain rates. On the other hand, it was found that adding furfural, a plasticizer component, significantly increased the flexibility of the composites (Flores et al., 2009).
Recent studies (Borrowman et al., 2020) show that spray-applied mulch films are a more environmentally friendly alternative to conventional plastic mulches as they require less labor, bind better to the soil surface, and are biodegradable.

Ultimately, one of these methods can be used successfully in the development of biodegradable mulch films, and the choice of the appropriate production technique should be based on the specific needs and constraints of the research or application.

4. CONCLUSION

The production, use, and post-use processes of petroleum-based plastic materials increase carbon emissions, which is one of the factors of the climate crisis. The use and production of plastics should be avoided since plastics, which persist in nature for a long time, decompose into small pieces and are found everywhere in rivers, oceans, and soil; in short, microplastics threaten the life of living things and are toxic. One of the areas to be worked on in line with the UN's SDGs is to reduce the use of plastics in agriculture and to use biodegradable, eco-friendly materials instead. Although mulches that contribute to productivity and quality in agricultural production are widespread, mulch materials made from petroleum-derived raw materials are generally used. Eco-friendly, biodegradable mulch film materials must be able to meet the required physical, chemical, and mechanical properties to provide the desired benefit and performance. Much research has been conducted to develop biodegradable mulch materials with the best properties to replace plastic mulch materials. In this review, we provide a comprehensive study of the literature on biodegradable mulch films to obtain the desired mechanical, water barrier, and other properties required for successful agricultural applications, summarise valuable information and analyze the key factors affecting the properties and performance of the films and highlight important points. Thus, it will be a guide for academic and sectoral studies to be carried out in this context.

According to the evaluation of these studies, the following results were obtained;

- **Mechanical Properties:** Mechanical properties of BDM films such as TS, YM, and EAB are critical for their performance during transport, installation, and use in agricultural applications. Many authors have applied different materials and/or methods to overcome the mechanical problems of biodegradable mulch films. Studies have shown that the matrix composition (biopolymers, synthetic polymers) and the type and amount of fillers (such as natural fibers and minerals) significantly influence mechanical properties. Optimizing matrix-filler compatibility and adding cross-linking agents can help improve these films' mechanical performance. Mechanical properties can be improved by different chemical/physical methodologies and/or by adding additives under international standards.

- **Water Vapor Permeability (WVP):** Controlling the WVP and surface hydrophobicity of biodegradable mulch films is essential for maintaining soil moisture and preventing excessive water loss, particularly in arid regions. Studies have shown that incorporating fillers obtains hydrophobic surfaces and hence can reduce WVP and, therefore, improve the water barrier properties of the films.

- **Chemical and Microstructural Analysis:** Techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), and X-Ray Diffraction (XRD) are used to characterize the chemical composition, morphology and crystallinity of biodegradable mulch films. These analyses provide valuable information on structure-property relationships that can guide the optimization of film composition and production methods, such as the intermolecular bonding, surface morphology, particle size, shape and distribution, particle-particle interphase, particle-matrix interphase, pore size, and distribution.

- **Factors Affecting the Biodegradable Mulch Properties:** The materials must meet the required mechanical and water vapor permeability properties for successful agricultural application with mulch materials. This study determined mulch film thickness, matrix-filler compatibility, type and amount of filler, optimum mulch composition, and appropriate chain developer addition and production method as the main factors to be focused on. The successful development of high-performance, cost-effective, and environmentally friendly biodegradable mulch films will contribute to more sustainable agricultural practices and reduction of environmental impact.

- **Thickness of Mulch:** Mulch film thickness affects the mechanical and water barrier properties of biopolymer films. As the thickness of biopolymer films increases, the film's resistance increases, and the mechanical and water barrier properties are expected to improve. Some studies support this. However, factors such as the type of matrix and filler used in film production, the amount of filler, matrix-filler compatibility, film composition, and production method affect the properties of the mulch film. Although the thickness affects the properties of the mulch film, it should be evaluated with other parameters to meet the most appropriate properties according to the place and conditions of use.

- **Matrix-Filler Compatibility:** In general, it has been shown that the addition of reinforcements compatible with the matrix in biocomposite films can improve the overall mechanical performance. Studies have shown that the similarity between the functional groups of the mulch matrix material and the filler, good interfacial adhesion, chemical compatibility, and the formation of an integrated structure improve the mechanical and water vapor permeability properties. In some studies, it was observed that the filler in the matrix was not distributed regularly and homogeneously and mechanical properties decreased as a result of agglomeration.

- **Type and Amount of Filler Material:** In biodegradable mulch films, the filler added to the mulch film matrix affects the both physical and mechanical properties of the film. Some studies have shown that as the weight or volume ratio of the added filler changes, the film properties also change. If there is matrix-filler compatibility, it has been found that the addition of filler up to a certain ratio improves the film properties, but if the filler is above a certain ratio, it reduces the mechanical properties of the film.

- **Use of Cross-Linking Substances:** The use of cross-linking agents in polymer matrix structures for mulch production can enhance the mechanical properties of the film by forming chemical bonds. However, the impact of cross-linking agents should be assessed in conjunction with other factors, such as material properties and composition.

- **Optimising the Composition of the Mulch Material:** Researchers have conducted studies to develop biodegradable mulch films with optimal compositions using various raw material sources. These studies evaluated the effects of altering the weight ratios of the matrix, fillers, and chain extenders on mechanical properties and water vapor permeability. The results demonstrated that the composition of biodegradable mulch films significantly influences these properties. By determining the optimal composition, it is possible to produce mulch films with superior characteristics suitable for agricultural applications within a sustainability framework.

- **Production Method:** While various methods exist, such as spraying and hot pressing, casting and extrusion are the most commonly employed techniques for producing biodegradable mulch films. Each of these methods offers distinct advantages. The casting method provides greater flexibility regarding material composition and film thickness, allowing precise control over the film's properties. Conversely, the extrusion method is more efficient and better suited for large-scale production, making it ideal for commercial applications.

- Information on the mechanical properties of biodegradable mulch films developed in the investigations showed that they fully or partially met the specifications of the EN 17033 EU standard, which includes criteria for bio-based plastics, in some studies. This indicates the need for further material studies in this area to improve mechanical and water resistance properties.

The stark disparity in production volumes highlights the critical importance of advancing research and development in the field of bioplastics. While petroleum-based plastics dominate the market with substantially higher production figures, the potential for bioplastics to mitigate environmental impacts underscores the necessity of continued innovation and investment in this area. This significant gap serves as a reminder of the urgent need to accelerate progress and adopt sustainable alternatives, emphasizing the pivotal role of ongoing studies and technological advancements in achieving a more eco-friendly future.

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EDUCATION STATUS

Start-End Date	Education Degree	Name of the Institution Received Training	Faculty	Section
10.2002-06.2005	High School	Republic High School		Science/Numerical
10.2005-06.2010	License	Dokuz Eylul University	Faculty of Engineering	Metallurgical and Materials Engineering
10.2020-01.2023	Associate Degree	Anadolu University	Faculty of Agriculture	Agricultural Machinery and Technologies

WORK EXPERIENCE

Start - End Date	Position	Company Name	Company Sector
02.07.2011-19.03.2012	Purchasing Engineer	Altunorak Mold Machine	Machine Manufacturing

23.03.2012-30.03.2013	Purchasing Engineer	Koluman Automotive	Automotive
01.04.2013-14.04.2015	Supplier Development and Lean Production Coordinator	Koluman Automotive	Automotive
20.04.2015-30.12.2015	Quality and Continuous Improvement Engineer	TEMSA	Automotive
01.01.2016-30.06.2018	Innovation and Corporate Entrepreneurship Team Leader	TEMSA	Automotive
19.10.2018-13.02.2022	Digital Agriculture Transformation and Innovation Associate Manager	Tekfen Agriculture	Agriculture
14.02.2022-24.06.2022	Technological Applications and Innovation Associate Manager	Toros Agriculture	Chemistry
18.07.2022-Continues	Agricultural Technologies Project Manager	TAT Food	Food

KEY ACHIEVEMENTS and AWARDS

- She led in the acceptance of projects from national and international funding organizations and take responsible in projects.

- Turkey Technology Development Foundation (TTGV)'s 2020 Refik Üreyen R&D and Innovation Organizations Leadership Award.

- InovaLIG 2020 semi-finalist ranking

- Innovalig 2017 Innovation cycle category champion (among 971 companies)

- Innovalig 2016 Innovation Resources Category Champion (among 761 companies)

- +35 honors and awards in Innovation, Digitalization and Digital Farming Technologies

Publication in the Last Three Years, Patent: None.