



YEDITEPE UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEVELOPMENT AND CHARACTERIZATION OF POLYMERS WITH
BIOADDITIVES

A Thesis Submitted
by
Nida Çelebi

In Partial Fulfillment
of the Requirements for the Degree of
Master of Science
in
Materials and Nanotechnology Engineering

Supervisor
Assist. Prof. Dr. Nebahat Aral Yılmaz

Istanbul - 2025

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by
Nida Çelebi

Approved by:

Assist. Prof. Dr. Nebahat Aral Yılmaz
(Yeditepe University)
(Thesis Supervisor)

.....

Prof. Dr. Taner Akbay
(Yeditepe University)

.....

Prof. Dr. Cevza Candan
(Istanbul Technical University)

.....

Assist. Prof. Dr. Özge Taştan Ülkü
(Yeditepe University)
(Co-Supervisor)

.....

DATE OF APPROVAL:/....../20...

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ABSTRACT

DEVELOPMENT AND CHARACTERIZATION OF POLYMERS WITH BIOADDITIVES

In this thesis, pomegranate peel powder—a natural bioadditive derived from agricultural waste—was evaluated for its potential use in the development of sustainable materials for both textile and packaging applications. The pomegranate peel powder was first characterized using various analytical techniques to determine its chemical and structural properties. It was then incorporated into waterborne polyurethane (WPU) and poly(ϵ -caprolactone) (PCL) matrices to fabricate textile coatings and biodegradable packaging films, respectively.

In textile applications, the addition of pomegranate peel powder resulted in noticeable and naturally warm color changes on the coated fabric surface. SEM images showed textural differences with additive incorporation, suggesting possible morphological effects, while mechanical tests indicated limited changes in mechanical integrity. Furthermore, the coatings exhibited increasing levels of antibacterial activity with higher additive content, especially against *Staphylococcus aureus* (ATCC 6538).

In packaging applications, the incorporation of the additive led to modifications in surface properties. A decrease in water contact angle indicated an increase in hydrophilicity, which, although potentially limiting for moisture barrier functionality, may offer advantages for active packaging systems where moisture exchange is desired. Additionally, increased color saturation and semi-opacity in the films indicated potential as visual barriers for protecting light-sensitive products. Thermal analyses showed slight reductions in thermal stability due to the organic nature of the additive, though these changes remained within acceptable application limits.

In conclusion, this study demonstrated that pomegranate peel powder—a low-cost and biodegradable waste-derived material—can be used as a functional, eco-friendly, and antibacterial bioadditive in both textile and packaging systems.

ÖZET

BİYOKATKILARLA HAZIRLANAN POLİMERLERİN GELİŞTİRİLMESİ VE KARAKTERİZASYONU

Bu tez çalışmasında, tarımsal atık niteliğindeki nar kabuklarından elde edilen toz formundaki doğal biyokatkının, hem tekstil hem de ambalaj uygulamalarında sürdürülebilir malzeme geliştirme amacıyla değerlendirilmesi hedeflenmiştir. Çalışma kapsamında, nar kabuğu tozunun kimyasal ve yapısal özellikleri çeşitli karakterizasyon teknikleriyle analiz edilmiş; ardından bu katkı maddesi, su bazlı poliüretan (WPU) ve poli(ε-kaprolakton) (PCL) matrislerine belirli oranlarda ilave edilerek, sırasıyla tekstil kaplamaları ve biyobozunur ambalaj filmleri üretilmiştir.

Tekstil uygulamaları özelinde, nar kabuğu tozunun kumaş yüzeyine kaplama yoluyla uygulanması sonucu renk tonlarında doğal ve sıcak bir değişim gözlemlenmiştir. Katkı ilavesiyle birlikte elde edilen SEM görüntüleri yüzey dokusunda farklılıklar göstermiş; bu durum morfolojik etkilerin olabileceğini düşündürmektedir. Mekanik testler ise malzeme bütünlüğünde sınırlı düzeyde değişim olduğunu ortaya koymuştur. Ayrıca, bu kaplamalar, katkı oranına bağlı olarak artan düzeyde antibakteriyel etki göstermiş; özellikle *Staphylococcus aureus* (ATCC 6538) bakterisine karşı anlamlı inhibisyon sağlanmıştır.

Ambalaj uygulamalarında ise katkı ilavesiyle birlikte yüzey özelliklerinde değişimler gözlemlenmiş; su teması açısından meydana gelen azalma ile yüzeyin daha hidrofilik hale geldiği belirlenmiştir. Bu durum, her ne kadar bazı ürünlerde nem bariyeri performansını sınırlandırabilecek olsa da, belirli “aktif ambalaj” konseptleri için işlevsel olabilir. Ayrıca film rengindeki doygunluk artışı ve yarı-opaklık, özellikle ışığa duyarlı ürünlerin korunması açısından görsel bariyer niteliği taşıyabilecek potansiyel çözümler sunmuştur. Termal analizler, nar kabuğu tozunun kompozitlerin ısı kararlılığı üzerinde sınırlı etkiler yarattığını, ancak uygulama performansını engellemeyecek düzeyde olduğunu ortaya koymuştur.

Genel olarak, bu çalışma ile nar kabuğu tozu gibi düşük maliyetli ve biyobozunur bir atık kaynağının hem tekstil hem de ambalaj sektöründe kullanılacak fonksiyonel, çevre dostu ve antibakteriyel katkı maddesi olarak değerlendirilmesi mümkün hale gelmiştir.

ACKNOWLEDGEMENTS

First of all, I would like to express my deepest gratitude to my advisor Assist. Prof. Dr. Nebahat Aral for her guidance, support, and precious feedback throughout my project.

I would like to thank my Co-Adviser Assist. Prof. Dr. Özge Taştan for her indispensable assistance in experimental processes and precious feedback throughout my project.

Furthermore, I would like to express my heartfelt gratitude to my beloved Batuhan Savaş, who has been my greatest source of strength and inspiration throughout this journey, always by my side with his patience, love, and unwavering support.

Additionally, I would like to express my sincere thanks to Sağanak Yağmur Arslan and Ömer Faruk Uslu for their valuable support and friendship.

I would also like to extend my gratitude to the TÜBİTAK 124N021 project, "Food Waste in the Development of Biodegradable Packaging Materials (AgriBioPack)", funded under the PRIMA (Partnership for Research and Innovation in the Mediterranean Area) program supported by the European Union, for their contribution to the research process.

Finally, I would like to thank my family, friends for their unconditional love, patience, and encouragement throughout my academic journey.

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LIST OF ABBREVIATIONS

PoP	Pomegranate Peel Powder
PCL	Poly(ϵ -caprolactone)
WPU	Waterborne Polyurethane
FT-IR	Fourier Transform Infrared Spectroscopy
SEM	Scanning Electron Microscopy
TGA	Thermogravimetric Analysis
DTGA	Derivative Thermogravimetric Analysis
UV	Ultraviolet
PU	Polyurethane
VOC	Volatile Organic Compounds
WPU-C	Waterborne Polyurethane Coated Fabric (Control)
PoPE	Pomegranate Peel Extract
ABTS	2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)
WBC	Water Binding Capacity
CFU	Colony-Forming Unit
TSB	Tryptic Soy Broth
ASTM	American Society for Testing and Materials
ISO	International Organization for Standardization

1. INTRODUCTION

In recent years, the emphasis on sustainable and environmentally friendly materials has gained significant momentum across industries such as packaging, polymers, composites, and textiles. Driven by escalating concerns over plastic pollution, fossil fuel dependency, and environmental degradation, research efforts have increasingly focused on developing bio-based materials derived from renewable resources. In this context, bio-based polymers, along with natural additives and fibers, are being explored not only as alternatives to synthetic counterparts but also as promising candidates for food packaging and textile applications. Furthermore, the valorization of plant-based wastes—such as those from fruits and vegetables processed in the food industry—offers a dual benefit: mitigating food waste and providing a sustainable source for environmentally benign materials.

In recent years, the integration of bio-additives with polymers has significantly augmented the performance and functionality of these materials, rendering them suitable for an extensive array of applications in both packaging and textiles. Particularly in the food and textile sectors, bio-additives—sourced from natural origins—play a pivotal role in enhancing the mechanical, barrier, and antimicrobial characteristics of polymer coatings. These improvements are critical for addressing the stringent requirements of food packaging, including preservation, protection, and extension of shelf life. Furthermore, its application in textile coatings not only contributes to the production of environmentally friendly materials but also offers a viable measure against microplastic pollution and plays a crucial role in managing agricultural waste.

This thesis aims to develop bio-content-based materials as alternatives in two major sectors contributing to microplastic pollution—packaging and textiles. The study also intends to support the management of plant-based waste. By incorporating synthesis methods, coating techniques, and characterization procedures, environmentally friendly materials have been developed for diverse industrial applications.

The significance of this study is multifaceted: by employing biodegradable polymers in conjunction with plant-based wastes, an alternative material has been developed for the packaging sector, while an environmentally friendly material suitable for textiles has been engineered through the application of plant waste and polymer mixtures onto fabric. These

sectors are among the primary contributors to plastic pollution, and the proper utilization of plant waste has further endowed the developed materials with antibacterial properties.

In summary, the thesis targets the urgent need for novel approaches in food packaging and textile coatings by examining the advantages of bio-based polymers and natural bio-additives. By bridging the divide between environmental sustainability and practical functionality, it aims to encourage the widespread adoption of bio-based materials in both sectors, thereby fostering a greener and more sustainable future.

1.1. POLYMERS

Polymers are formed through the polymerization reaction of small molecules known as monomers, which under appropriate conditions bond together via covalent bonds to create long chains. These chains are predominantly composed of hydrogen, carbon, and hydrocarbon segments [1]. The chemical structure of the monomer constitutes the primary structure of the polymer, and therefore, the properties of the polymer are inherently linked to the structure of its monomeric units.

Understanding the nature of the monomer is crucial for elucidating both the structure and the properties of the resulting polymer. The physical and mechanical characteristics of the monomer influence the molecular weight and the overall dimensions of the polymer chains, whereas the monomer's chemical makeup significantly affects the chemical and electrical properties of the polymer [2,3].

Polymers can be broadly classified into two primary types: natural and synthetic. Natural polymers, such as cellulose, proteins, and natural rubber, are found in nature and have been utilized for centuries, while synthetic polymers like polyethylene, polystyrene, and nylon are man-made, engineered to deliver specific performance characteristics.

Table 1. 1. Characteristics of biopolymers vs. synthetic polymers [4].

Characteristic of Materials	Biopolymers	Synthetic Polymers
Main source	Agro resources	Petroleum and gas
Biodegradability/ environmentally friendly	Yes	No/slow
Structure	Well defined	Stochastic
Chemical backbone structure	Carbon, oxygen, nitrogen	Mostly carbon
Dispersity	Unity	>1
Physicochemical resistance	Low	High
Toxicity	Low	High
Thermal stability	Low	High
Mechanical properties	Low	High
Sustainability	High	Low
Availability	High	Decreasing
Cost	High (depend on the type)	Low

Beyond their origin, polymers are also classified based on their characteristic properties. One common categorization distinguishes between bio-based and fossil-based polymers. It is important to note that both bio-based polymers—derived from renewable biological resources, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs)—and fossil-based polymers, typically originating from petroleum resources such as polyethylene (PE) and polycaprolactone (PCL), both of these polymer types can be either biodegradable or non-biodegradable, depending on their chemical structure (Figure 1.1). This dual possibility underscores the complexity of polymer design, where the environmental impact is determined not solely by the raw material source but also by the polymer's degradation behavior.

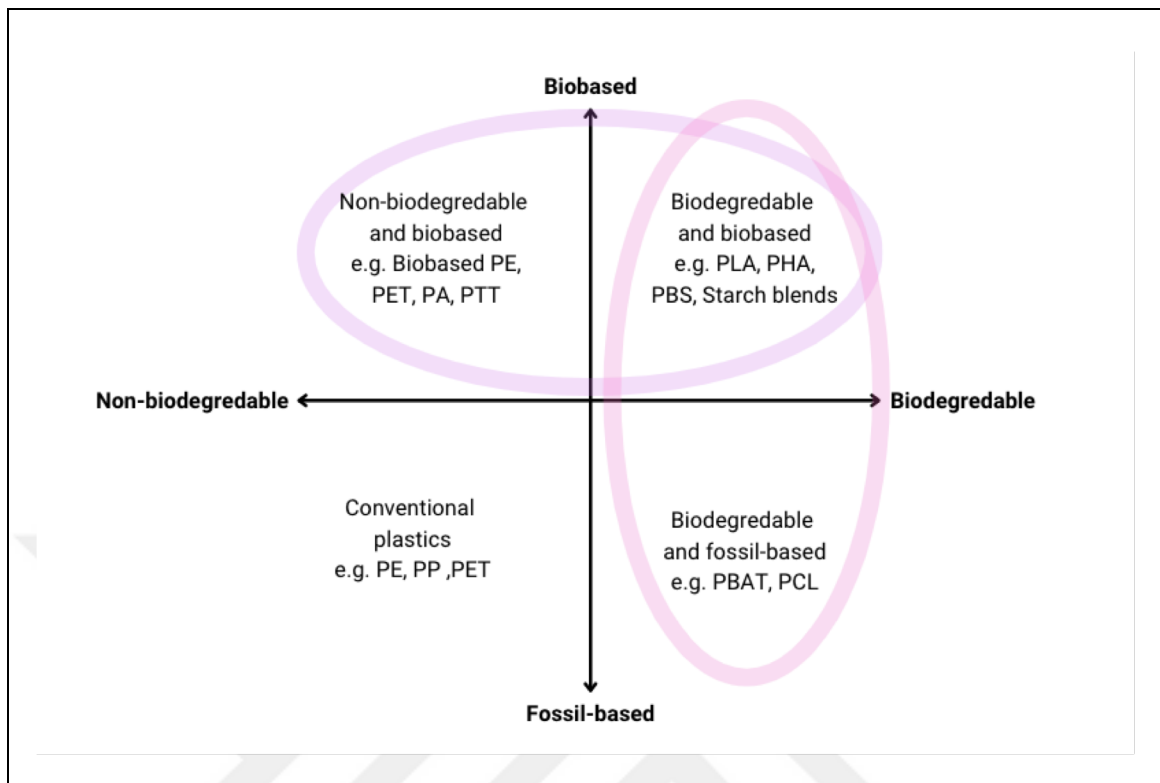


Figure 1. 1. Polymer classifications according to characteristics [5].

The utility of polymers spans a wide array of applications. They serve as integral components in packaging materials, automotive parts, electronics, medical devices, and textiles. Their unique combination of lightweight properties, chemical resistance, and ease of processing renders them indispensable across multiple sectors.

In recent years, the drive toward more sustainable materials has accelerated across multiple sectors, driven by growing concerns over the long-term environmental persistence of conventional plastics. While traditional polymers—most of which are synthesized from non-renewable fossil fuels—can take centuries or longer to degrade and contribute significantly to greenhouse gas emissions and pollution, the adoption of both biobased and advanced synthetic alternatives offers a more balanced approach. Biobased and biodegradable polymers, derived from renewable resources, are increasingly championed for their ability to diminish the ecological footprint of plastic products [6]. At the same time, high-performance synthetic polyurethanes—particularly waterborne formulations—play a crucial role in applications requiring exceptional durability, flexibility, and barrier properties. For instance, the European Green Deal actively supports the development and

commercialization of both biobased polymers and low-VOC synthetic systems to meet environmental targets. By combining renewable-resource polymers with engineered synthetics, industry can achieve the dual goals of reducing reliance on fossil feedstocks and maintaining the rigorous performance standards demanded by modern applications.

Non-biodegradable synthetic polymers, widely used in modern industrial applications, deliver exceptional mechanical and chemical performance but also generate persistent plastic pollution that undermines ecosystem health and human welfare. To reconcile these materials' functional advantages with environmental imperatives, it is essential to both advance renewable-content alternatives and retrofit synthetic polymers for greener end-of-life scenarios. Embracing bio-based, biodegradable polymers not only curbs long-term waste accumulation but also fosters closed-loop material systems. Furthermore, the addition of natural bioadditives can decrease overall polymer consumption and raw material costs, thereby reducing dependence on fully synthetic resins. This strategy both diminishes the ecological footprint of polymer products and ensures compliance with stringent sustainability standards. The shift toward renewable-content materials thus represents a critical nexus of technological innovation and environmental stewardship, highlighting the pivotal role of cutting-edge polymer research in building a more sustainable future.

1.1.1. Facts and Numbers About Biobased and Fossil-Based Polymers

Plastics have become an integral component of modern life due to their exceptional durability, stability, and ease of fabrication. In 2022, global plastic production soared to approximately 400 million tons, representing a 39% increase from the 288 million tons produced in 2012 [22].

Packaging alone accounts for nearly 40% of this production, while textiles and consumer goods comprise about 11% and 12%, respectively. However, it is important to note that around 99% of these plastics are derived from non-renewable, petroleum-based sources [23]. Common synthetic polymers—including polyester, polypropylene, nylon, polyethylene, polytetrafluoroethylene, and epoxy—originate from petroleum hydrocarbons, favored for their versatility, flexibility, and chemical inertness.

Nonetheless, the production and processing of these materials are highly energy-intensive, leading to significant greenhouse gas emissions. Moreover, the combustion of conventional

plastics releases a host of toxic substances, such as carbon monoxide, chlorine, nitrides, hydrochloric acid, furans, dioxins, styrene, amines, benzene, and 1,3-butadiene, among other hazardous compounds, thereby posing serious risks to environmental and public health [24].

In light of these challenges, there has been a growing emphasis on the development of biopolymers as viable alternatives to traditional plastics. Bioplastics, produced from renewable resources like plant biomass, offer considerable promise in mitigating environmental impacts. Not only do these materials require approximately 65% less energy to manufacture than their petroleum-derived counterparts, but they also emit 30–80% fewer greenhouse gases during production.

Biodegradable polymers sourced from renewable materials break down naturally while exhibiting physical and chemical properties comparable to conventional plastics such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET).

According to recent data, the global production of biopolymers reached 2.02 million tons in 2023. Geographically, Asia is the dominant producer, accounting for 50.9% of total output, followed by North America with 20.1%, Europe with 16.9%, and South America with 11.7% (refer to Figure 1.2) [25]. This paradigm shift toward bioplastics not only aims to alleviate the environmental burdens associated with plastic production and waste but also represents a strategic move towards a more sustainable and resource-efficient future.

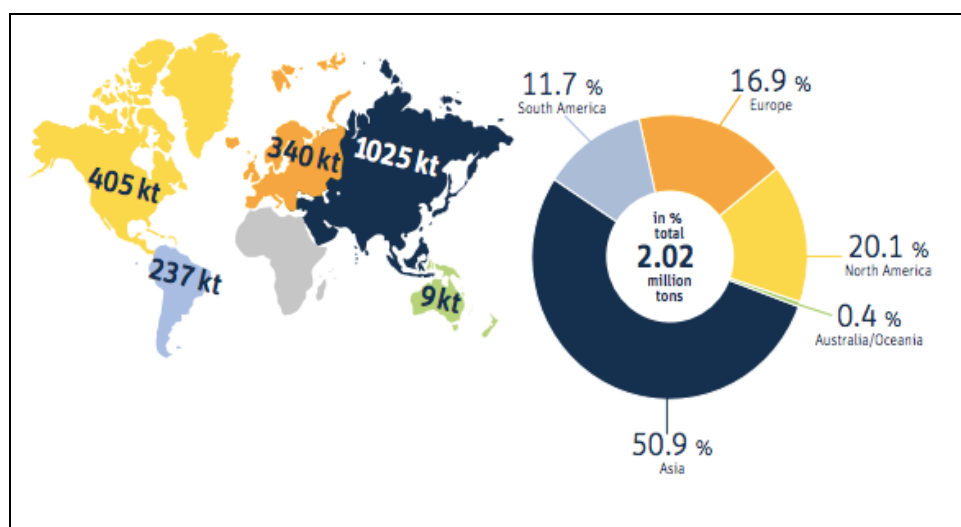


Figure 1. 2. Biopolymer production capacities by region [25].

1.1.2. Fossil-based Polymers

Fossil-based polymers, derived from the petrochemical industry, are extensively utilized in conventional plastic production. These polymers are synthesized from raw materials extracted from fossil fuels and offer a wide range of molecular weights, flexibility, and chemical resistance [16]. Notably, polymers such as polyethylene, polypropylene, polystyrene, polyurethane and polyvinyl chloride are favored in industrial applications due to their optimized properties achieved through advanced manufacturing techniques.

These polymers are employed in a multitude of sectors, including packaging, textile, automotive, construction, electronics, and medical devices. In the packaging industry, they provide cost efficiency and durability, whereas in the textile sector, they are widely applied as coatings, enhancing fabric durability, abrasion resistance, and overall performance [17]. Their versatility underscores the critical role of fossil-based polymers in meeting modern industrial demands.

However, the environmental implications of fossil-based polymers are significant. Their slow degradation rates lead to persistent environmental pollution and contribute to the accumulation of microplastics, thereby exacerbating waste management challenges. Additionally, the reliance on fossil fuels not only results in lower recycling rates but also intensifies greenhouse gas emissions, further impacting climate change.

In conclusion, while fossil-based polymers deliver considerable technical and economic advantages, their environmental drawbacks necessitate urgent attention. Advancing the development of eco-friendly alternative materials and enhancing recycling processes for these polymers are essential steps toward achieving a more sustainable future.

Biodegradable and Fossil-Based Polymers

Biodegradable polymers that originate from fossil resources represent a niche category that integrates the favorable mechanical and chemical attributes of conventional plastics with the environmental advantages inherent in biodegradability. Although these polymers are produced from finite petroleum-based feedstocks, they are specifically engineered to decompose more readily under certain environmental conditions, thereby curbing long-term pollution and reducing the build-up of waste.

These fossil-derived biodegradable polymers are produced via petrochemical methods yet are designed with molecular structures that promote degradation when exposed to predefined conditions. For instance, polycaprolactone (PCL) is synthesized from caprolactone—a monomer obtained from crude oil. Despite its petrochemical origins, PCL is formulated to break down under composting conditions, rendering it useful in various fields such as biomedical device fabrication, controlled drug delivery systems, and packaging, where its biodegradability provides substantial added value.

Common applications of these materials include agricultural films, compostable bags, disposable food service items, and certain medical devices like sutures and implants. Their use capitalizes on the ability to deliver essential functionality during service while ensuring that the polymer does not persist in the environment post-disposal. This balance renders fossil-derived biodegradable polymers a more environmentally responsible alternative when compared to traditional, non-degradable plastics [16].

Non-Biodegradable and Fossil-Based Polymers

Non-biodegradable and fossil-based polymers are a class of materials predominantly derived from petroleum resources, exhibiting robust chemical and physical properties that have cemented their role in modern manufacturing. These polymers are characterized by their resistance to degradation under natural environmental conditions, which, while enhancing durability and longevity in service, also contributes to long-term waste accumulation and environmental pollution [14]. Their inherent stability makes them a critical component in applications where prolonged performance and structural integrity are paramount.

Polyurethanes serve as a prime example within this category. Synthesized through the reaction between diisocyanates and polyols [20], polyurethanes exhibit a unique combination of elasticity, abrasion resistance, and mechanical strength. Their molecular architecture allows for the fine-tuning of properties, ranging from soft, flexible foams to rigid, high-strength plastics. This versatility, along with their ability to maintain performance over extended periods, underscores their importance in various industrial applications.

In the textile sector [21], polyurethanes are extensively utilized as coatings to enhance fabric performance. When applied as a finishing treatment, polyurethane coatings provide improved resistance to wear, tear, and environmental factors while also imparting flexibility and durability to textile surfaces. This application not only extends the service life of textiles

but also contributes to improved functionality and aesthetics, making polyurethanes an indispensable material in the development of high-performance textile products.

1.1.3. Biobased Polymers

One of the most important features of biopolymers is their contribution to environmental sustainability. The production, use and waste management of traditional plastics cause serious environmental problems. However, biopolymers are derived from renewable resources and are recyclable. These materials, under favour of their biodegradable and compostable properties, do not harm the environment by easily decomposing in nature. Under favour of these properties, biopolymers create solutions to waste management problems and offer an environmentally friendly alternative.

Another important aspect of biopolymers is that they are derived from renewable resources. Fossil fuels, which are the raw material of traditional plastics, are a limited resource and have great environmental impacts [15]. However, the sources of biopolymers are usually renewable sources such as plants, microorganisms or marine sources. For example, starches obtained from plants such as corn, sugar cane, potatoes can be used for the production of biopolymers. This indicates that biopolymers are an important option for a sustainable future.

Wide application areas of biopolymers also increase their importance. Biopolymers are used in many areas from the packaging industry to medical applications, from agricultural products to the textile industry. The mechanical properties and flexibility of biopolymers are suitable for a variety of applications. For example, packaging materials using biopolymers are more environmentally friendly and biodegradable than conventional plastics. This helps reduce plastic waste and reduce the risk of decomposing and damaging the environment. Likewise, biopolymers used in medical applications have biodegradable properties and dissolve in the body and decompose without leaving any traces. This provides a safer option in applications such as medical implants, suture materials and drug delivery systems [16].

The use of biopolymers is also important in the agricultural sector. Biopolymers are preferred in agricultural product packaging materials and agricultural film applications. This reduces the risk that traditional plastic use will increase agricultural waste and soil pollution.

In addition, the use of biopolymers in agricultural film applications increases soil fertility by increasing the organic matter content in soils.

The importance of biopolymers is not limited to environmental benefits. It also offers economic and social benefits. Producing from renewable sources can reduce energy consumption and carbon footprint, contribute to economic sustainability and aid the transition to a green economy. In addition, the use of biopolymers encourages the development of innovative technologies and creates green jobs.

There are also some challenges for the widespread use and applicability of biopolymers. Costs and scaling are an important factor in biopolymer production. Compared to conventional plastics, the cost of biopolymers is generally higher. Therefore, improving and scaling production processes is important. Supporting research and technological developments can reduce costs in biopolymer production and encourage its widespread use [28].

Besides, the performance optimization of biopolymers is also a challenge. Some properties of conventional plastics may not be fully achieved in biopolymers yet. Improving properties such as mechanical strength, flexibility, heat resistance allows biopolymers to enter a wider range of applications. Research and development can provide innovative solutions to improve the performance and functionality of biopolymers.

In conclusion, the importance of biopolymers stems from environmental sustainability, renewability and wide application areas. These materials have the potential to reduce environmental impacts compared to traditional plastics and are one of the keys to a sustainable future as they are derived from renewable resources. The use of biopolymers supports environmental protection efforts, improves waste management and provides economic benefits. Therefore, more investments are required in the research, development and application areas of biopolymers. Thus, the potential of biopolymers to build a more sustainable world can be fully exploited.

Biodegradable and Biobased Polymers

Biodegradable and biobased polymers hold significant promise for mitigating the environmental issues linked to conventional plastics. Although these terms are frequently used together in academic discourse, it is essential to differentiate them clearly. Biobased

polymers originate from renewable sources—namely plants, animals, or microorganisms—underscoring their potential as sustainable materials.

Biodegradable polymers, in contrast, are primarily defined by their capacity to decompose under the influence of microorganisms (e.g., bacteria, fungi, and molds) within specific timeframes and environmental settings. However, the term “biodegradable” can be ambiguous if not properly contextualized, leading to misconceptions in both research and practice [24].

The now-withdrawn ASTM D-5488-94 d standard characterizes biodegradable polymers as those capable of breaking down into carbon dioxide, methane, water, inorganic compounds, or biomass, chiefly through microbial enzymatic activity. This degradation process can be quantified via standardized tests over a defined duration, replicating typical disposal environments [30].

Moreover, certain biobased polymers can also be biodegradable. For example, polylactic acid (PLA) is synthesized from fermented plant starch—commonly sourced from corn or sugarcane—rendering it both biobased and biodegradable. Additional examples include polyhydroxyalkanoates (PHAs), polybutylene succinate (PBS), and various starch blends [31].

To date, the majority of these polymers have been employed in short-term applications, such as packaging. Nevertheless, their scope of use is rapidly expanding, driven by the advent of novel biobased monomers like succinic acid, butanediol, propane diol, and fatty acid derivatives, which open new possibilities for broader industrial applications.

Non-biodegradable and Biobased Polymers

Biobased and non-biodegradable polymers represent a significant category of materials that provide a sustainable alternative to conventional plastics derived from fossil fuels. These polymers not only help decrease reliance on finite petroleum resources but also typically result in a lower carbon footprint [32].

Non-biodegradable polymers are distinguished by their resistance to degradation in environmental conditions, maintaining their physical and chemical integrity over prolonged periods. This persistence can be advantageous for applications requiring durability and long-term stability, though it generally raises environmental concerns. Nonetheless, when these

polymers are biobased, their renewable origins help mitigate some of the associated ecological impacts.

Typically, non-biodegradable polymers are synthesized from renewable feedstocks such as sugarcane, corn, and other biomass. A prime example is bio-PE, a biobased and non-biodegradable polymer. Bio-PE is chemically identical to conventional polyethylene but is produced from bioethanol sourced from renewable materials like sugarcane. As illustrated in Figure 1.2, the production process of bio-PE highlights its sustainable production method. Although it does not undergo biodegradation, bio-PE offers the environmental advantage of reduced carbon emissions during manufacturing compared to its fossil fuel-derived counterpart, making it a preferable option for applications where material durability is critical, such as packaging, agricultural films, and plastic bottles [33].

These polymers are widely employed across various industries, including the production of textile fibers for seat covers and carpets, automotive components like seating foams, casings, cables, hoses, and covers, and notably in the packaging sector. Their renewable origin combined with their robust properties underscores their importance in advancing more sustainable material solutions.

1.2. POLYMERS FOR TEXTILE COATINGS

Textile coatings represent an important technological approach for enhancing fabric functionality and extending product lifespan. By forming a thin film on the fabric surface, these coatings offer protection against water, contaminants, and mechanical abrasion, while also enhancing aesthetic appeal and adding specialized functions. As a result, textile coating technologies play a crucial role in both industrial applications and consumer products.

A variety of polymers can be employed in fabric coatings, including polyurethanes, acrylic polymers, vinyl acetate derivatives, polyvinyl chloride and polyvinylidene chloride materials. [34] These polymers are favored for their ease of application and their ability to provide desirable mechanical, thermal, and barrier properties. Optimizing coating performance requires careful selection of the polymer matrix and the application technique, as well as the development of tailored formulations suited to specific end-use requirements.

The integration of bioadditives into textile coatings offers a promising strategy for further enhancing functionality. Natural bioadditives can impart additional properties such as antibacterial activity, UV protection, and water repellency, thus expanding the range of potential applications [35]. This approach is particularly beneficial in markets where hygiene and sustainability are paramount, as it allows fabrics to meet stringent performance standards while reducing environmental impact.

In summary, textile coatings not only improve the protective and functional qualities of fabrics but also pave the way for innovative, sustainable product development. The combined use of advanced polymer matrices and bioadditives enables the creation of textiles with superior mechanical and chemical properties, meeting the evolving demands of modern applications.

1.2.1. Materials Used in Textile Coating

Acrylic Polymers

Acrylic polymers represent a widely utilized class of materials with a broad spectrum of properties and price points. They are predominantly employed as backing coatings for upholstery—including fabrics and carpets—serving as adhesives for laminates, and functioning as lacquers for tarpaulins. Among this group, poly(methyl methacrylate) (PMMA), synthesized from the monomer methyl methacrylate (MMA), stands out as a key representative. Moreover, acrylic resin coatings are effectively used as waterproof layers on woven nylon or polyester substrates, often in conjunction with crushed foam coatings for curtain applications. In automotive settings, contemporary car seats are frequently back-coated with acrylic formulations to enhance abrasion resistance and improve fire safety [34].

Acrylic polymers offer several notable advantages when applied as coatings. They are characterized by excellent clarity and high resistance to ultraviolet radiation, which preserves the aesthetic quality of the coated surfaces over time. Their exceptional resilience against a variety of chemicals and water further contributes to their durability, while their cost-effectiveness makes them an attractive option for large-scale applications. Additionally, their compatibility with other polymers—particularly with PVC—allows for the creation of blended systems that can be tailored to meet specific performance requirements [34].

However, the use of acrylic coatings is not without its challenges. One of the primary limitations is their inherently low fire-retardant capacity, necessitating the addition of fire retardant agents to achieve adequate safety standards. Furthermore, the monomer MMA, although classified as non-carcinogenic by the IARC, is toxic and can persist in the polymer matrix as a residual component or be released through the thermal degradation of PMMA. This aspect underscores the need for careful formulation and processing to mitigate potential health and environmental risks [34].

Vinyl Acetate Derivatives

Polyvinyl acetate (PVAc) is synthesized through the polymerization of vinyl acetate, typically via suspension or emulsion polymerization methods. As a vinyl ester, PVAc is completely amorphous and is most commonly utilized in the form of emulsions. Moreover, it serves as a precursor for the production of polyvinyl alcohol and poly(vinyl acetal). Within this polymer family, one of the most prominent materials used for textile coating applications is the EVA polymer, a copolymer of polyethylene and vinyl acetate. EVA is extensively employed as a backing material for carpets and upholstery, as well as in the coating of wall coverings [34].

PVAc offers a number of notable advantages when used as a coating material. It exhibits excellent adhesion properties, ensuring strong bonding with a wide variety of polymer substrates, and provides very effective binding characteristics. Additionally, PVAc remains flexible at low temperatures, is economically viable, and can be easily heat-welded. Its stability under light exposure further contributes to its utility in coating applications. However, there are also certain limitations associated with PVAc. The polymer is highly sensitive to moisture, displaying poor resistance to washing and readily dissolving in common solvents. Over time, PVAc-coated materials may also undergo some degree of discoloration, which can affect their long-term aesthetic and functional performance [34].

Polyvinyl Chloride

Polyvinyl chloride (PVC) is produced through the polymerization of vinyl chloride monomers and stands as one of the most extensively utilized commodity polymers. It is a white, water-insoluble thermoplastic resin that is predominantly employed in applications such as coatings, insulation, and piping. At 25 °C, PVC exhibits a density of approximately

1.38 g/cm³ and possesses a primarily amorphous structure, with a crystallinity level of around 10% [34].

When used as a coating material, PVC offers several distinct advantages. It is recognized for its versatility and cost-effectiveness, which make it a favorable option in various industrial applications. Additionally, PVC displays excellent resistance to oil, solvents, and abrasion, while also offering beneficial characteristics in terms of heat and radio frequency weldability. Its capacity to be compounded rapidly with a wide range of additives, such as plasticizers, further enhances its utility. Furthermore, PVC inherently possesses good fire-retardant properties that can be improved even further through formulation adjustments. However, there are notable disadvantages associated with PVC coatings. The material is susceptible to cracking under cold conditions, exhibits only moderate heat resistance, and its durability is compromised by low aging resistance. Moreover, the uncontrolled use of PVC significantly contributes to the proliferation of microplastic pollution in the environment [34].

Polyurethane (PU)

Polyurethanes (PU) are synthesized through a polyaddition reaction between isocyanates and polyols, with variations in the R and R' groups allowing for a wide range of urethane structures. Most PU materials exhibit a segmented block copolymer architecture composed of alternating soft segments from polyols and hard segments formed via reactions involving diols, diamines, or diisocyanates. This two-phase structure creates physical crosslinks as the dispersed hard segments reinforce the soft matrix, resulting in elastomeric behavior. The low glass transition temperature (T_g) of the soft segments ensures flexibility at ambient conditions, while the reversible thermoplastic nature of these materials facilitates thermoforming and solution processing. These systems are commonly referred to as thermoplastic polyurethanes (TPU) [34].

PU coatings are highly valued for their excellent resistance to abrasion and solvent attack, as well as for their flexibility and impact resistance. They are typically prepared using conventional solution-based techniques and exhibit strong adhesion to a variety of substrates. PU coatings can be formulated as one-component systems—either as reactive prepolymers with terminal isocyanate groups that crosslink upon exposure to ambient moisture or as completely reacted high molecular weight solutions—or as two-component systems where a polyisocyanate is mixed with a polyhydroxy compound prior to application.

For environmentally conscious applications, aqueous dispersions of PU, which incorporate emulsifiers to stabilize PU-urea elastomer networks in water, are also utilized [34].

These coatings are particularly favored in applications demanding superior impact and abrasion resistance, such as flooring in public buildings and various outdoor and marine environments, due to their excellent weatherability. PU coatings are also extensively used in the production of tents, upholstery, waterproof protective clothing, and consumer products like luggage, footwear, gloves, and waterproof mattress covers. Moreover, they serve as a base for imitation leather and suede produced from coagulated PU, demonstrating the material's versatility [34].

Despite their many advantages, PU coatings have notable drawbacks. While the polyols used are generally considered non-toxic, isocyanates are highly hazardous. Residual isocyanate levels, even as low as 0.02 parts per million, can impart significant toxicity to the final product, potentially causing skin irritation, redness, blistering, and, with prolonged exposure, respiratory issues. Additionally, in the event of a fire, even flame-retardant grades of PU can release toxic fumes such as carbon monoxide and cyanic acid, underscoring the need for careful formulation and handling in PU-based applications [34].

Waterborne Polyurethane

Waterborne polyurethane (WPU) represents a modern and sustainable solution in the field of polymer technology. Developed as a greener alternative to conventional solvent-based systems, WPU harnesses water as the primary medium for dispersion, significantly reducing environmental and health concerns associated with volatile organic compounds. This innovative approach has led to the creation of materials that combine high performance with environmental responsibility, making WPU a subject of considerable interest across various industries [34].

The versatility of waterborne polyurethane is reflected in its ability to form robust, uniform coatings while accommodating a range of additives to tailor its properties for specific applications. Whether used as a protective layer, adhesive, or structural component, WPU exhibits a balanced combination of mechanical resilience, thermal stability, and processability. Its adaptability makes it particularly well-suited for applications in automotive, construction, packaging, and textile coatings, where the demand for durable, eco-friendly solutions continues to grow.

Properties of Waterborne Polyurethane

Waterborne polyurethane (WPU) is an eco-friendly polymer system synthesized via the polyaddition reaction between diisocyanates and polyols, with hydrophilic chain extenders incorporated to achieve water dispersibility. In other words, the type of polyurethane that uses water as a solvent is called Waterborne Polyurethane [36]. This process eliminates the need for organic solvents, thereby reducing volatile organic compound (VOC) emissions and promoting a more sustainable manufacturing process. The resulting polymer exhibits a segmented microstructure, comprising alternating soft and hard domains. The soft segments are characterized by a low glass transition temperature (T_g), which imparts excellent flexibility and enhances film-forming capabilities under ambient conditions. In contrast, the hard segments contribute to the material's overall mechanical strength, chemical resistance, and thermal stability, ensuring reliable performance across diverse applications [37,38].

WPU has properties such as flexibility with low temperatures, low emission of volatile organic compounds, stable pH, resistance to weathering [39]. For this reason, it is one of the polymer types that are widely used in the field of textiles with the coating method.

Beyond its microstructural attributes, the thermal behavior of WPU can be fine-tuned by selecting appropriate polyols, chain extenders, and diisocyanates. Although waterborne polyurethane does not exhibit a sharp melting point due to its amorphous or semi-crystalline nature, differential scanning calorimetry (DSC) typically reveals a broad thermal transition associated with the soft segments. This transition emphasizes the polymer's ability to maintain elasticity over a wide temperature range, which is critical for applications demanding sustained mechanical integrity. Moreover, WPU demonstrates robust adhesion, high tensile strength, and resistance to abrasion and chemical attack, rendering it an ideal candidate for a variety of industrial applications.

Water-borne polyurethanes exhibit remarkable film-forming capabilities, elevated viscosity, resilience at low temperatures, and cost-effectiveness [40]. In response to growing environmental concerns, these water-based systems have increasingly replaced their solvent-based counterparts in applications such as paints, printing inks, and adhesives [41]. Traditional batch synthesis methods, although commonly employed, are time- and energy-intensive, typically resulting in formulations with low solid content, high viscosity, and inconsistent performance. In contrast, continuous production processes—which utilize water as the primary solvent or incorporate only minimal amounts of organic solvents—offer a

more eco-friendly alternative. This approach enables the precise control of viscosity and hydrophilicity while supporting large-scale manufacturing and ensuring enhanced product stability.

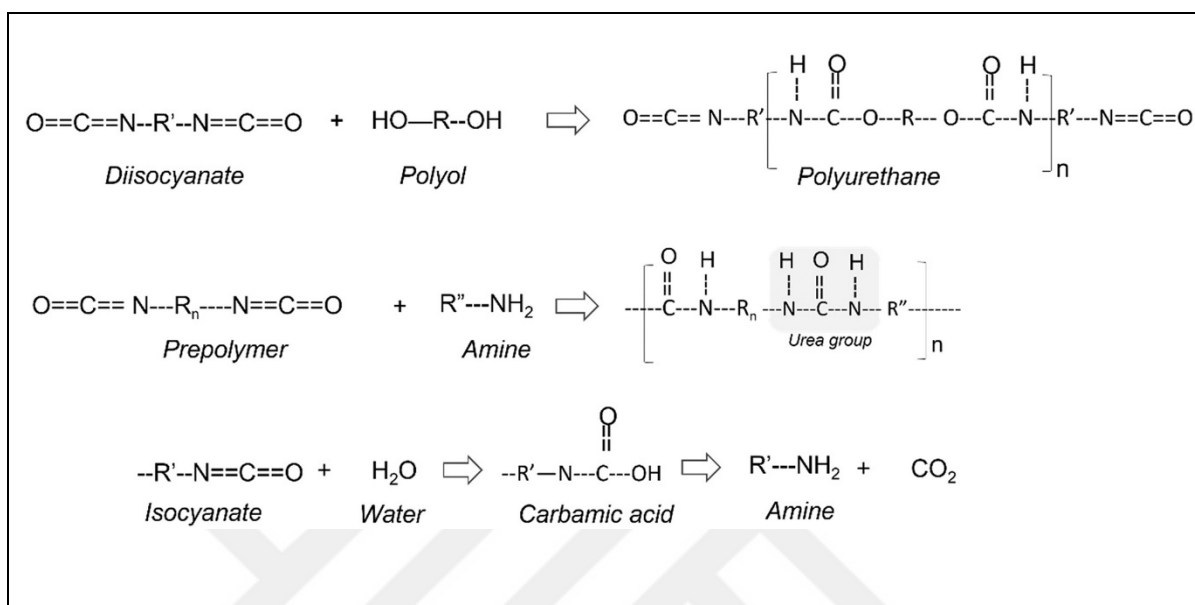


Figure 1.3. Reaction process of waterborne polyurethane [42].

Waterborne Polyurethane Coatings

The versatile properties of waterborne polyurethane have led to its widespread use across multiple industries. In the automotive sector, WPU coatings are extensively applied to provide durable, weather-resistant finishes that protect vehicle exteriors from UV degradation, moisture, and chemical exposure. These coatings ensure both aesthetic appeal and long-term performance of the surfaces they cover. In the construction industry, WPU-based sealants and coatings form resilient, flexible films that safeguard building materials against environmental stressors, thereby enhancing durability and energy efficiency. Moreover, the inherent properties of water-borne polyurethanes—such as low toxicity, non-flammability, and superior wear and corrosion resistance—render them suitable for various applications including construction and automotive coatings, leather finishing, and adhesive systems [43,44].

In packaging, WPU offers significant advantages due to its superior film-forming capabilities and robust adhesion to various substrates. These properties translate into enhanced barrier performance against oxygen and moisture, which is crucial for extending

the shelf life of packaged goods and maintaining product quality. Additionally, the adaptability of WPU formulations allows for the incorporation of a wide range of additives—such as pigments, plasticizers, and functional nanomaterials—to tailor its mechanical and thermal properties to meet specific application requirements [45]. This flexibility also paves the way for advanced applications in fields such as flexible electronics and biomedical devices, where precise control over film characteristics is essential. Overall, waterborne polyurethane represents a key material in advancing sustainable, high-performance coatings and composites, aligning with the global shift toward greener manufacturing practices.

In addition to its broad use in automotive, construction, and packaging sectors, waterborne polyurethane has also gained traction in the textile coating industry. Its outstanding film-forming ability, strong adhesion, and inherent flexibility enable the creation of uniform and durable coatings on various fabric substrates. When applied to textiles, WPU significantly enhances resistance to abrasion, water, and chemical exposure, thereby improving the overall longevity and performance of the material [46]. Moreover, the low-temperature processing characteristic of WPU ensures that even heat-sensitive fabrics can be treated without compromising their integrity. This eco-friendly and versatile coating technology aligns with modern sustainability goals, offering a promising alternative to conventional solvent-based finishes in the textile industry.

1.3. POLYMERS FOR PACKAGING

Polymeric materials play a central role in modern packaging, offering a spectrum of options that range from fully synthetic to bio-sourced and from non-degradable to readily biodegradable. Conventional plastics such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS) have long dominated the market thanks to their low cost, mechanical robustness, and excellent barrier properties. Simultaneously, the emergence of bio-based polymers—including polylactic acid (PLA), polyhydroxyalkanoates (PHA), polycaprolactone (PCL), and starch blends—has introduced renewable alternatives that may or may not be engineered for biodegradation. These materials can be tailored to meet diverse performance requirements, whether for moisture resistance, gas barrier functionality, or mechanical strength. In recent years, however, the imperative for environmentally responsible solutions has elevated the significance of truly

biodegradable packaging: materials that not only originate from sustainable feedstocks but also decompose under end-of-life conditions, thereby reducing persistent plastic waste and aligning with circular-economy principles.

Biodegradable packaging materials have gained substantial attention in recent years as a sustainable alternative to conventional plastics. These materials are designed to break down naturally through the action of microorganisms, reducing the accumulation of persistent waste in the environment [47]. Their degradation process not only minimizes landfill volumes but also mitigates the risk of long-term pollution. As consumer awareness of environmental issues grows, the demand for biodegradable packaging is rising, prompting significant research into novel formulations and enhanced performance characteristics [48].

In addition to biodegradability, the integration of antibacterial properties in packaging materials is becoming increasingly critical. Antibacterial packaging is engineered to inhibit the growth of pathogens, thereby extending the shelf life of food products and ensuring safer consumption [49]. This functionality is particularly valuable in the food industry, where contamination can have serious health implications. The incorporation of natural antibacterial agents (bioadditives, AgNps etc.) or the development of surface treatments that reduce microbial adhesion is at the forefront of current research, aiming to create packaging solutions that are both safe and sustainable.

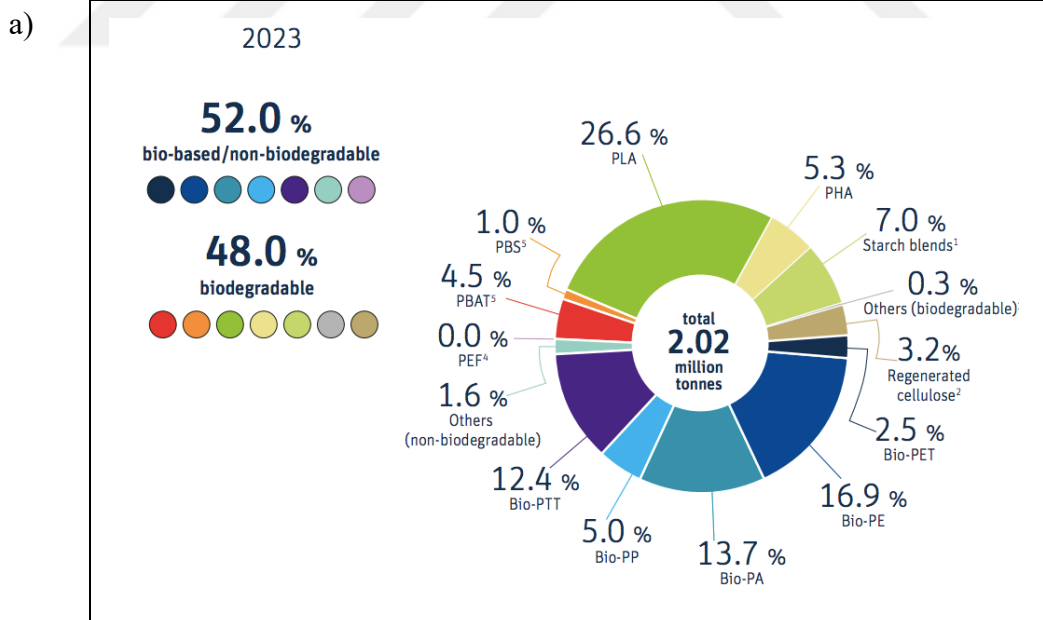
Overall, the convergence of biodegradability and antibacterial functionality in packaging materials addresses multiple contemporary challenges. These dual attributes not only contribute to environmental sustainability by reducing waste and pollution but also enhance product safety and quality [50]. As industries and consumers alike seek to balance performance with environmental responsibility, the popularity of such multifunctional materials is expected to continue its upward trend. This innovative approach paves the way for advanced packaging solutions that support a circular economy while meeting the stringent demands of modern food safety standards.

1.3.1. Materials Used in Biodegradable Film Packaging

In the packaging industry, conventional plastics such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), and polyvinyl chloride (PVC) dominate due to their low cost, mechanical robustness, and effective barrier properties.

Biodegradable packaging materials have emerged as alternatives to conventional plastics in response to growing concerns regarding environmental sustainability and waste management. The polymers used in this field can be broadly classified into two main categories: those derived from natural resources and fossil-based polymers that are engineered to degrade under specific conditions. Examples of naturally sourced polymers include starch, cellulose, proteins, and polylactic acid (PLA), whereas fossil-based biodegradable polymers encompass materials such as polycaprolactone (PCL), polybutylene succinate (PBS), and poly(butylene adipate-co-terephthalate) (PBAT).

This diversity enables the tailoring of packaging solutions to meet a range of mechanical, barrier, and aesthetic requirements. The utilization of both natural and fossil-based biodegradable polymers not only contributes to reducing environmental impacts but also supports essential criteria such as food safety, extended shelf life, and effective waste management. As a result, these polymers, sourced from various origins, play a pivotal role in advancing the development of sustainable packaging solutions.



b)

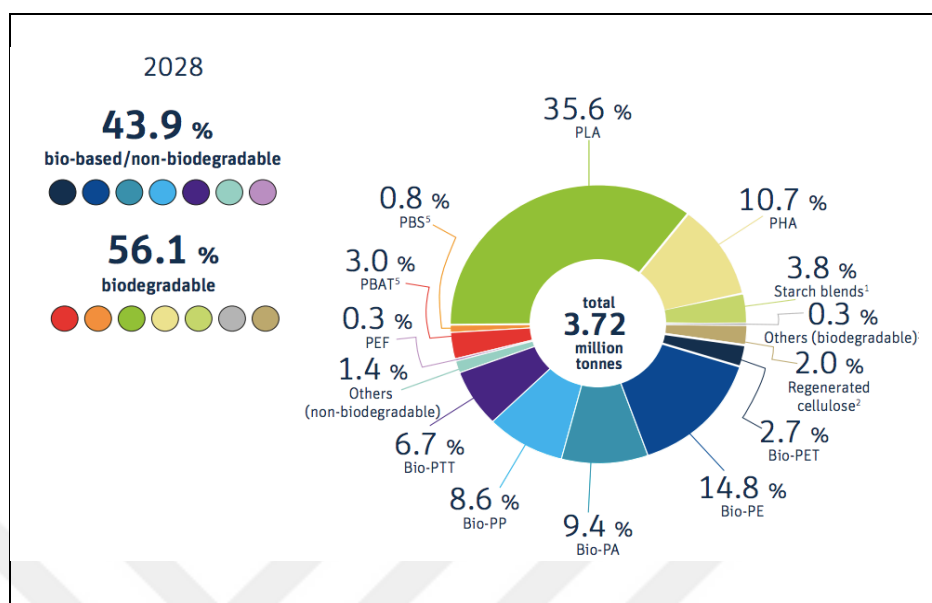


Figure 1. 3 a) Biopolymer production capacities by material type for 2023. b) Biopolymer production capacities by material type for 2028 [30].

Cellulose

Cellulose is one of the most widely available biopolymers in nature. Cellulose, which is found in the cell walls of plants, provides structural support to the plants and keeps the cells together. Its chemical formula is $(C_6H_{10}O_5)_n$. Cellulose is a polysaccharide composed of glucose units. These units are linked by β -1,4 glycosidic bonds and extend along the chains. Cellulose is naturally crystalline and comes together in microfibrils in an orderly fashion. This crystal structure provides cellulose with high mechanical strength and rigidity. Cellulose is also water resistant and has high tensile strength [52]. These properties enable cellulose to be used in many industrial applications. For example, cellulose is used as a base material in many fields such as paper, cardboard, textiles, pharmaceutical coatings and food packaging. In addition, cellulose-based biopolymers are gaining importance as an environmentally friendly and sustainable alternative [53].

Table 1. 2. Properties of cellulose polymer [54].

Cellulose-based polymers	Elastic Modulus (GPa)	Tensile Strength
Cotton	5-13	0.28-0.60
Flax	27-100	0.34-1.03
Jute	26-65	0.39-0.77
Ramie	60-128	0.40-0.94
Wood	10-40	1

Starch

Starch is a polysaccharide found in plants and an important biopolymer. Starch is the energy storage mechanism of plants and is abundant in plant storage organs such as seeds, roots, tubers and fruits. Chemically, starch is usually formed by the polymerization of α -glucose units. Starch molecules consist of two main components called amylose and amylopectin. Amylose is a straight chain unit linked by α -1,4 glycosidic bonds. On the other hand, amylopectin has a branched chain structure and contains both α -1,4 and α -1,6 glycosidic bonds. Starch is a water-soluble biopolymer and shows gelatinization property [55]. This feature allows starch to form gel as a result of heating it and taking it into water. While starch is widely used in the food industry, it is also an important material in the manufacture of paper, the textile industry, and the production of bioplastics. Being sustainable and biodegradable makes starch an environmentally friendly option.

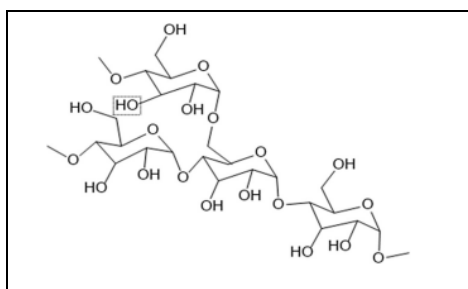


Figure 1. 4. Chemical structure of starch [56].

Poly(lactic Acid (PLA)

Poly(lactic acid (PLA) is a biopolymer derived from renewable resources found in nature. PLA usually starts with the production of lactic acid from plant sources such as corn starch or sugar cane. The lactic acid is then converted into PLA biopolymer by subjecting it to the polymerization process. The physical and mechanical properties of PLA often vary

depending on the polymer's structure and composition. It has good thermoplastic properties, meaning it can be easily melted and shaped under heat and pressure. This means that PLA can be produced in different shapes by processes such as injection molding, extrusion, and 3D printing. The usage areas of PLA are gradually expanding. Especially in the packaging industry, PLA biopolymer has become a preferred material for the manufacture of various products such as plastic bottles, containers, bags and films. It is also used in different areas such as disposable medical supplies, agricultural applications, the textile industry and the automotive industry [57].

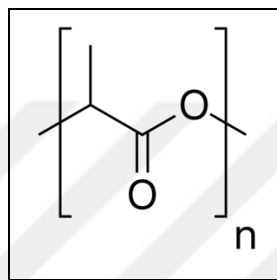


Figure 1. 5. Chemical structure of PLA [58].

Table 1. 3. Properties of PLA [58].

Properties	Value
Density	1.3 g/cm ³
T _g	45 °C
Melting Point	160 °C
Young's Modulus	3.5 GPa
Yield Tensile Strength	25.0 MPa
Elongation at Break	6.0 %

Poly(vinyl Alcohol) (PVA):

Poly(vinyl alcohol) (PVA) is extensively utilized in food packaging applications owing to its biodegradability, non-toxic profile, excellent film-forming capability, water processability, and cost-effectiveness. Its synthesis is achieved via a two-step process, beginning with the polymerization of poly(vinyl acetate) followed by the hydrolysis of its acetate groups. Despite these favorable attributes, PVA exhibits certain limitations when employed as a packaging material, such as high water solubility, relatively low tensile strength, and a propensity for water absorption.

These challenges can be mitigated through polymer blending, which allows for the enhancement of targeted properties. The inherent hydrophilicity and polarity of PVA render it particularly amenable to blending with a variety of natural polymers and functional additives. For example, incorporating starch, chitosan, and cellulose—as well as antimicrobial agents such as essential oils, ethanolic extracts, and organic acids—has proven effective in enhancing the performance of PVA in food packaging applications [59].

Polycaprolactone (PCL)

Polycaprolactone (PCL) is a synthetic, biodegradable polyester produced from petroleum-derived feedstocks. It is typically manufactured via the ring-opening polymerization of ϵ -caprolactone, a cyclic ester, which leads to a polymer with a distinct block structure. PCL is characterized by its hydrophobic and semi-crystalline nature, possessing a glass transition temperature around $-60\text{ }^{\circ}\text{C}$ and a melting point between 59 and $64\text{ }^{\circ}\text{C}$. Its molecular weight usually falls between $3,000$ and $90,000\text{ g/mol}$, with higher molecular weights generally correlating with reduced crystallinity. These attributes render PCL readily formable at relatively low temperatures, making it a versatile material in various processing conditions [60].

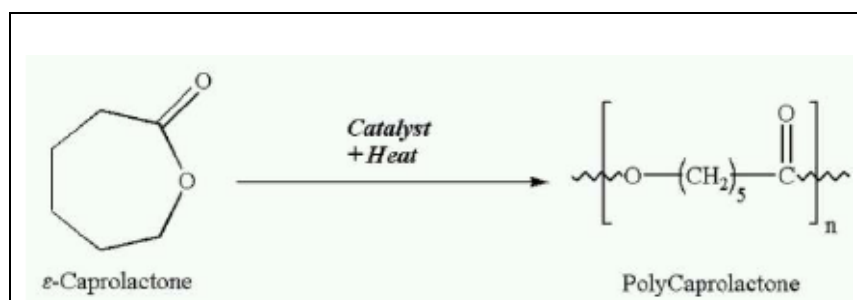


Figure 1. 6 Ring opening polymerization of ϵ -Caprolactone [61].

Table 1. 4. Properties of PCL [58].

Properties	Range
Molecular Weight	80000
Melting Point	60°C
Density	1.145 g/cm^3
Tg	60°C

The solubility profile of PCL is notable; it dissolves well in solvents such as chloroform, dichloromethane, carbon tetrachloride, benzene, toluene, cyclohexanone, and 2-nitropropane at ambient temperature, while exhibiting limited solubility in acetone, 2-butanone, ethyl acetate, dimethylformamide, and acetonitrile, and is insoluble in alcohol, petroleum ether, and diethyl ether. PCL can be synthesized using a variety of catalytic systems—anionic, cationic, coordination, and radical catalysts—which significantly influence its molecular weight distribution, end group composition, and overall chemical structure [60].

Owing to its low melting point, excellent solvent compatibility, and blend versatility, PCL has attracted considerable attention in biomedical applications, including medical implants, controlled drug delivery systems, and tissue engineering scaffolds for bone and cartilage. Additionally, its biodegradability offers a distinct commercial advantage over conventional plastics such as polypropylene and polyethylene, as it degrades within a few years under appropriate conditions. Despite the complexities and higher production costs associated with PCL, the development of PCL-based composites—particularly those incorporating natural fibers—presents promising opportunities to overcome these limitations and expand its range of applications.

Properties of PCL

Polycaprolactone (PCL), like many biopolymers, initially exhibited limited mechanical strength, which constrained its use in applications that demand high load-bearing capabilities. Despite these shortcomings, its notable rheological and viscoelastic behavior surpasses that of many resorbable polymers. To overcome these limitations while preserving its inherent biodegradability, extensive research has focused on the development of PCL-based nanocomposites. In these systems, various fillers are incorporated to reinforce the polymer matrix. For instance, cellulose-derived nanofillers, carbon nanotubes (CNTs), and other functional nanomaterials have been explored due to their ability to enhance mechanical, thermal, and even electrical properties [60].

Among these reinforcing agents, cellulose nanofillers offer the advantage of being renewable and biodegradable; however, their hydrophilic nature presents compatibility challenges when dispersed in the hydrophobic PCL matrix. Addressing these challenges typically involves chemical modifications aimed at improving filler dispersion and interfacial

adhesion. Carbon nanotubes, on the other hand, provide exceptional physicochemical attributes that can significantly boost the mechanical and thermal performance of PCL composites. Yet, the tendency of CNTs to agglomerate—stemming from their high aspect ratios and strong van der Waals forces—necessitates surface treatments to ensure uniform distribution and effective reinforcement, especially in applications such as medical implants where both mechanical integrity and biocompatibility are critical.

In the biomedical arena, PCL has garnered attention for its suitability in long-term implantable devices, largely due to its slow degradation rate which results from the random hydrolytic scission of ester bonds. The integration of nanostructured fillers, such as hydroxyapatite and layered double hydroxides, has further enhanced the bioactivity and mechanical properties of these materials, rendering them more effective in tissue engineering and controlled drug delivery systems. Additionally, the incorporation of copolymers like thermoplastic starch has been shown to accelerate the biodegradation of PCL, thereby increasing its bio-based content and optimizing its environmental performance.

Beyond biomedical applications, PCL nanocomposites have also demonstrated promise in addressing the polymer's inherent deficiencies in barrier properties. The inclusion of carbon nanotubes, for example, can modify the diffusion pathways within the polymer matrix, thereby enhancing its resistance to the permeation of water and gases. Achieving an optimal balance between the matrix's crystallinity, the chemical compatibility between PCL and the fillers, and the dispersion quality of the reinforcing agents is crucial for tailoring both the barrier performance and the biodegradation behavior in soil environments [60].

Application Areas of PCL

Polycaprolactone (PCL) is a highly adaptable polymer that has found extensive use in controlled drug delivery systems. Its excellent biocompatibility and permeability to a wide variety of pharmaceutical compounds render it ideal for applications requiring sustained release over extended periods. In contrast to polymers such as PLA or PLGA, which degrade more rapidly, PCL's slower degradation rate makes it particularly suitable for long-term therapeutic interventions. Moreover, its compatibility with numerous other polymers facilitates the creation of composite materials with adjustable degradation profiles, allowing formulations to be tailored to meet specific clinical demands [60].

In the realm of medical devices, PCL is prized for its ease of processing and its ability to be fabricated into complex, precise geometries. These characteristics are invaluable in the production of devices that require a high degree of dimensional accuracy and mechanical reliability. Additionally, PCL serves as a fundamental component in tissue engineering, where it is used to produce scaffolds that offer both structural support and a favorable environment for cellular attachment, proliferation, and differentiation. The material's mechanical properties, which closely mimic those of natural tissues, enable the design of versatile scaffolds suitable for regenerating various tissues, including bone, blood vessels, skin, and nerves [60].

Beyond biomedical applications, PCL shows considerable promise in the development of biodegradable packaging materials. By incorporating PCL into packaging formulations, it is possible to produce eco-friendly solutions that offer enhanced barrier properties against oxygen, carbon dioxide, and moisture. Such improvements contribute to extending the shelf life of packaged goods while reducing reliance on conventional, non-biodegradable plastics. Furthermore, the inherent biodegradability of PCL ensures that these materials break down naturally over time, thereby mitigating environmental pollution and reducing the accumulation of plastic waste.

1.4. BIOADDITIVES IN POLYMERS

In the polymer industry, additives are non-reactive substances incorporated into base polymers to enhance or modify their physical, chemical, and processing properties. These multifunctional ingredients include plasticizers, which increase flexibility and reduce brittleness; stabilizers and antioxidants, which protect against thermal, UV, and oxidative degradation; fillers and reinforcements, such as calcium carbonate or glass fibers, which improve mechanical strength and dimensional stability; flame retardants, which inhibit or delay combustion; and colorants, which impart desired hues and opacity. By carefully selecting and optimizing additive types and concentrations, manufacturers can tailor polymer formulations to meet specific performance requirements—ranging from improved processability and weather resistance to specialized electrical, barrier, or biomedical functionalities—while also addressing cost, sustainability, and regulatory considerations.

To improve both the mechanical performance and sustainability of polymeric materials, it is essential to incorporate a range of functional and structural additives. Polymer formulations require various reinforcing agents—such as fibers and particles—to enhance mechanical strength, thermal stability, and chemical resistance. In addition, stabilizers that protect against heat and light, as well as flame retardants, are commonly added to slow down polymer aging and impart fire resistance [62]. Plasticizers, on the other hand, are employed to reduce brittleness. However, many of these additives are derived from petroleum, which raises concerns regarding toxicity and the potential for migration from the finished products. Recent issues, such as those related to phthalates in flexible polyvinyl chloride (PVC) and halogenated flame retardants in electronic devices, highlight the negative health and environmental impacts of these substances [63].

1.4.1. Definiton of Bioadditives

Bioadditives are naturally derived substances—such as plant extracts, essential oils, and fruit peel powders—incorporated into polymer matrices to enhance mechanical, barrier, and antimicrobial functionalities in composite materials. In light of the environmental and health challenges posed by petroleum-based additives, as well as the anticipated decline in petroleum resources, both academic and industrial sectors are increasingly focusing on developing bio-based alternatives. Meanwhile, within the European Union, an estimated 120–140 million tons of biological waste are generated annually, with approximately 40% of this waste ending up in landfills. In certain member states, such as Bulgaria, Romania, Latvia, Greece, Lithuania, and the Czech Republic, the proportion of biological waste disposed of in landfills can reach 100% (EU, 2011; EEA, 2013). This significant accumulation of biological waste further underscores the importance of valorizing natural resources to develop sustainable, high-performance polymer materials [64].

In the food sector, natural additives have gained prominence as bio-preservatives and functional components within active and intelligent packaging systems, especially for food preservation and packaging. Integrating biodegradable polymers with these natural compounds presents a promising route for creating materials that possess enhanced properties and tailored functionalities. In particular, embedding natural antimicrobial agents into biodegradable polymer films is an innovative strategy to improve packaging performance, thereby extending the shelf life of food products and bolstering food safety.

Among the diverse sources of natural antimicrobials, fruits such as pomegranate, blueberry, and grapefruit stand out due to their high concentrations of bioactive compounds. Essential oils, fruit extracts, and components derived from fruit peels offer considerable potential as antimicrobial additives. This section examines how these naturally derived substances can be effectively incorporated into biodegradable polymer films, paving the way for advanced food packaging solutions that meet both safety and sustainability criteria [65].

1.4.2. Bioadditives Used In Composite Materials

Global climate change and its impact on ecosystems have rendered the management of biological waste an increasingly pressing issue. In response, governments, environmental and social organizations, industry stakeholders, and researchers have all intensified efforts to remove biological waste from landfills—a concern extensively addressed in the scientific literature. Globally, anaerobic digestion and composting remain the predominant methods for processing urban biological waste, despite the inherent challenges associated with its high nutrient content. Improper disposal of such waste in open environments poses significant risks to both ecological systems and public health. Traditional management strategies—including landfilling, biocomposting, and incineration—tend to yield low-value outputs, as they do not effectively recover the valuable constituents present within the waste streams [66]. In contrast, these recoverable components can be upcycled into higher-value products in sectors such as chemical manufacturing, agriculture, and pharmaceuticals [67; 68], underscoring the need for research focused on the efficient utilization of this largely inevitable raw material.

Moreover, by-products from food sources—comprising parts of plants, animals, vegetables, fruits, and fungi—are increasingly being incorporated into polymer composites. Materials derived from renewable resources offer the dual benefit of reducing CO₂ emissions while maintaining comparable chemical and physical properties to their petroleum-based analogs. The valorization of biological waste not only enhances sustainability but also capitalizes on the rich nutrient content and functional components that can serve as foundational building blocks in plastic formulations.

In recent years, polymer composites that integrate natural additives have found diverse applications across various sectors, including automotive, household goods, construction materials, and packaging. Natural additives, whether in the form of fibers or powders,

effectively reduce the overall plastic content in these products [69]. Despite their organic origin, agricultural wastes pose environmental hazards when improperly managed, as they are often burned or disposed of in landfills, which significantly delays biodegradation. These wastes typically contain natural cellulose fillers, phenolic acids, and pectin structures, which can bolster the mechanical properties of composites and provide inherent antibacterial functions. Consequently, incorporating these natural fillers not only promotes the advanced recycling of waste but also curtails plastic consumption [70].

Within polymer matrix composites, bio-waste particles serve as reinforcing agents that help mitigate brittleness and enhance the modulus of the matrix. While these particles may exhibit various shapes—ranging from plate-like and spherical to irregular—they generally possess similar dimensions in all directions. Compared to fiber-reinforced systems, composites augmented with bio-waste particles are typically more cost-effective. Although these particles do not dramatically improve the fracture resistance of the composite, they do contribute to increased stiffness. The primary objective of reinforcing polymer matrices with bio-waste particles is to improve high-temperature performance, augment surface hardness, enhance wear and friction resistance, modify thermal and electrical conductivity, and ultimately improve processability [71].

Plant-based Bioadditives

Plant-based bioadditives are valuable functional ingredients sourced from renewable botanical materials that enhance the performance of polymer systems. These natural additives—ranging from fibrous components and polysaccharides to phenolic compounds and flavonoids—can improve mechanical strength, barrier properties, and resistance to UV and oxidative degradation, as well as impart antimicrobial activity. In particular, fruit-based bioadditives such as peel powders, concentrated extracts, and essential oils offer versatile applications: pomegranate, blueberry, and grapefruit peels can be processed into extracts or oils and incorporated into biodegradable films and coatings to confer both protective and functional benefits.

Collectively, the incorporation of natural additives from pomegranate, blueberry, and grapefruit into biodegradable polymer films represents a promising, sustainable strategy for advancing food packaging technology. By leveraging essential oils, extracts, and powdered by-products, these natural additives contribute a wide spectrum of bioactive compounds that

not only bolster the antimicrobial and antioxidant properties of the films but also promote the efficient utilization of agricultural residues. This approach not only extends the shelf life and safety of packaged foods but also aligns with environmental sustainability goals through waste valorization and reduced reliance on synthetic additives.

Peels

Fruit peels, frequently regarded as mere waste, are in fact a rich source of essential oils, fibers, and phenolic compounds. These by-products can be dried and milled into fine powders or processed further to extract valuable bioactive ingredients. Serving as sustainable reservoirs of natural antimicrobials and antioxidants, fruit peels offer significant potential for enhancing material functionality.

Integrating peel powders into biodegradable films not only improves their performance by imparting antimicrobial and antioxidant properties but also promotes the efficient utilization of organic waste. This approach aligns with sustainable practices by transforming discarded fruit residues into value-added components for advanced packaging solutions [72].

Pomegranate (*Punica granatum* L.) stands out as a significant natural source of antimicrobial compounds. Notably, the peel—which represents roughly 30–40% of the fruit as a by-product of juice extraction—is abundant in tannins (including ellagitannins, punicalin, gallotannins, and punicalagin) as well as various polyphenols. These bioactive compounds are recognized for their strong antioxidant, antimicrobial, antiviral, and antifungal effects. Several studies have indicated that incorporating pomegranate peel into food packaging systems can effectively suppress microbial growth, thereby prolonging the freshness and shelf life of food products [73–75].

Extracts

Fruit extracts are obtained from multiple fruit components—including the pulp, seeds, and skin—through solvent extraction and other advanced techniques. These extracts are highly concentrated in bioactive phytochemicals such as flavonoids, anthocyanins, and phenolic acids. Due to their strong antimicrobial and antioxidant properties, fruit extracts have been shown to effectively inhibit various foodborne pathogens. For example, extracts derived

from berries, grapes, and pomegranates have demonstrated significant antimicrobial efficacy against a broad spectrum of pathogens [73].

Blueberries (*Vaccinium* spp.) also contribute valuable antimicrobial properties due to their high content of anthocyanins, flavonoids, and phenolic acids. The potent antioxidant activity of blueberry extracts further assists in mitigating oxidative spoilage in packaged foods, providing a dual function of microbial inhibition and preservation. This multifaceted bioactivity underscores the potential of blueberry-derived compounds in enhancing the performance of biodegradable packaging films [73, 77, 78].

Essential Oils

Essential oils are highly concentrated, hydrophobic extracts derived from plant materials and are characterized by a complex blend of volatile compounds. They are most commonly isolated through techniques such as steam distillation or mechanical expression. These oils are particularly rich in bioactive constituents, including terpenes and phenolic compounds, which impart potent antimicrobial, antifungal, and antioxidant properties. Consequently, essential oils offer a promising natural alternative to synthetic antimicrobials, paving the way for more sustainable food packaging solutions and contributing to a greener future [79].

Grapefruit (*Citrus paradisi*) offers an additional source of natural antimicrobial agents through its essential oil and seed extracts. The essential oil, rich in compounds such as limonene, myrcene, and linalool, exhibits notable antimicrobial and antifungal properties. Additionally, extracts derived from grapefruit seeds, which contain bioflavonoids and vitamin C, further enhance both antimicrobial and antioxidant capabilities. The peel, a plentiful by-product of grapefruit juice production, can be processed into powder or further extracted to recover these bioactive constituents [73,80].

Table 1.5 presents a comprehensive literature review on the incorporation of various bioadditives into composite materials, including grapefruit peel, orange peel, pumpkin waste powder, hazelnut shell powder, pomegranate extract, pomegranate peels, sour cherry shell powder, and olive fruit polyphenols. These studies reflect a growing trend in utilizing agro-industrial residues to improve the mechanical strength, thermal stability, and biofunctionality of polymer-based composite systems, aligning with sustainability and circular economy goals.

Table 1. 5. Literature reviews of bioadditives in composite materials.

REF.	PLANT WASTE	POLYMER	POWDER RATIO	METHOD	RESULTS
[81]	Orange peel	Chitosan/ PVA	%0 %0.25 %0.50 %1.0 %1.25	Chitosan and PVA solutions were prepared separately and blended in a 2:1 ratio. Orange peel powder (0–1.25 wt%) and glycerol were added, and the mixture was stirred and cast into Petri dishes. Films were dried at 50 °C for 18 hours to obtain composite structures.	Increased elongation at break and antioxidant activity; decreased tensile strength, transparency, and surface hydrophobicity; improved film thickness and flexibility; enhanced thermal stability; increased water vapor transmission; reduced oxygen permeability; visible color changes observed.
[82]	Pumpkin waste powder	Epoxy	1% 2% 3% 4% 5% 6% 7% 8%	Squash peels were dried, milled, and sieved to 2.5 µm and 1.25 µm sizes, then incorporated into epoxy resin at 1–8 wt%. The mixtures were cast into silicone molds and cured at room temperature for 48 hours.	The incorporation of squash fiber powder into epoxy composites significantly improved impact strength, flexural strength, wear resistance, and thermal conductivity. The 2.5 µm fiber at 1 wt% showed superior performance in mechanical and thermal properties compared to the 1.25 µm variant. However, for applications prioritizing thermal insulation and low water absorption, the 1.25 µm fiber at 1 wt% offered the best balance.

[83]	Hazelnut shell powder	Polystyrene	%10 %20 %30 %40 %50	Polystyrene granules and modified hazelnut shell powder (10–50 wt%) were mixed in a planetary mixer for homogeneity. The blend was preheated at 165 °C for 60 minutes, then compression molded at 110 MPa for 5 minutes.	Polystyrene-coated hazelnut shell powder significantly increased hydrophobicity, raising the water contact angle from ~60° to ~87°. With proper pretreatment, the filler was successfully incorporated up to 50 wt%. The composites exhibited high thermal resistance (265–376 °C), with optimal performance at 20–40 wt% filler content.
[84]	Pomegranate peel extract	Bacterial Cellulose	20%	Pomegranate peels were dried, milled, and extracted with ethanol via Soxhlet for 8 hours. The extract was concentrated, dried, and dissolved at 20 wt%. Bacterial cellulose (BC) pellets were agitated in the solution for 24 hours, then rinsed to remove unbound extract.	Pomegranate peel extract (PGPE) was effectively incorporated into bacterial cellulose and demonstrated strong antibacterial activity, particularly against <i>Staphylococcus aureus</i> . Its low MIC and MBC values confirmed high efficacy, and structural analyses (FTIR, FE-SEM) validated successful integration into the matrix.
[85]	Pomegranate peels and Ajwa seed powder in nanomete size (53.38-93.78 nm)	PMMA	%0 %0.4 %0.8 %1.2 %1.6	PMMA powder and monomer were mixed at a 3:1 ratio and cast into thermally coated molds. Polymerization was performed at 55 °C under 2.5 bar, followed by a 30-minute hold and a 3-hour post-cure at the same temperature to relieve residual stress and enhance mechanical properties.	Incorporating pomegranate peel and Ajwa seed powders into PMMA significantly enhanced all mechanical properties. Pomegranate peel-reinforced composites showed superior performance, reaching maximum flexural strength (114 MPa), modulus (5.124 GPa), impact resistance (13.75 kJ/m ²), and fracture toughness (8.276 MPa·m ^{1/2}) at 0.8 wt%. Ajwa seed composites peaked at higher filler contents but consistently underperformed compared to pomegranate-based samples.

[86]	Sour cherry shell powder	Polyethylene	%0 %2.5 %5 %7.5	Sour cherry shells were ground, sieved, and added (0–7.5 wt%) to a polyethylene blend (LDPE/LLDPE/MAPE). The mixture was processed in a single-screw extruder at 165 °C and 85 bar, then pelletized for further use.	Sour cherry shell powder at 2.5 wt% significantly improved tensile strength (~26%) and reduced water uptake in the composite films. Higher loadings (5–7.5%) increased moisture absorption. SEM analysis confirmed strong interfacial adhesion, indicating effective particle dispersion and load transfer.
[87]	Olive fruit polyphenols, citrus fruit extracts	PLA	%1 %5 %10 %15 %20 %25	PLA-based composites incorporating varying ratios of olive polyphenols and citrus extracts were fabricated via a hot roll milling process conducted at 180 °C.	The study observed that increasing the bioadditive concentration correspondingly enhanced the antibacterial efficacy.

1.4.3. Pomegranate Peels As Bioadditives

Pomegranate (*Punica granatum* L.; Punicaceae) has garnered increasing attention due to its multifunctional properties and nutritional benefits. Rich in tannins and phenolic compounds, pomegranate is associated with reduced disease risk. Notably, the peel—accounting for nearly 50% of the fruit's total weight—has been shown to contain higher levels of bioactive substances than the juice, exhibiting more potent biological activities. Growing consumer health awareness has fueled demand for natural antioxidants, which can be sourced from plant materials, including agricultural by-products. Plant phenolics, as aromatic compounds, play a vital role in combating degenerative diseases and serve as key antioxidant components in the human diet. Consequently, food and agricultural waste, such as onion skins, potato residues, apple peels, olive leaves, and raspberry by-products, have been explored as promising substrates for extracting polyphenols [88].

Among these, pomegranate peels are particularly promising for the efficient recovery of bioactive and phytochemical compounds. Studies have demonstrated that extracts from pomegranate peels exhibit a considerably higher antioxidant capacity than those obtained from pomegranate juice, as evidenced by tests measuring the scavenging of hydroxyl radicals, superoxide anions, and the inhibition of CuSO₄-induced LDL oxidation. Moreover, pomegranate peel extracts have been reported to display a broad spectrum of biological activities—including antimicrobial, anticancer, antidiarrheal, anti-inflammatory, antidiabetic, apoptotic, and antimutagenic effects—although the bioavailability of these antioxidants can vary based on pomegranate variety, cultivation conditions, and processing methods [88].

Literature reviews indicate that pomegranate peels are predominantly used as natural dyes in textile applications [89]. It is well-known that plants have significant potential as natural dye sources in textile applications. In this context, extracts of PoP (Pomegranate peels) are commonly employed as dye sources. Fabrics are dyed using various dyeing methods with PoP extracts. Studies have reported that, due to the rich phenolic content of PoP, not only does it color fabrics effectively, but it also provides antibacterial effects. These phenolic compounds impart antibacterial properties to the fabric surface, thereby enhancing the functionality of textile products [89].

In nanotechnology applications, PoP extracts have been demonstrated to serve as reducing agents in the green synthesis of nanoparticles. In this process, PoP extracts play a crucial role in the production of nanoparticles for functionalizing fabrics. These applications offer environmentally sustainable solutions and enhance the performance of textile products. Consequently, the use of PoP as both a natural dye source and a functional additive in nanotechnology applications is gaining increasing attention in the textile industry [90].



2. LITERATURE SURVEY

2.1. BIOADDITIVES IN TEXTILE COATING

In textile finishing, a wide range of plant-derived bioadditives can be incorporated to confer specific functionalities—such as natural dyes for coloration, essential-oil extracts for antimicrobial protection, and fragrant botanicals for odor management—while simultaneously enhancing sustainability and reducing reliance on synthetic chemicals. These bioadditives, which include pigments (e.g., anthocyanins, carotenoids), polyphenolic extracts, and volatile oils, are typically applied via pad-dry-cure or coating processes and can be tailored to achieve desired performance characteristics. The following section presents a selection of recent literature examples in which bioadditives have been successfully employed to impart dyeing, antimicrobial, and olfactory properties to textile substrates.

When the literature on biocomposite structures is obtained by adding natural additives to coatings and polymers, it can be said that their common goal is to obtain sustainable and environmentally friendly materials. Although the researches on this subject are limited, it is seen that natural additives are used in the field of textile, defense industry, health field and aviation. For example, in a study [91], biocomposites were produced using natural additives from Coir, Aloe vera, Banana fiber, Bagasse, Kenaf, and it was suggested that these biocomposites could be used in many areas in the aviation field. For example, for decorative purposes in aircraft interiors, in the manufacture of aircraft doors, as floor mats on aircraft floors, as flooring material on interior walls of aircraft, in automobiles; It is said that these biocomposites can be used in places such as doors, seats, wall upholstery.

Phan et. al. [92] explores the feasibility of using anthocyanins extracted from blueberry waste as an eco-friendly dye for cotton, combining systematic experimental optimization with molecular modeling to understand dye–mordant–fiber interactions. Initially, the authors optimized extraction and dyeing parameters (temperature, pH, time, and dye concentration) and evaluated the effects of both metal salts (e.g., SnCl_2 , alum) and various biomordants (tannic acid, β -cyclodextrin, alginate, oxalic, gallic, and caffeic acids) on color uptake and fastness using FTIR, UV–Vis spectroscopy, and ISO standard wash and light tests. Concurrently, density functional theory and molecular dynamics simulations quantified the interaction energies underpinning metal-dye coordination, hydrogen bonding,

ionic, and π - π interactions. Experimentally, stannous chloride emerged as the most effective mordant, delivering the highest dye exhaustion ($\approx 33.4\%$ vs. 25.1% control) and superior wash/light fastness, while none of the biomordants could fully replicate this performance. Modeling results corroborated these findings by revealing significantly stronger interaction energies for Sn(II) complexes compared to those of the biomordants, thereby highlighting the current limitations—and future potential—of truly green dyeing agents

Ajmal et. al. [93] investigates the use of high-energy gamma radiation to enhance both the extraction of natural colorants from pomegranate (*Punica granatum* L.) peels and the dye-uptake and fastness properties of silk fabrics dyed with those extracts. Experimentally, pomegranate peel powder and degummed silk were each exposed to Cs-137 gamma doses (20–40 kGy), and aqueous, alkaline, and alcoholic extracts were prepared and assessed. Dyeing trials optimized key parameters—temperature (30–70 °C), time (30–70 min), pH (5–12), salt concentration (4–12 g/L), and material-to-liquor ratio (1:30–1:70)—while pre- and post-mordanting with Al^{3+} , Cr^{3+} , Cu^{2+} , and tannic acid (2–10%) was systematically evaluated. The authors found that 40 kGy irradiation, followed by dyeing at 50 °C for 40 min at pH 6.0 with 10 g/L NaCl, maximized dye exhaustion and produced uniformly deep shades; pre-mordanting with 10% aluminum and post-mordanting with 10% tannic acid yielded the best color strength and fastness improvements.

Yang et. al. [94] evaluates the dyeing of silk fabrics using pomegranate (*Punica granatum*) peel extract in combination with natural mordants and a natural fixing agent to develop a greener textile coloration process. The authors first characterized the peel extract—identifying ellagic acid as the principal pigment—via UV-Vis and FTIR spectroscopy, then employed an L_9 orthogonal design to optimize dyeing parameters (pH, temperature, time) on silk, and screened three natural mordants (*Chaenomeles speciosa* extract, mineral salts, rare earth) alongside a gum rosin fixing treatment. Dyeing was conducted at pH 9 and 60 °C for 60 min, with pre-, simultaneous, and post-mordanting protocols, followed by gum rosin application; color strength (K/S), colorimetric values, and fastness (wash, perspiration, rubbing) were systematically measured, and SEM was used to observe fiber surface morphology before and after fixing. The optimized natural mordanting and rosin fixing sequence (mineral salts post-mordanting + gum rosin) yielded the highest K/S value (11.74) and excellent fastness ratings (level 5), demonstrating that pomegranate peel extract, in tandem with eco-friendly auxiliaries, can produce vibrant, durable silk dyeings.

In another study [95] evaluates the enhancement of pineapple leaf fibers (PALF) by coating them with a custom-synthesized thermoplastic polyurethane (TPU) elastomer to overcome the inherent brittleness of the natural fibers. After an initial 5% NaOH treatment to increase surface roughness, PALFs were immersed in TPU prepolymer under varying dipping times (5–20 min), cured at temperatures from 30 °C to 85 °C, and post-cured for 6–24 h. Coating quality and fiber–polymer interactions were analyzed via FTIR (notably H-bond formation at 3300 and 1530 cm^{-1}), SEM (showing uniform coverage at 10 min dipping), DSC, and TGA (revealing improved thermal stability to ~ 500 °C). Tensile testing demonstrated that fibers dipped for 10 min and cured at 85 °C for 6 h achieved the optimal balance of stiffness (≈ 900 MPa modulus) and extensibility ($\approx 30\%$ elongation), confirming TPU coating as an effective strategy to impart elasticity and durability to PALF.

According to another study [96] the use of aqueous extracts from orange peel as a sustainable dye and UV-protective treatment for wool fabrics, aiming to replace conventional synthetic dyes with an eco-friendly alternative. The authors first optimized extraction parameters (temperature 70–100 °C, time 0.5–3 h) to maximize phenolic colorant yield, then applied the crude extract to wool using direct and one-bath mordanting methods (Al^{3+} , Fe^{2+}) across varied pH (3–10), temperatures (70–100 °C), and times (60–180 min), characterizing uptake via K/S measurements, FTIR, and UV–Vis spectroscopy. Colorfastness to washing, rubbing, and light was assessed by ISO standards, and UV protection was quantified by UPF testing before and after up to 30 home-laundrying cycles. Under optimal conditions (100 °C, 120 min, pH 3 for direct, pH 7–9 for mordanting), wool dyed with orange peel extract exhibited good fastness ratings and achieved UPF values up to ~ 6000 —approximately six times higher than synthetic-dyed controls—with durable performance even after repeated laundrying.

This review article [97] examines the use of essential oils extracted from green, orange, and mixed (“black”) lemon peels (*Citrus limon*) as natural antimicrobial finishes for cotton textiles. The authors prepared methanolic extracts of each peel type via steam distillation, then applied them to bleached cotton fabric using optimized pad–dry–cure parameters (80% pick-up, 70 °C drying for 5 min, 140 °C curing for 3 min) and evaluated antibacterial efficacy against *Staphylococcus aureus* and *Escherichia coli* through inhibition-zone assays. Green lemon peel extract yielded the largest zones of inhibition (24–30 mm for *S. aureus* and 22–

26 mm for *E. coli*), outperforming both orange and black lemon peels, and maintained its antimicrobial activity even after five standardized wash cycles.

In a study by Singh et. al. [98], pomegranate peel extract (PoPE), known for its rich phenolic content including punicalagin and ellagic acid, was used to develop antimicrobial cotton fabrics. The researchers incorporated the aqueous extract of pomegranate peels into cotton textiles using a pad-dry-cure method without synthetic mordants. The treated fabrics demonstrated notable antibacterial activity, particularly against *Staphylococcus aureus* and *Escherichia coli*, which was attributed to the bioactive compounds penetrating the fiber matrix. The study also reported that the PoPE-treated fabrics retained their antimicrobial efficacy even after several wash cycles, suggesting potential use in medical and hygiene applications. Additionally, FTIR and SEM analyses confirmed the uniform adherence of the extract to the fiber surface, highlighting the extract's compatibility with cellulose-based substrates. This research supports the integration of fruit-derived extracts into sustainable textile finishing formulations.

A study by Phan et. al. [92] utilized blueberry extract for its natural dyeing properties on cotton fabrics, aiming to replace synthetic dyes with plant-based alternatives. The extract, containing anthocyanins and flavonoids, was applied using a conventional dye bath followed by natural mordants such as alum and tannic acid. Colorimetric analysis indicated deep purple and blue hues with high saturation and good fastness properties. Moreover, treated samples exhibited mild antioxidant and antimicrobial effects due to the residual bioactive compounds. The dyed fabrics also showed good resistance to photo-degradation, enhancing their potential use in lifestyle or fashion textiles. The study underlines the multifunctionality of fruit-derived extracts in textile applications and promotes sustainable dyeing practices.

In the work of Ji et. al. [100], orange peel essential oil (OPEO) was microencapsulated and applied to polyester/cotton blend fabrics to impart deodorizing properties. Using a pad-dry-cure process combined with melamine-formaldehyde crosslinking agents, the microcapsules were effectively fixed onto the textile surface. Evaluation through gas chromatography and odor intensity analysis revealed a significant reduction in sweat and amine-related odors after wear simulations. SEM images confirmed uniform distribution of the capsules on the fiber surface, while tensile strength tests showed that mechanical integrity was not compromised. The treated fabrics maintained over 60% odor reduction efficiency after five washing cycles. This study demonstrated that fruit-derived essential oils can be utilized for value-added textile finishes aimed at functional and cosmetic textile markets.

2.2. BIOADDITIVES FOR FOOD PACKAGING

In the packaging industry, plant-derived bioadditives have gained increasing attention as functional components that not only enhance material performance but also promote environmental sustainability. These bioadditives—ranging from polyphenol-rich fruit extracts and antioxidant-loaded peel powders to antimicrobial essential oils—can be incorporated into polymeric matrices to improve properties such as biodegradability, barrier efficiency, UV resistance, and microbial inhibition. When added to biopolymer films, these natural compounds serve dual functions: they reduce the reliance on synthetic additives and contribute to extending the shelf life and safety of packaged goods. Depending on the type and concentration used, bioadditives can influence film morphology, optical transparency, and hydrophobicity, enabling the design of active and intelligent packaging systems. The following section presents a review of recent scientific studies that have successfully demonstrated the integration of bioadditives into biodegradable packaging films to achieve enhanced antimicrobial, antioxidant, and protective functionalities.

For example, one study [80] developed packaging films by blending PCL with chitosan and grapefruit seed extract (GFSE), revealing that varying the GFSE/chitosan ratio significantly influenced surface morphology, mechanical integrity, and antimicrobial effectiveness against bacteria such as *Escherichia coli* and *Pseudomonas aeruginosa*. Packaging trials further illustrated that these films effectively inhibited *E. coli* growth on salmon and prevented mold formation on bread when GFSE was incorporated at concentrations of at least 1.0 mL/g, highlighting the potential of such composites for active antimicrobial food packaging.

Other investigations have focused on the antimicrobial properties of fruit extracts. Blueberry extracts, for instance, have been shown to exhibit dose-dependent inhibition of pathogens like *Listeria monocytogenes* and *Salmonella Enteritidis*, with key active compounds including chlorogenic acid, quercetin, and ellagic acid contributing to their efficacy [77]. In a related study, hydroethanolic extracts from *Crocus sativus* L. petals, rich in flavonoids such as kaempferol and quercetin derivatives, demonstrated potent bactericidal effects against *Staphylococcus aureus* and *Listeria monocytogenes*, while exhibiting bacteriostatic activity against *Escherichia coli* and *Salmonella typhimurium* [101].

Research has also examined the use of natural derivatives in edible coatings. For instance, edible films formulated with chitosan, nanochitosan, and pomegranate peel extract (PoPE) have proven effective in controlling mycotoxigenic fungal contamination on date fruits, with combinations of nanochitosan and PoPE yielding the most promising antifungal results [102]. Similarly, citrus essential oils blended with chitosan and locust bean gum have been reported to significantly inhibit the growth of *Aspergillus flavus* on dates, particularly when concentrations exceed 2%, thereby offering a natural alternative to synthetic antifungal agents [103].

Additional studies have emphasized the dual role of pomegranate peel (PoP) as both an antimicrobial and reinforcing agent in packaging materials. When incorporated into starch-based films, PoP not only inhibited the growth of both Gram-positive and Gram-negative bacteria but also enhanced mechanical properties, such as stiffness and tensile strength, by retaining its semi-crystalline structure within the film matrix [104]. Moreover, PoPE has been successfully applied in chitosan and alginate coatings on capsicum, where its antifungal properties, attributed to compounds like punicalagin, catechin, and rutin, preserved key physiological attributes and extended shelf life to 25 days [105]. Similarly, antimicrobial chitosan coatings carrying nisin, natamycin, PoPE, and grape seed extract have demonstrated significant preservation effects on strawberries stored at 4°C, with natamycin-containing formulations exhibiting superior performance in maintaining quality and reducing microbial load over a 40-day period [106].

In the context of active packaging, innovative strategies have also been reported using PCL films integrated with cinnamaldehyde (CNMA) and various pomegranate extracts, which delayed bacterial proliferation by controlling the release of active compounds over time [107]. Electrospun nanofiber membranes loaded with PoPE have shown promise as wound dressings due to their smooth morphology, sustained release profiles, potent antioxidant and antimicrobial activities, and favorable cellular compatibility [108]. Furthermore, composite facial mask materials produced by blending PoPE with polylactic acid (PLA) exhibited excellent mechanical and air permeability properties while providing antibacterial and antioxidant benefits, with significant inhibition rates against *Staphylococcus aureus* and *Escherichia coli* [109].

In a further development, active electrospun nanofibers composed of PLA and hydroxypropyl methylcellulose (HPMC), incorporating PoPE, have been optimized to

deliver enhanced hydrophilicity, thermal stability, tensile strength, porosity, and water vapor transmission rates, thereby improving both antioxidant and antibacterial properties. These nanofibers demonstrated an effective controlled release of PoPE and promising antimicrobial performance without cytotoxic effects, supporting their potential application in active packaging systems to extend food shelf life [110]. Additionally, studies have investigated the incorporation of *D. cinnabari* resin into chitosan/PCL nanofibers for wound healing, highlighting synergistic effects that enhance both antimicrobial activity and tissue repair, further validating the utility of natural compounds in biomedical applications [111].

Other research has focused on the development of antimicrobial composite materials for food packaging by integrating olive fruit polyphenols and citrus extracts encapsulated in maltodextrin into PLA nanocomposites, which exhibited enhanced antimicrobial activity against both Gram-positive and Gram-negative bacteria. This approach emphasizes the shift toward natural alternatives for food safety and shelf-life extension [112]. High-barrier PLA films enriched with cinnamaldehyde have also been formulated, demonstrating improved oxygen and water vapor barrier properties, increased tensile strength, and sustained antibacterial activity over prolonged periods, further supporting the efficacy of controlled-release packaging strategies [113]. Comparative studies on low-density polyethylene (LDPE) and PLA films incorporating grapefruit seed extract and thermoplasticized starch have underscored the critical role of polymer selection in achieving the desired antimicrobial and optical properties, with PLA-based systems showing superior performance in preventing bacterial growth in packaged food products [114].

Collectively, these research findings underscore the significant potential of natural additives—ranging from essential oils to fruit peels and extracts—in enhancing the antimicrobial, mechanical, and barrier properties of biodegradable packaging films. The integration of these natural compounds into polymer matrices not only improves the functional performance of the materials but also aligns with the increasing demand for sustainable, eco-friendly alternatives to synthetic additives, thereby contributing to improved food safety and extended shelf life.

3. MATERIALS AND METHOD

In this study, pomegranate peels were employed as a bioadditive to develop both textile coatings and food-packaging films. First, the peels were processed and prepared for use. Next, textile coatings incorporating the pomegranate peel powder were formulated and applied to fabric substrates. Finally, biodegradable packaging films were produced using the same peel-based additive. Each stage followed a standardized preparation protocol to ensure consistency across the different applications.

3.1. PREPARATION OF POMEGRANATE PEELS

Figure 3.1 shows the preparation stages of PoP as bioadditives in composite materials.

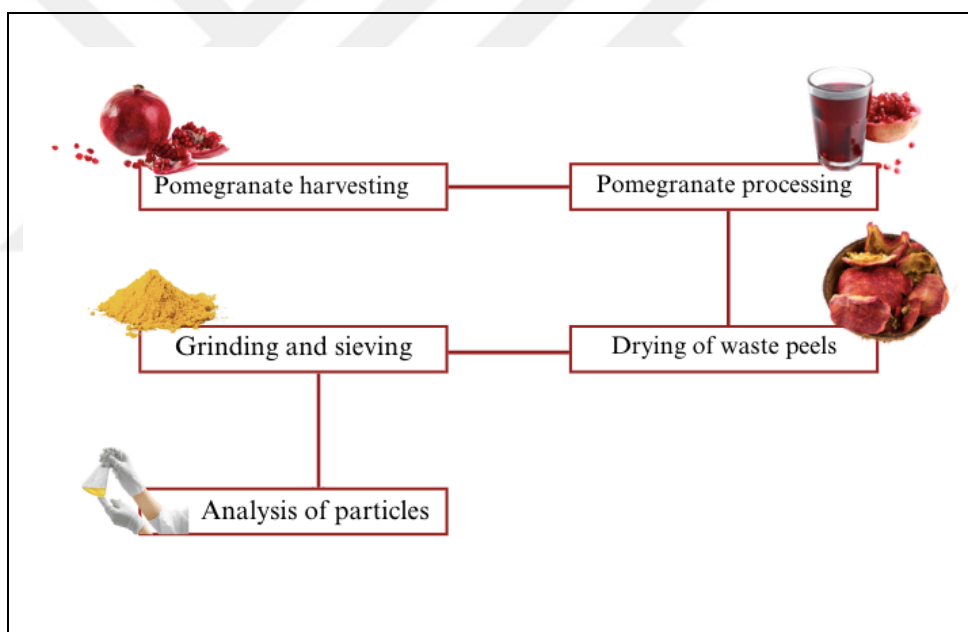


Figure 3. 1. Pomegranate processing by-products (peel, seed, pomace).

3.1.1. Preparation and Characterization of Pomegranate Peel Powders

In this study, pomegranate peels, which are generated as by-products in the fruit juice industry, were utilized as bioadditives. The peels were obtained from pomegranates cultivated in the İzmir region of Türkiye and subsequently dried in ambient air at 50 °C. As part of a waste valorization strategy, the collected pomegranate peels were subjected to a systematic preparation process involving drying, grinding, and sieving to obtain fine

powders suitable for composite applications. Following particle size classification, the powders underwent compositional and structural analyses to evaluate their suitability for further incorporation into polymer matrices. The aim of this preparatory step was to transform agricultural waste into functional bioactive powder for potential use in food packaging and textile coating applications.

Dried PoP was converted into a fine powder by processing it in a blade grinder (Demsan) for 2 minutes. Subsequently, the resulting powder was fractionated into distinct particle size ranges using a sieve winding device (Miprolab) in accordance with the BS-410-1 standard. Sieves with mesh sizes of 230 (63 μm), 200 (75 μm), 170 (90 μm), and 140 (106 μm) were utilized for this purpose. The powder retained on the 230 mesh (65 μm), 200 mesh (73 μm), and 170 mesh (90 μm) sieves was collected and designated as 75/63, 90/75, and 106/90, respectively. Figure 3.2 shows the PoP in different particle sizes.

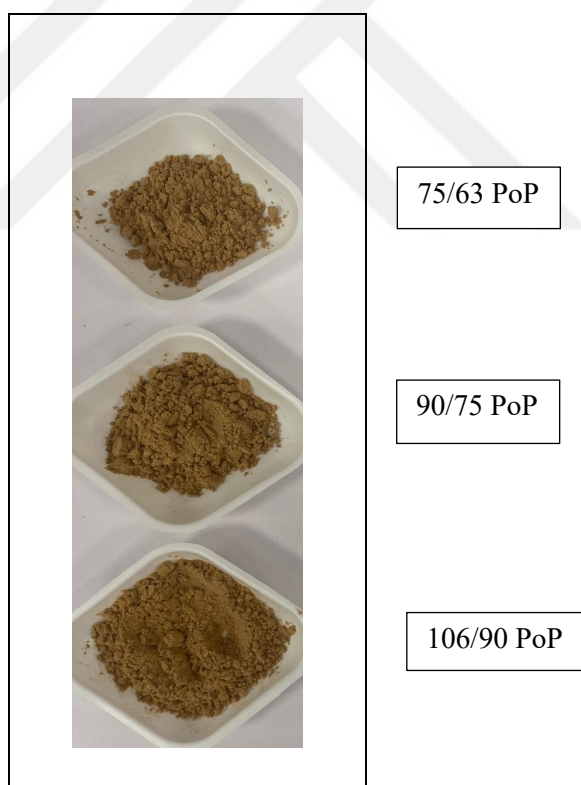


Figure 3. 2. PoP in different particle sizes.

3.1.2. Analyses of Pomegranate Peel Powders

Particle Size Measurement

The particle size distribution of these PoP powders was determined using a laser diffraction particle size analyzer (Mastersizer 3000, Malvern Panalytical), with each sample measured three times to ensure reliability. The parameters D_{10} , D_{50} , and D_{90} denote the particle diameters corresponding to 10%, 50%, and 90% of the cumulative volume, respectively, and are expressed in microns. Additionally, the uniformity of the particle sizes was quantified by calculating the particle size span, as defined in Equation (3.1) :

$$\text{Particle Size Span} = \frac{D_{90} - D_{10}}{D_{50}} \quad (3.1)$$

Moisture Content Measurement

Moisture content in the PoP powders was measured using an infrared heater moisture analyzer (Ohaus MB 45). For this analysis, a 2.5 g sample of the powder was initially heated to 150 °C and subsequently maintained at 105 °C for a duration of 3 minutes. The loss in mass during this process was used to calculate the moisture content, with the procedure being conducted three times to obtain an average value expressed as a percentage.

Water Activity Measurement

Water activity was determined at 25 °C using a water activity meter (Rotronic Hygropalm, Switzerland). Measurements were carried out in duplicate to ensure reproducibility and reliability of the results.

Water Binding Capacity

The water binding capacity of the PoP powders was evaluated following the method described by Jeong and Yoo. [115] In this procedure, 1 g of PoP powder was mixed with 10 mL of distilled water in a centrifuge tube. After vortexing the suspension for 10 seconds, the mixture was centrifuged at 700 g for 10 minutes. The supernatant was then carefully removed, and the tube was weighed again to assess the water retained by the powder. The water binding capacity was calculated as the grams of water absorbed per gram of PoP powder, and this measurement was repeated three times for consistency.

3.1.3. Preparation and Characterization of Pomegranate Peel Extract (PoPE)

Extraction was conducted using a shaking incubator set at 100 rpm and maintained at 25 °C for 24 hours, with a dried PoP-to-solvent ratio of 1:30 (w/v). Following the extraction period, the mixture was subjected to centrifugation at 9000 rpm for 15 minutes, and the supernatant was subsequently collected for analysis. Three different solvents—distilled water, 80% methanol, and 70% ethanol—were employed in this process. The extracts obtained from each solvent were then analyzed to determine their total phenolic content and antioxidant activity.

3.1.4. Quantification of Total Phenolic Content in the PoPE

The total phenolic content (TPC) of the PoP extract was quantified following the method proposed by Ertek et al. In this procedure, 200 μ L of the diluted extract was combined with 1 mL of a 0.2 N Folin–Ciocalteu reagent and 800 μ L of a 7.5% Na_2CO_3 solution. The reaction mixture was then incubated at 25 °C for 1 hour, after which its absorbance was recorded at 765 nm using a microplate UV–Vis spectrophotometer. The TPC was subsequently expressed in terms of milligrams of gallic acid equivalents per gram of dry matter (mg GAE/g).

3.1.5. Evaluation of Total Antioxidant Capacity of the PoPE

DPPH Radical Scavenging Activity

The antioxidant potential of the PoP extract was assessed via the DPPH assay following the procedure described by Kumaran et al. In this method, 0.1 mL of a 100-fold diluted PoP extract was mixed with 2 mL of a 0.1 mM DPPH solution in methanol. The reaction mixture was then kept in the dark at room temperature for 30 minutes to allow the reaction to proceed. The reduction in the DPPH radical was quantified by measuring the absorbance at 517 nm using a UV–visible spectrophotometer. The antioxidant activity was subsequently expressed as millimoles of Trolox equivalents per gram of sample (mM Trolox/g).

ABTS Radical Scavenging Activity

The ABTS assay was performed to evaluate the antioxidant capacity of the PoP extract, based on the method by Shi et al. Initially, the ABTS reagent was diluted with distilled water to prepare a working solution with an absorbance of 0.70 ± 0.02 at 734 nm. Subsequently,

20 μL of the PoP extract was combined with 200 μL of the ABTS⁺ working solution and allowed to react in the dark at room temperature for 30 minutes. The absorbance of the resultant solution was measured at 734 nm using a microplate reader. For comparison, a blank was prepared by replacing the 200 μL ABTS⁺ solution with water, while the control consisted of 20 μL of water mixed with 200 μL of ABTS⁺ solution. The percentage of ABTS⁺ radical scavenging activity was then calculated using the appropriate Equation 3.2.

$$ABTS^+ \text{ radical scavenging activity (\%)} = \left[1 - \left(A_s - \frac{A_0}{A_1} \right) \right] \times 100 \quad (3.2)$$

where A_s represents the absorbance measured for the PoP extract, A_0 corresponds to the absorbance of the blank sample, and A_1 denotes the absorbance of the control.

3.2. POMEGRANATE PEEL POWDER CONTAINING TEXTILE COATINGS

100% plain weave cotton fabrics were sourced from Pena Textile (Türkiye), featuring a weight of 124 g/m² and a thickness of 0.27 mm. The fabrics were constructed using yarns designated as Ne 40/1 for both warp and weft, with a warp density of 45 threads/cm and a weft density of 30 threads/cm. As the coating material, a waterborne polyacrylate polyurethane dispersion (WPU) from CHT Chemistry Company was employed. Figure 3.3 describes the preparation of textile coatings.

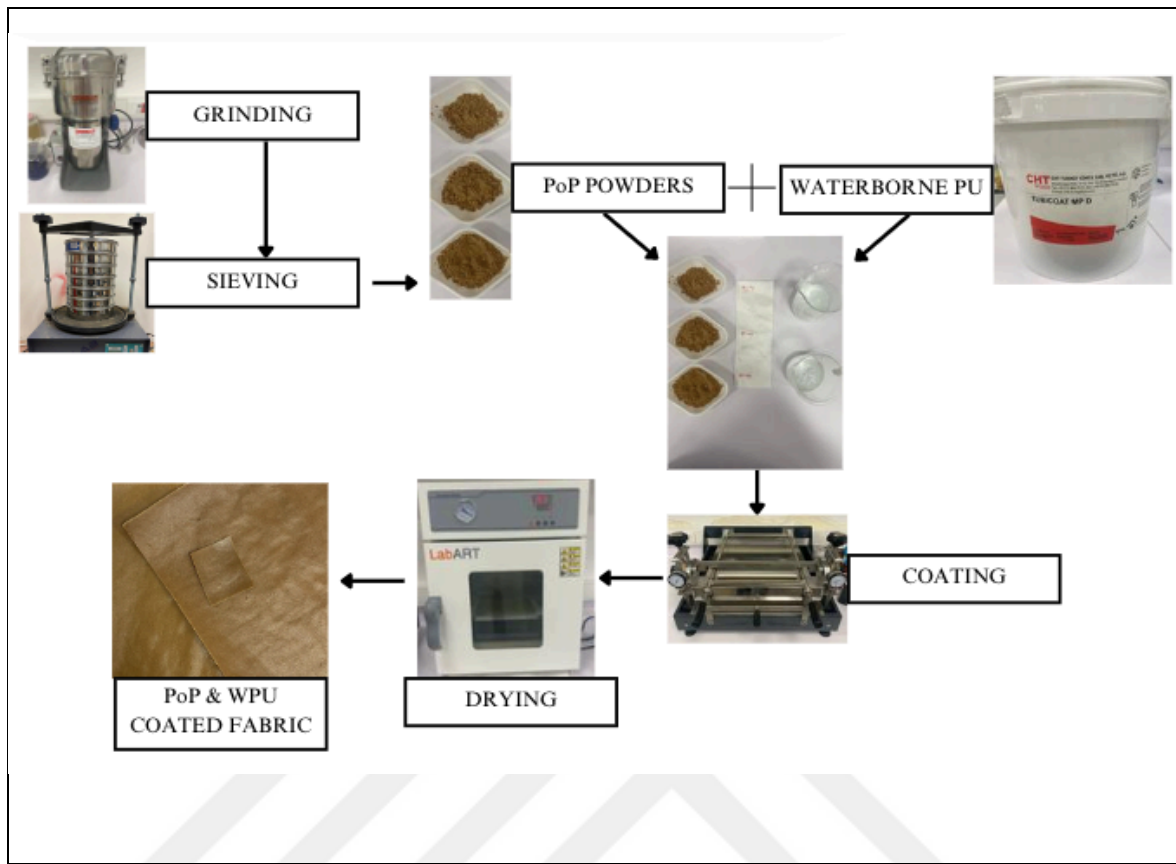


Figure 3. 3. Preparation of PoP/WPU Textile Coatings.

3.2.1. Fabric Coating

Pomegranate peel powders of varying particle sizes were incorporated into the waterborne polyacrylate polyurethane dispersion (WPU) at a 10% weight ratio and homogenized using a mechanical mixer for 30 minutes. Subsequently, the coating procedure was initiated by applying the first layer onto the fabric using a coating device (Ataç RKL 40) set to a 0.35 mm gap. The coated fabric was then dried in a preheated oven at 110 °C for 10 minutes.

Following the initial drying step, a second layer was applied using the same device, this time with the gap adjusted to 0.45 mm. The fabric was finally subjected to an additional drying cycle at 110 °C for 10 minutes to ensure complete curing of the coating layers. Figure 3.4 shows the three layers of the coating and Figure 3.5 shows the last product of the PoP&WPU textile coatings.

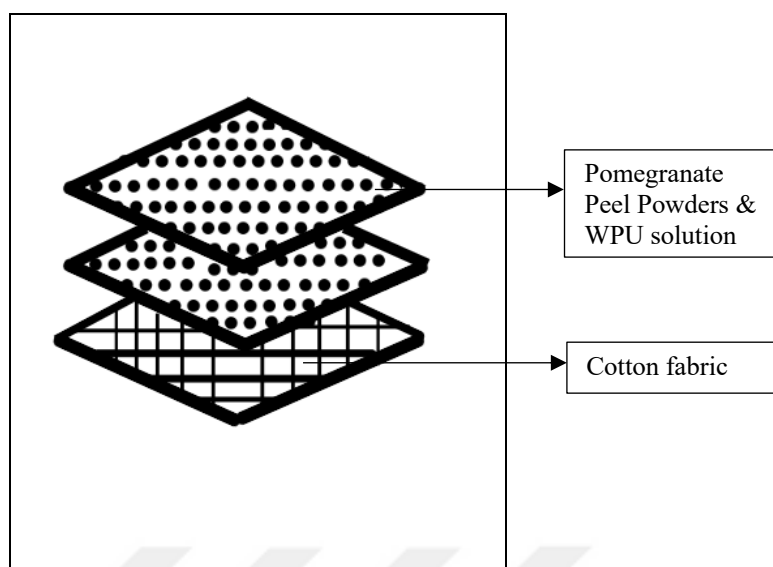


Figure 3. 4. Layers of the coating.



Figure 3. 5. Textile coatings with WPU&PoP.

3.2.2. Characterization and Analyzes of Coated Fabrics

FT-IR

The surface characteristics of the coated fabrics were examined using a Nicolet IS50 ATR Fourier Transform Infrared (FTIR) spectrometer, with transmittance data collected across the 500–4000 cm^{-1} frequency range. For morphological analysis, a ZEISS EVO40 scanning electron microscope (SEM) was utilized; prior to imaging, the samples were sputter-coated

with a palladium/gold layer, and micrographs were captured at magnifications of x250 and x1000.

Tensile Test

Mechanical properties, including fabric thickness and tensile strength, were evaluated in accordance with ASTM D751-19. Tensile tests were performed on an Instron 5966 machine, and both stress and strain values were calculated. The breaking strength was determined along the warp and weft directions, with each measurement repeated four times to obtain average values along with standard deviations.

Color Test

The color properties of the coated fabrics were assessed using a Konica Minolta CM-5 colorimeter, with color parameters reported as L* (lightness), a* (red/green), and b* (yellow/blue). Chroma (C*) and hue angle (°Hue) were computed using established Equations (3.3), (3.4), and the final color values represent the average of three independent replicates.

$$C^* = (a^2 + b^2)^{1/2} \quad (3.3)$$

$$^{\circ}\text{Hue} = \tan^{-1} \left(\frac{b}{a} \right) \quad (3.4)$$

Antibacterial Activity of PoP/WPU Coated Fabrics

The antibacterial efficacy of the fabrics was assessed using an inhibition zone method, adapted slightly from the procedure described by Atta et al. [116]. Two well-known pathogenic bacteria were employed in this evaluation: *Staphylococcus aureus* ATCC 6538, representing Gram-positive bacteria, and *Pseudomonas aeruginosa* ATCC 15442, representing Gram-negative bacteria. Initially, bacterial cultures were grown on solid agar media. A single colony from each bacterium was then transferred into a tube containing sterile Tryptic Soy Broth (TSB) and incubated for 18 hours at 37 °C. After incubation, the bacterial suspensions were homogenized, and 1 mL aliquots were placed in sterile Eppendorf tubes and centrifuged to collect the bacterial pellets. These pellets were re-suspended in fresh

TSB, then transferred into a glass tube containing TSB and diluted to achieve a concentration of approximately 10^6 CFU/mL.

Each bacterial strain was separately spread onto culture plates using the spreading method. Disks with a 6 mm diameter, prepared from coated fabric samples, were then placed on the surface of these inoculated petri dishes. Following an incubation period of 24 hours at 37 °C, the diameters of the inhibition zones around the disks were measured with a digital micrometer (Absolute Digimatic, Germany). The inhibition zone diameter was recorded in millimeters (mm) as an indicator of the antimicrobial activity of the coated fabrics.

Statistical Analysis

Results are reported as mean $\pm$ standard deviation. All experiments were conducted at least in triplicate, and data were analyzed using ANOVA with SPSS 20.0. Significant differences among group means ($P < 0.05$) were evaluated via Duncan's multiple range tests, while Pearson's correlation analysis was employed to examine the relationships between the various parameters.

3.3. POMEGRANATE PEEL POWDER CONTAINING PACKAGING MATERIALS

In this study, a range of equipment was utilized, including a rotary evaporator, filtration paper, magnetic stirrer, heater, beaker, petri dish, thermocouple, pipette, precision scale, ultrasonic bath, vacuum oven, vacuum pump, falcon tubes, grinder, transfer paper, funnel, and a sieve shaker. Poly(ϵ -caprolactone) (PCL) with an average M_n of 80,000 (2-Oxepanone homopolymer, 6-Caprolactone polymer) was sourced from Sigma-Aldrich, and chloroform was obtained from Carlo Erba. Additionally, pomegranate peels, ethanol, and distilled water were employed as reagents.

Film production was carried out with a transfer coating device, by using transfer papers and PCL solution was coated and dried on special non-stick papers. Initially, the optimal coating thickness was established, after which the transfer paper was positioned between the rollers, and the polymer solution was applied onto the transfer paper to form the coating. Figure 3.6 describes the preparation method of the PoP&PCL packaging films.

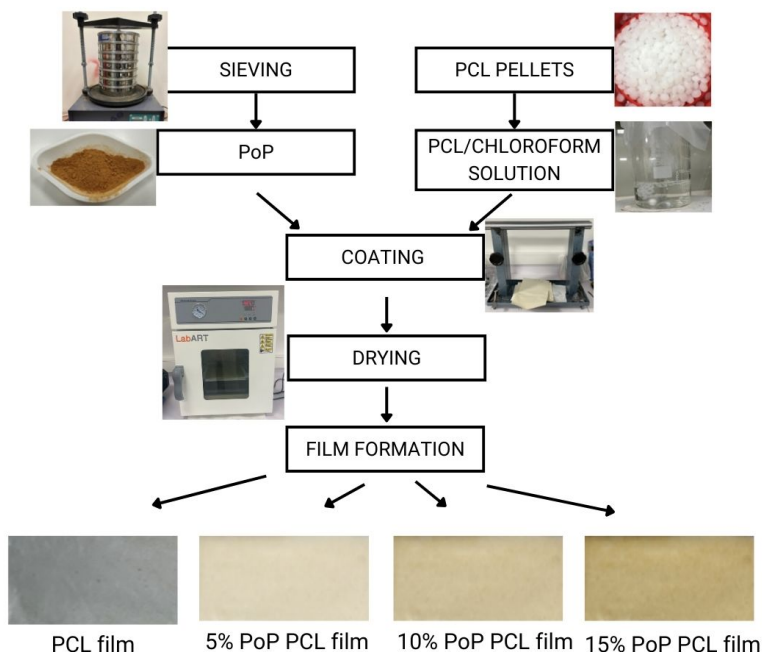


Figure 3. 6. Preparation of PoP/PCL Films.

3.3.1. Preparation of PCL/Chloroform Solution

To prepare the solutions, a 5% concentration of PCL was employed in accordance with previous studies [80]. Initially, 1 gram of PCL pellets was precisely weighed into separate measurement cups using a precision balance. Next, a beaker was placed on the balance to measure 19 grams of chloroform. This procedure was repeated six times, resulting in six sets, each consisting of 1 gram of PCL and 19 grams of chloroform. Within a fume hood, stirrers were preheated to 30 °C, and the beakers were positioned on these stirrers. Each beaker was assigned an individual stir bar, and the stirring speed was set to 400 rpm. The PCL was then incrementally added to the chloroform in roughly 0.25 g portions over four sessions. Once all the polymer was added, the beaker mouths were securely sealed, and the stirring process was continued for 24 hours.

3.3.2. Mixing of Pomegranate Peel Powders with the PCL Solution

To assess the effects of different concentrations of pomegranate peel powder on biodegradability and antibacterial performance, an experimental design was developed. Pomegranate peel powders with a particle size range of +63 to -75 microns were selected for the study. Two distinct formulations were prepared, targeting 10% and 15% ratios, respectively, based on the solid content of the PCL/chloroform solution with an emphasis on the PCL fraction. Specifically, 0.5 g of pomegranate peel powder was incorporated for the 10% formulation, whereas 0.75 g was used for the 15% formulation. Each formulation was prepared in separate beakers, and the powders were blended with the solvent mixture using a mechanical stirrer for 5 minutes to ensure uniform dispersion throughout the solution.

3.3.3. Coating/Drying

The coating process was carried out using a transfer coating device, as shown in Figure 3.4. Initially, the gap between the two cylinders was set to 0.40 mm to ensure precise control over the coating thickness. To facilitate the transfer of the coating onto the transfer paper, the paper was positioned between the cylinders, with a small section tucked beneath to secure it, while the area designated for coating remained exposed above the rollers. Next, a mixture of pomegranate peel powders and the PCL/Chloroform solution was poured onto the transfer paper from the top, and the coating was applied by drawing the remaining portion downward. After application, the coated surface was dried in an oven at 40°C for 5 minutes to allow for complete chloroform evaporation. Once dried, the transfer paper was removed, resulting in the films listed in Figure 3.4. This entire procedure was repeated for all prepared solutions.

3.3.4. Characterization and Analyzes of Packaging Films

FT-IR

Surface analysis of the packaging films and pomegranate samples was conducted using a Nicolet IS50 ATR Fourier Transform Infrared (FT-IR) spectrometer. Transmittance data were collected over the spectral range of 500–4000 cm^{-1} . Prior to measurement, the sample placement area was meticulously cleaned to ensure proper contact with the probe. The instrument's software then processed the data, yielding the final analytical results.

Water Contact Angle

Water contact angle (WCA) measurements were conducted using a Biolin Scientific goniometer equipped with a 360° rotating stage, based on the pendant drop method. Prior to each measurement, the instrument was carefully calibrated using a spirit level to ensure precise alignment of the sample stage. The optical axis of the camera system was adjusted for sharp and symmetrical droplet profiling. Distilled water was filled into a clean glass beaker, and subsequently drawn into the pipette that was mounted on the dispensing unit of the device. For all measurements, the droplet volume was set to 18 μL , which was achieved by increasing the droplet size at a controlled rate of 1 $\mu\text{L/s}$. The dispersion rate and fill rate of the system were adjusted to 5 $\mu\text{L/s}$ and 20 $\mu\text{L/s}$, respectively, to ensure smooth droplet formation without turbulence or pre-detachment. Each sample film was sequentially positioned directly beneath the pipette tip and aligned with the center of the camera's field of view. Image acquisition was performed at a frame rate of 33 frames per second, capturing the droplet's geometry during deposition. Contact angle values were calculated by the system software based on the droplet profile and fitting algorithms, and all measurements were conducted under ambient laboratory conditions.

Thermal Characterization of Packaging Films

A Perkin Elmer Pyris 1 thermogravimetric analyzer (TGA) was employed to monitor the weight changes of the films as a function of temperature and time under controlled conditions. Approximately 5 to 6 mg of each film sample was placed in an alumina crucible for analysis. The experiments were performed under a nitrogen atmosphere with a constant flow rate of 20 mL/min, and the samples were heated from 25 °C to 550 °C at a rate of 10 °C/min.

Antibacterial Testing of Packaging Films

To assess the antibacterial activity of the produced PCL-based packaging films containing varying ratios of pomegranate peel (PoP), the zone of inhibition method was employed. The methodology followed the procedure previously described in section 3.2.2.4, where the standard disk diffusion technique was applied using *Staphylococcus aureus* ATCC 6538 (Gram-positive) and *Pseudomonas aeruginosa* ATCC 15442 (Gram-negative) bacterial strains. Circular film samples were prepared in consistent dimensions and placed onto inoculated agar surfaces. Following incubation at 37 °C for 24 hours, the diameter of the inhibition zones around the film samples was measured using a digital micrometer, and the

results were recorded in millimeters. This procedure was applied to all film formulations (PoP-5, PoP-10, and PoP-15) to evaluate their antibacterial effectiveness.



4. RESULT AND DISCUSSION

In this section, the findings obtained throughout the study are systematically presented and interpreted. Initially, structural, and functional properties of pomegranate peel (PoP) powders were characterized in detail. Following this, the performance of textile coatings prepared by incorporating PoP into a waterborne polyurethane (WPU) matrix and applied onto cotton fabrics was examined through a series of analytical methods. Finally, packaging films produced by blending PoP powders with a polycaprolactone (PCL) matrix were evaluated. All results were interpreted comparatively, highlighting the influence of PoP content and its potential role as a bioadditive in different polymer systems and applications.

4.1. ANALYSIS OF POMEGRANATE PEEL POWDERS

4.1.1. Particle Size Analysis of PoP Powders

The particle size analysis of PoP powders was conducted using a laser diffraction particle size analyzer, with the resulting data summarized in Figure 4.1. The analysis revealed that by employing standard sieves with mesh sizes of 230 (63 μm), 200 (75 μm), 170 (90 μm), and 140 (106 μm), it was possible to fractionate the powders into distinct groups based on their size distribution. For example, the fraction labeled 75/63—comprising powder that passed through the 200 mesh sieve and was retained on the 230 mesh sieve—displayed a particle size range from 18.2 to 81.7 μm . In comparison, the 90/75 fraction had a range of 29.7–103.9 μm , and the 106/90 group ranged from 30.5 to 136.7 μm . Moreover, the calculated particle size spans indicated similar distribution patterns across the different groups. These findings confirm that sieve separation, coupled with laser diffraction measurements, effectively delineates PoP powders into groups with distinct particle size distributions ($P < 0.05$).

Table 4. 1 Particle Size Analysis of different particle size of PoP

	D10 (μm)	D50 (μm)	D90 (μm)	Particle Size Span
75/63	18.2 ± 0.1^c	42.8 ± 0.1^c	81.8 ± 0.1^c	1.5
90/75	29.7 ± 0.2^b	58.0 ± 0.1^b	103.9 ± 3.8^b	1.3
106/90	30.5 ± 0.2^a	74.3 ± 0.2^a	136.7 ± 0.6^a	1.4

^{a-b} Different letters at the same column indicate statistically significant differences between the groups ($P < 0.05$).

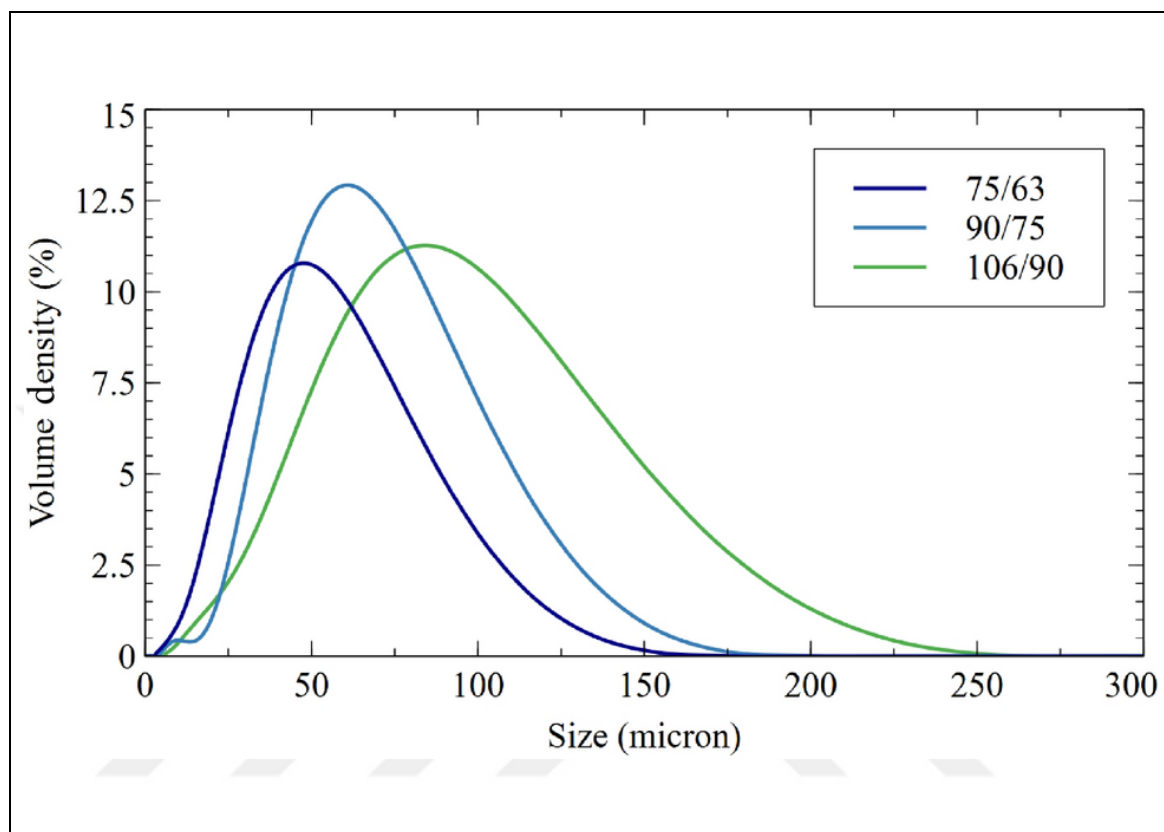


Figure 4. 1. Particle size analyses of PoP.

4.1.2. Moisture Content, Water Activity and Water Binding Capacity of PoP Powders

The quality of fruit powders is frequently gauged by parameters such as moisture content and water activity, which are essential for evaluating the efficiency of drying processes [118]. In this study, the moisture content of pomegranate peel (PoP) powders, stratified by particle size, ranged from 4.26% to 6.05% (refer to Table 4.1). A statistically significant increase in moisture content was observed as the particle size decreased ($P < 0.05$), which may be attributed to a reduction in hydrophobicity with smaller particles. Additionally, powders with lower moisture levels are prone to greater water absorption due to higher concentration gradients between the product and the surrounding environment, thereby exhibiting enhanced hygroscopicity.

Table 4. 2. Moisture content, Water activity and Water binding capacity of the PoP.

PoP Powders	Moisture Content (%)	Water Activity	Water Binding Capacity (g water/g powder)
75/63	6.05 ± 0.15 ^a	0.530 ± 0.009 ^a	3.382 ± 0.0018 ^a
90/75	4.74 ± 0.01 ^b	0.497 ± 0.001 ^b	3.002 ± 0.071 ^b
106/90	4.26 ± 0.20 ^c	0.482 ± 0.001 ^b	2.879 ± 0.057 ^b

^{a-b} Different letters at the same column indicate statistically significant differences between the groups ($P < 0.05$).

Water activity measurements for the PoP powders varied between 0.482 and 0.530, with the highest value recorded for the 75/63 fraction ($P < 0.05$, see Table 2). For context, Galaz et al. [119] reported moisture content and water activity values of 5% and 0.39, respectively, for PoP dried using a drum dryer at 100°C; these differences are likely due to variations in drying techniques and operational temperatures.

The water binding capacity (WBC) of the PoP powders was determined to be between 2.879 and 3.382 g water per gram of powder, with the finest particles exhibiting the highest WBC ($P < 0.05$). A strong positive correlation was found between moisture content and both water activity ($r = 0.969$) and WBC ($r = 0.981$), while a significant negative correlation ($r > 0.915$) was observed between moisture content and particle size.

Overall, the moisture content of the PoP powders, ranging from 3.69% to 5.84%, meets the desired criteria of less than 6%, making them suitable for long-term storage. Furthermore, powders with higher moisture content demonstrated improved water binding capacity. In comparison, recent studies by Mall and Patel [120] and Hasnaoui et al. [121] reported water absorption indices of 4.83 g/g and 3.53 g/g, respectively, which may be due to differences in the pomegranate peel varieties employed.

4.1.3. Total Phenolic Content and Antioxidant Activity of PoP Powders

Pomegranate peel (PoP) is recognized for its abundance of phenolic compounds and antioxidants, which contribute significantly to its bioactivity and wide-ranging applications. [122] Notably, the peel exhibits higher phytonutritional value and more pronounced pharmaceutical and nutraceutical properties compared to the edible arils of the fruit. [123]

In vitro antioxidant potential of PoP is commonly evaluated using radical scavenging assays such as DPPH and ABTS. As shown in Table 3, total phenolic content (TPC) and antioxidant

activity (AA) varied across samples with different particle sizes. TPC values ranged from 605.9 to 1152.8 mg GAE/g, with the highest phenolic content observed in samples with finer particle sizes and extracted using methanol. A parallel trend was observed in antioxidant capacity measured via both DPPH and ABTS methods, indicating enhanced activity in correlation with decreasing particle size.

Table 4. 3. Total phenolic content (TPC) and antioxidant activity (AC) of PPEs.

PPE*	TPM (mg GAE/g)	AA	
		DPPH (mM TE/g)	ABTS (%)
Water-A	874.5 ± 16.0 ^d	337.1 ± 11.1 ^d	42.3 ^f
Water-B	677.1 ± 56.3 ^e	247.6 ± 4.2 ^e	33.5 ^g
Water-C	605.9 ± 13.7 ^f	212.7 ± 10.1 ^f	26.9 ^h
EtOH-A	1042.7 ± 8.5 ^b	396.1 ± 18.1 ^b	51.4 ^b
EtOH-B	1028.6 ± 20.6 ^b	377.5 ± 0.4 ^{bc}	48.8 ^c
EtOH-C	901.2 ± 48.2 ^d	349.1 ± 38.7 ^{cd}	45.0 ^c
MeOH-A	1152.8 ± 6.1 ^a	425.6 ± 21.2 ^a	51.9 ^a
MeOH-B	1106.4 ± 39.1 ^a	391.6 ± 2.4 ^b	51.8 ^a
MeOH-C	953.4 ± 1.6 ^c	352.6 ± 1.9 ^{cd}	45.4 ^d

^{a-b} Different letters at the same column indicate statistically significant differences between the groups ($P < 0.05$).

The antioxidant activity present in various fruit and vegetable extracts is largely attributed to their content of bioactive compounds, particularly phenolic compounds and flavonoids. [124] Numerous scientific investigations have confirmed the association between phenolic content and antioxidant potential. [125] In the current study, a significant increase in both total phenolic content (TPC) and antioxidant activity (AA) was observed as the particle size of pomegranate peel (PoP) decreased, regardless of the solvent used for extraction ($P < 0.05$). Moreover, a strong positive correlation ($r = 0.973$) was found between TPC and AA, suggesting that phenolic compounds are the primary contributors to the antioxidant capacity of PoP extracts.

Numerous investigations have examined the total phenolic content (TPC) and antioxidant activity of pomegranate peel (PoP) powders in the literature. For example, Singh et al. [126] reported a TPC value of 155.78 mg GAE/g for PoP. In a comparative study conducted by Azmat et al. [127], it was demonstrated that acetone extracts yielded the highest TPC (427.2 mg GAE/g extract) when compared to those obtained using methanol (367.9 mg GAE/g), ethanol (361.8 mg GAE/g), and water (273.5 mg GAE/g). Similarly, Sweidan et al. [128]

determined that ethanolic PoP extracts contained 297.7 mg GAE/g of phenolic compounds. With respect to antioxidant activity, their study also showed that water-based extracts provided the greatest DPPH radical scavenging effect (9.43 ± 0.06 $\mu\text{mol TE/g dry weight}$), whereas both methanolic and ethanolic extracts achieved the highest ABTS⁺ radical inhibition values (11.09 ± 0.02 and 11.09 ± 0.06 $\mu\text{mol TE/g dry weight}$, respectively). Furthermore, Singh et al. [126] reported a notably high TPC range for PoP, varying between 4892.00 and 6138.2 mg per 100 g of peel.

Studies have indicated that the efficiency of extracting phenolic compounds from pomegranate peel (PoP) varies significantly depending on the solvent used. Ethanol-based extractions generally yielded lower phenolic content when compared to methanol and water extractions, likely due to ethanol's limited polarity. Supporting this, Kumar et al. [127] demonstrated that methanol, owing to its high polarity, was more effective in extracting key compounds such as gallic acid, ellagic acid, quercetin, and punicalagin from PoP. Similarly, Tabaraki et al. [129] reported antioxidant activity (AA) ranging between 60.1% and 83.5% in PoP extracts from Iranian cultivars. Vacuum–microwave-dried PoP extracts were also found to possess substantial AA levels, ranging from 64.21% to 74.39% [123]. In further investigations by Abid et al. [131], DPPH radical scavenging activities for water, ethanol, and acetone extracts were measured at 71.11–84.16%, 71.73–96.73%, and 77.32–97.82%, respectively. Similarly, Yassin et al. [132] noted that methanolic and acetonetic extracts exhibited high radical scavenging efficiencies of 79.4% and 86.9%, respectively.

The total phenolic content (TPC) of PoP extracts has been widely studied, showing significant variation based on solvent type and processing conditions. For example, air-dried PoP at 60 °C yielded TPC values of 4720 mg GAE/100 g using methanol, 2320 mg GAE/100 g using ethanol, and 4650 mg GAE/100 g using water [133]. Another study recorded TPC and AA values between 276–413 mg GAE/g and 45–58%, respectively [134]. Campos et al. [135] found TPC levels ranging from 160 to 730 mg GAE/g, while Zahed et al. [136] reported 589.31 mg GAE/100 g for ethanolic PoP extract. Feng et al. [137] documented values of 335.6 and 333.9 mg GAE/g for 80% ethanol and water extracts, respectively, and Mansour et al. [138] observed 230.4 mg GAE/g for methanol-extracted PoP. Notably, Okumuş and Bakkalbaşı [139] revealed a broad TPC range of 84.15 to 28,611.11 mg GAE/100 g depending on source and method. Further results include 867 mg GAE/g by

Ibrahim [140], 63.2 mg GAE/g TPC and 312.52 mg TE/g AA by Mall and Patel [120], and 522.82 ± 6.94 mg GAE/g by Yang et al. [141]

Kam et al. [142] also showed that methanolic PoP extracts obtained from three different countries displayed varying phenolic levels ranging between 201.5 ± 5.7 and 629.5 ± 5.2 mg GAE/g. These disparities underline the impact of several factors—such as fruit variety, harvesting conditions, maturity level, drying technique, and solvent type—on both TPC and antioxidant efficacy. In support of this, Laroze et al. [143] reported that in polyphenol extraction from raspberry pomace, finer particle sizes (0.15–1 mm) significantly enhanced extraction efficiency under methanol, due to increased surface area, improved solvent penetration, and higher degrees of cell wall disruption, thereby facilitating greater release of bioactive compounds.

4.2. ANALYSIS OF TEXTILE COATINGS

During the fabrication of the coated textiles, only PoP powders with varying particle sizes were incorporated, while all other production parameters remained unchanged. The thickness of the coated fabrics was determined following the ASTM D751-19 standard, with the results presented in Table 4.2. The samples prepared using PoP powders with particle sizes of 75/63, 90/75, and 106/90 were designated as PoP75/63-WPU, PoP90/75-WPU, and PoP106/90-WPU, respectively.

Table 4. 4. Textile coating samples, PoP powder ratios, particle size ranges, coated fabric thickness.

Sample name	PoP powder ratio (wt%)	Particle size range (μ)	Coated fabric thickness (mm)
PoP75/63-WPU	10	18.2–81.7	0.8
PoP90/75-WPU	10	29.7–103.9	0.8
PoP106/90-WPU	10	30.5–136.7	0.8

4.2.1. FTIR Analysis of the Textile Coating

FTIR spectra were recorded for the PoP75/63-WPU, PoP90/75-WPU, and PoP106/90-WPU samples, along with a reference sample of WPU-coated fabric without any PoP (designated as WPU-C in Fig. 2). Given that the spectra for PoP75/63-WPU, PoP90/75-WPU, and

PoP106/90-WPU were almost identical, only a single representative spectrum for the PoP-containing coating (referred to as PoP-WPU in Fig. 2) is displayed. Additionally, the FTIR spectrum of the PoP powder itself is presented for further comparison.

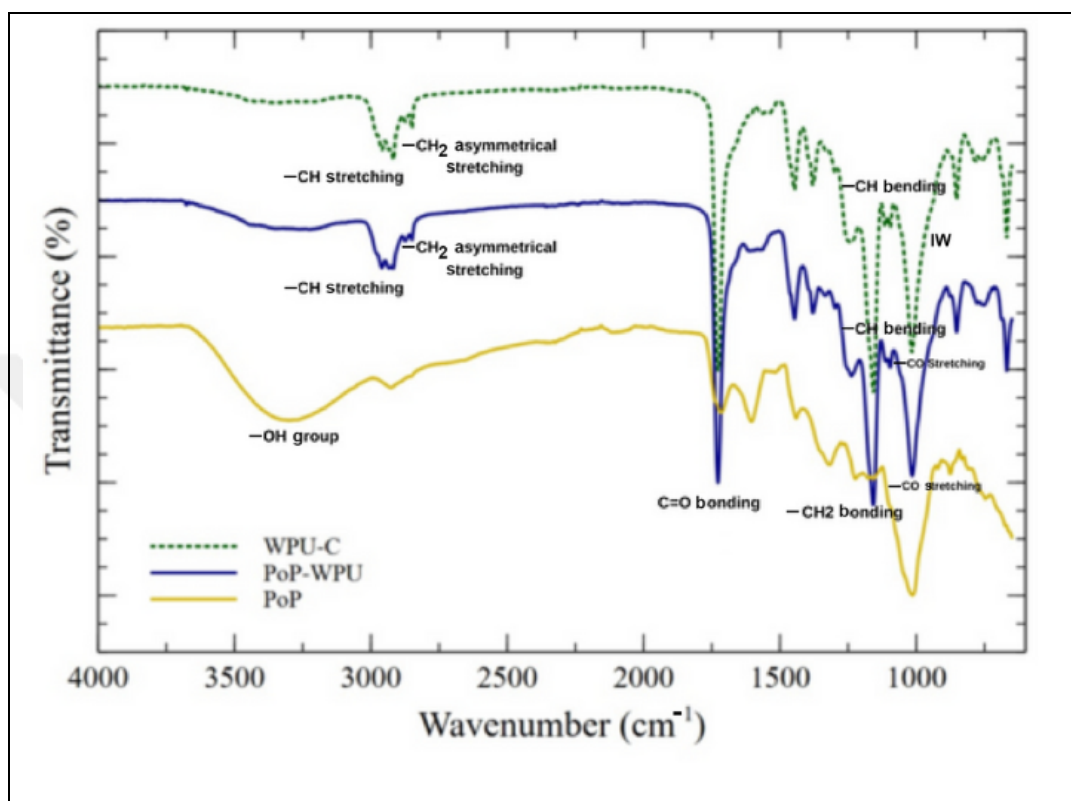


Figure 4. 2. FT-IR Results of textile coating.

The FTIR spectra for both PoP-WPU and WPU-C reveal distinct absorption features that correspond to specific chemical bonds. For instance, a prominent peak at 2937 cm^{-1} is attributed to -CH stretching, and the interval between 2937 and 2850 cm^{-1} corresponds to the asymmetrical stretching of -CH_2 groups. Additional characteristic bands include those between 1710 and 1690 cm^{-1} , which are indicative of C=O bonds, as well as peaks in the $1480\text{--}1450\text{ cm}^{-1}$ range for -CH_2 bending. Other notable absorptions are observed between 1370 and 1320 cm^{-1} (related to -CH bending), at 1150 cm^{-1} for C-O stretching of an ether group, and around 1000 cm^{-1} corresponding to C-C stretching vibrations. These features are consistently present in both the PoP-WPU and the WPU-C samples.

However, a marked difference is evident in the -OH region; the PoP-WPU sample, which includes pomegranate peel powders, exhibits a significantly more pronounced -OH signal. In the pure PoP powders, a broad band ranging from 3100 to 3700 cm^{-1} , centered at

approximately 3332 cm^{-1} , confirms the abundant presence of hydroxyl functional groups. Therefore, the addition of PoP powders to the WPU formulation results in a more distinct –OH signature on the surface of the coated fabric, reflecting the enhanced incorporation of bioactive components.

4.2.2. SEM of the Textile Coating

Figure 4.2. presents SEM micrographs of the PoP75/63-WPU, PoP90/75-WPU, and PoP106/90-WPU samples captured at $250\times$ and $1000\times$ magnifications. The cross-sectional images reveal the internal woven cotton fabric structure as well as the overlaying WPU coating infused with PoP powders, clearly illustrating the composite nature of the coated fabrics.

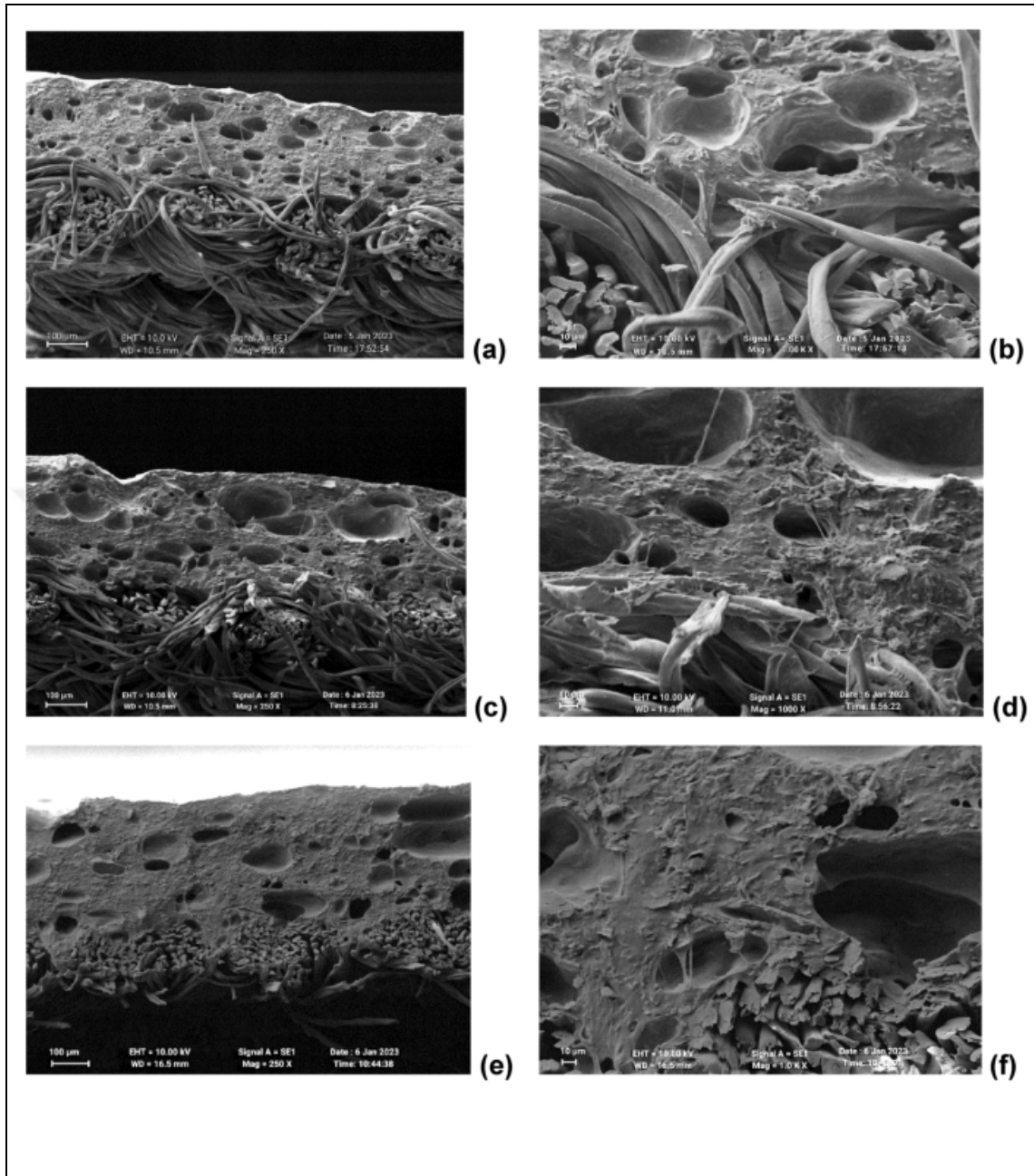


Figure 4. 3. SEM image of PoP75/63-WPU at x250 (a), PoP75/63-WPU at x1000 (b), PoP90/75-WPU at x250 (c), PoP90/75-WPU at x1000 (d), PoP106/90-WPU at x250 (e), PoP106/90-WPU at x1000 (f).

WPU used in this study is a dispersion that forms microporous structures in textile coatings. Despite the inclusion of pomegranate peel (PoP) powders of various sizes, no significant differences in pore formation were observed in the coatings (Fig. 4.3.).

At higher magnifications (Figs. 4.3.b, 4.3.d, 4.3.f), the interface between the cotton fibers and the polymer coating is clearly visible. These close-up images reveal that the WPU

coating thoroughly covers the fiber surfaces, indicating excellent adhesion between the polymer and the cotton substrate.

4.2.3. Color Measurement of the Textile Coatings

Incorporation of PoP powders as natural colorants is a well-established approach in textile dyeing [144-150].

In this investigation, the color properties of the WPU-coated fabrics containing PoP powders of different particle sizes were evaluated to determine their influence on the final appearance of the coating.

Table 4.4 presents the color metrics of the coated fabrics. Regarding lightness (L^*), a decrease in particle size from the 90/75 fraction to the 75/63 fraction resulted in a statistically significant increase in surface brightness ($P < 0.05$). Conversely, no significant variations were observed in the a^* values, which represent the red-green component, as particle size decreased. However, the b^* values, indicative of yellowness, showed a significant increase for the 75/63 fraction ($P < 0.05$), suggesting a shift toward a more yellow hue. Additionally, the chroma (C^*) values, which denote color intensity, increased with decreasing particle size ($P < 0.05$), and a strong negative correlation ($r > 0.87$) was found between chroma and particle size. The hue angle, which differentiates between red and yellow tones, remained statistically unchanged among the samples ($P > 0.05$), with all treated fabrics falling within a color range from red to yellow.

Table 4. 5. Color measurement of the textile coating.

Sample	L^*	a^*	b^*	C^*	Hue°	Color
PoP75/63WPU	50.6 ± 0.7^a	6.0 ± 0.0^a	24.4 ± 0.7^a	25.1 ± 0.7^a	76.2 ± 0.0^a	
PoP90/75WPU	48.4 ± 0.1^b	5.8 ± 0.1^a	22.7 ± 0.1^b	23.5 ± 0.1^b	76.1 ± 0.0^a	
PoP106/90WPU	49.6 ± 0.9^{ab}	5.8 ± 0.3^a	22.0 ± 0.5^b	22.70 ± 0.5^b	76.1 ± 0.0^a	

^{a-b} Different letters at the same column indicate statistically significant differences between the groups ($P < 0.05$).

In one study, Galaz et al. [119] reported that pomegranate peel (PoP) dried in a drum dryer at 100°C exhibited L^* , a^* , and b^* values of 30.89, 1.88, and 5.67, respectively. In contrast, Karakuş et al. [75] found that the L^* and a^* values of PoP-based films remained unchanged with decreasing particle size. Additionally, Rahman et al. [151] observed that cotton fabrics

treated with an aqueous pomegranate extract displayed L^* , a^* , b^* , C^* , and hue values of 79.4, 5.36, 16.11, 16.98, and 71.6° , respectively. Furthermore, Dundar et al. [152] reported that the ethanolic (70%) PoP extract resulted in L^* , a^* , and b^* values of 32.89, 17.3, and 21.2, respectively.

4.2.4. Tensile Strength of the Textile Coating

Table 4.3. presents the stress and strain measurements for the PoP75/63-WPU, PoP90/75-WPU, and PoP106/90-WPU samples. It was observed that both stress and strain values were higher in the warp direction than in the weft direction, which can be attributed to the greater yarn density in the warp of the cotton fabric. Consequently, in the weft direction, the stress values were found to be approximately 15–16 MPa, while the elongation values ranged between 7% and 9%.

Table 4. 6. Tensile test results of the textile coating.

	Stress (MPa)	Strain (%)
PoP75/63-WPU Warp	20.0 ± 2.3^a	27.0 ± 0.6^b
PoP90/75-WPU Warp	20.1 ± 0.4^a	28.8 ± 0.2^a
PoP106/90-WPU Warp	18.4 ± 2.9^a	24.4 ± 1.3^c
PoP75/63-WPU Weft	16.3 ± 1.4^b	7.6 ± 1.3^e
PoP90/75-WPU Weft	16.5 ± 0.8^b	7.5 ± 0.2^e
PoP106/90-WPU Weft	15.8 ± 0.8^b	9.2 ± 0.6^d

^{a-c} Different letters in the same column indicate statistically significant differences between the groups ($P < 0.05$).

In the warp direction, all three sample groups exhibited higher tensile properties. Although the PoP75/63-WPU and PoP90/75-WPU samples reached strength values of approximately 20 MPa, the PoP106/90-WPU sample—with the larger filler particles—displayed slightly lower strength. However, statistical analysis revealed no significant differences among the three formulations. This indicates that when employing three distinct particle sizes as fillers, the resulting tensile strength remains comparable regardless of particle size.

Furthermore, unlike the weft direction, the warp direction demonstrated substantially higher elongation values, ranging from 24% to 29%. Overall, these observations suggest that the coated fabrics, irrespective of the particle size of the filler, exhibit similar stress and elongation properties, emphasizing that the mechanical behavior of the coatings is primarily dictated by the inherent characteristics of the woven fabric substrate.

4.2.5. Antibacterial Activity of the Textile Coatings

The antimicrobial efficacy of PoP is primarily attributed to its rich composition of bioactive constituents, including tannins—particularly punicalagins—and polyphenols, such as ellagic acid. These compounds exert their antibacterial effects through a variety of mechanisms, including the inhibition of microbial enzymes, disruption of membrane fluidity, and induction of membrane damage in pathogenic cells [153]. A multitude of studies have demonstrated that incorporating PoP extract into various film matrices effectively suppresses the growth of both Gram-positive and Gram-negative bacteria, such as *Escherichia coli*, *Pseudomonas* spp., *Salmonella* spp., *Staphylococcus aureus*, *Bacillus cereus*, and *Listeria monocytogenes* [154].

The antibacterial performance of fabrics coated with PoP powder was assessed against *Staphylococcus aureus* and *Pseudomonas aeruginosa* using an inhibition zone assay, with the outcomes presented in Table 4.7. and Fig. 4.4. The results indicate that all coated fabrics containing PoP exhibited significant antibacterial activity against *S. aureus*, with larger inhibition zones observed as the particle size of the PoP powder decreased ($P < 0.05$). These observations are consistent with previous research underscoring the efficacy of PoP extracts against both *S. aureus* and *P. aeruginosa*. Notably, strong positive correlations were found between the inhibition zone diameters for *S. aureus* ($r > 0.893$) and *P. aeruginosa* ($r > 0.850$) and the total phenolic content of the PoP extract. Similarly, a robust positive correlation was observed between antioxidant capacity and antibacterial activity, with correlation coefficients exceeding 0.806 and 0.903, respectively. These findings are in line with earlier studies [155] that reported a strong association between the antimicrobial properties of plant extracts and their overall phenolic content.

Table 4. 7. Antibacterial activity of textile coatings.

	S. aureus	P. aureginosa
PoP75/63-WPU	25.7 mm ^b	14.1 mm ^a
PoP90/75-WPU	26.2 mm ^a	13.2 mm ^b
PoP106/90-WPU	23.6 mm ^c	12.8 mm ^c

^{a-c}Mean values (n = 3) with different letters within the same column are significantly different a-c ($P < 0.05$)

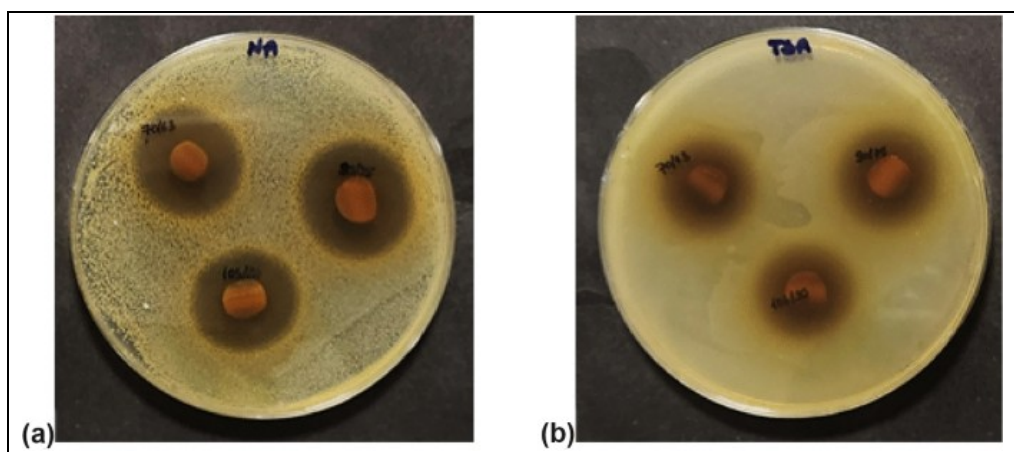


Figure 4. 4. Agar disks to observe the zone of inhibition of (a) *S. aureus* and (b) *P. aeruginosa* of the coated fabric samples.

Numerous studies have examined the antimicrobial properties of pomegranate peel (PoP) extracts and biodegradable films or coatings incorporating these extracts against both Gram-positive and Gram-negative bacteria. In particular, research has demonstrated that methanolic extracts of PoP exhibit superior antibacterial efficacy compared to extracts obtained from other parts of the plant, such as the flower, leaf, and stem, against a variety of pathogens including *Staphylococcus aureus*, *Staphylococcus epidermidis*, *Streptococcus mutans*, *Listeria monocytogenes*, *Yersinia enterocolitica*, *Escherichia coli*, *Shigella dysenteriae*, *Salmonella typhimurium*, *Bacillus cereus*, and *Salmonella enteritidis* [156,157].

Recent investigations into biodegradable films containing pomegranate peel have revealed that these films display enhanced inhibitory activity against Gram-positive bacteria (e.g., *S. aureus*) relative to Gram-negative bacteria (e.g., *E. coli*). This differential activity is largely attributed to the higher concentration of phenolic compounds in the peel extract, which appears to be more potent against Gram-positive microorganisms. For instance, in disk diffusion assays, a composite film comprising bacterial cellulose and PoP demonstrated an inhibition zone of 17 mm against *S. aureus*, while showing no detectable inhibition against *E. coli* [70].

Further research by Abbas and Abdul-Rahman [158] showed that incorporating PoP extract into chitosan-based films effectively suppressed the growth of a range of microorganisms, including Gram-negative bacteria (such as *Escherichia coli*, *Salmonella* spp., and *Pseudomonas aeruginosa*), Gram-positive bacteria (such as *Staphylococcus aureus* and *Bacillus* spp.), as well as the yeast *Candida albicans*. Similarly, Ali et al. [104] reported that

films enriched with 10% PoP produced inhibition zones of 16.31 mm for *Salmonella* and 18.40 mm for *S. aureus*. In general, *S. aureus* has consistently been identified as one of the most susceptible bacteria to PoP extracts, with Campos et al. [135] documenting inhibition zones ranging from 7.9 to 11.5 mm for conventionally extracted PoP and 9.3 to 14.0 mm for extracts obtained via sonication. Correspondingly, Rahman et al. [151] observed that cotton fabrics treated with an aqueous pomegranate extract exhibited stronger activity against *S. aureus* compared to the Gram-negative *Klebsiella pneumoniae*. Moreover, Panichayupakaranant et al. [160] found that while PoP extracts at a concentration of 0.20 g/mL did not inhibit *E. coli*, they were effective against *S. aureus*, generating inhibition zones between 15.2 and 19.4 mm. In contrast, Alexandre et al. [161] reported that a PoP extract at 0.50 g/mL produced inhibition zones of 22 mm for *E. coli*, 31 mm for *P. aeruginosa*, and 22 mm for *S. aureus*. Furthermore, the methanolic fraction of PoP exhibited significant antimicrobial activity, with inhibition zones of 23.7 mm for *S. aureus*, 15.6 mm for *E. coli*, and 14.7 mm for *S. typhimurium* [162].

The antibacterial assays revealed that reducing the particle size of the pomegranate peel powder enhanced the antimicrobial efficacy. Consequently, only the smallest particle fraction was selected for the formulation of the packaging films to maximize their antibacterial performance.

These variations in antimicrobial activity are thought to be a result of the toxic effects of phenolic compounds, which interact with the sulfhydryl groups of microbial proteins in a dose-dependent manner. To our knowledge, there have been no prior studies focusing on the development and characterization of PoP/WPU-based fabrics, including assessments of their antibacterial performance. The results of this study indicate that fabrics coated with PoP/WPU formulations hold considerable promise for antimicrobial applications across a range of industries.

4.3. ANALYSIS OF PACKAGING FILMS

In this part of the study, packaging films were developed by incorporating varying weight ratios of pomegranate peel (PoP) powder into a polycaprolactone (PCL)/chloroform solution. The particle size of the PoP powder was consistently selected as +63/−75 microns, based on previous findings from the textile coating experiments, where this particle size

range demonstrated the most effective performance in terms of antibacterial properties. Therefore, to isolate the effect of PoP content on the properties of the films, only this particle size was used across all packaging formulations. The primary variable in this study was the weight percentage of PoP powder added to the polymer matrix, which was adjusted to 5%, 10%, and 15%. The prepared samples were labeled as PoP-5, PoP-10, and PoP-15, respectively. The specific properties and compositions of each film are presented in Table 4.8, providing an overview of the structural design for further analysis and discussion.

Table 4. 8. Packaging film samples, PoP powder ratios, particle size ranges, packaging films thickness.

Sample name	PoP powder ratio (wt%)	Particle size range (μ)	Packaging films thickness (mm)
PCL	0	-	0.06 mm
PoP-5	5	18.2-81.7	0.06 mm
PoP-10	10	18.2-81.7	0.06 mm
PoP-15	15	18.2-81.7	0.06 mm

4.3.1. FT-IR Analysis of the Packaging Films

When pomegranate peel powder is added, changes associated with OH group is observed in the PCL spectrum. As the amount of pomegranate peel increases, the effect of the OH group becomes more pronounced. This indicates that there is a physical or chemical interaction between the pomegranate peel and PCL, and that the functional groups contribute to this interaction.

Due to the structure of PCL, a prominent C=O (Carbonyl) stretching peak is observed around $\sim 1720\text{ cm}^{-1}$. A CH stretching peak is detected around $\sim 2940\text{ cm}^{-1}$, while CH₂ asymmetric stretchings are observed around $\sim 2700\text{ cm}^{-1}$. Due to the structure of pomegranate peel, the broad peak observed in the range of $\sim 3200\text{-}3500\text{ cm}^{-1}$ indicates the presence of -OH stretchings. Compared to PCL, a smaller peak is present around $\sim 2900\text{ cm}^{-1}$, suggesting that the C-H stretching is lower in pomegranate peel compared to PCL. The C=O stretching observed around $\sim 1720\text{ cm}^{-1}$ may be attributed to the presence of organic acids or ester groups.

With the addition of pomegranate peel powder, the OH peaks in the PCL spectrum become more pronounced. The OH stretching observed at $\sim 3200\text{-}3500\text{ cm}^{-1}$ shows a slight increase

at 5%, while it becomes more prominent at 10% and 15%. This indicates the effect of phenolic groups in the pomegranate peel. The increase in OH bond concentration correlates with an increase in the hydrophilicity of the resulting films. Although there is no shift in the C=O band ($\sim 1720\text{ cm}^{-1}$), an increase in intensity may be observed, which is attributed to the contribution of organic acids or ester groups in the pomegranate peel. Figure 4.5 shows the FT-IR results of PCL films with PoP, pure PCL film and PoP.

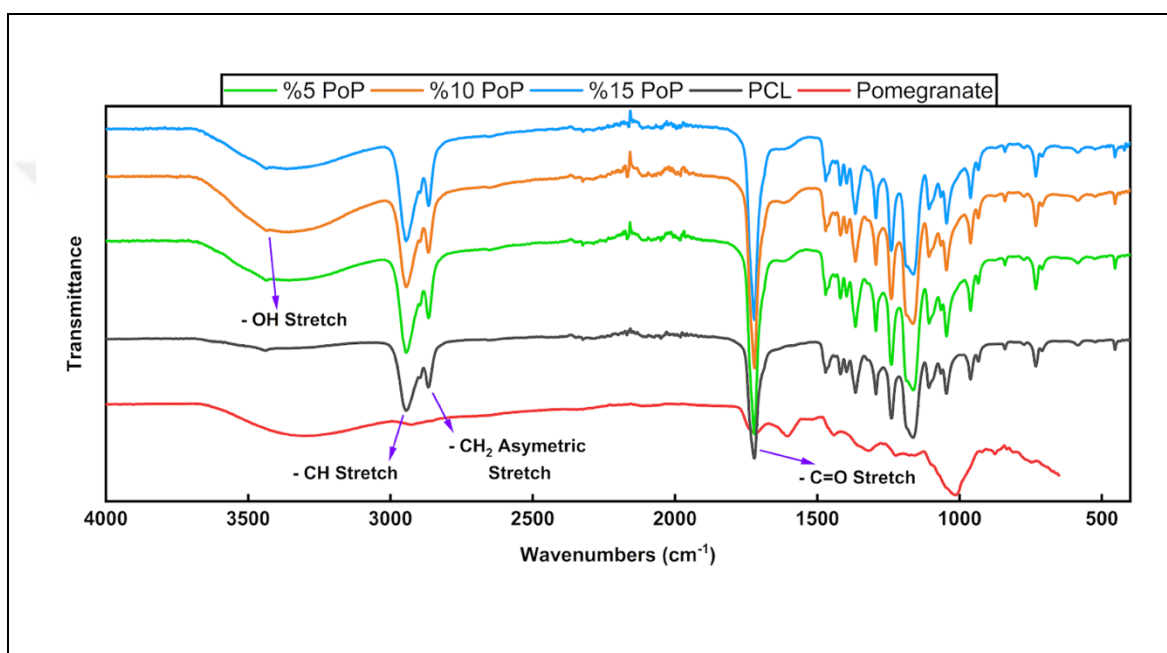


Figure 4. 5. FT-IR graph of the PCL films with bioadditive, pure PCL film and PoP.

4.3.2. TGA Analysis of the Packaging Films

The mass loss of pomegranate peel begins around 100°C [163]. This decrease is generally associated with the evaporation of moisture and the loss of volatile organic compounds within the sample. In addition to moisture, it is possible for low molecular weight organic compounds (e.g., volatile oils or light phenols) in biological materials like pomegranate peel to decompose at this temperature. Natural materials such as pomegranate peel typically have a high moisture content, so it is likely that a significant portion of this mass loss is due to water.

Between $300\text{--}400^{\circ}\text{C}$, a more significant mass loss is observed in the pomegranate peel. This can be attributed to the thermal decomposition of biopolymers such as cellulose, hemicellulose, and lignin present in pomegranate peel powder. While cellulose and

hemicellulose decompose between 200-350°C, lignin degrades over a broader temperature range (200-500°C). From the graph, it is evident that the pomegranate peel forms a residual material after carbonization, as it does not fully decompose even at temperatures reaching ~600°C. This indicates that the components of pomegranate peel have a high carbon content, leaving a carbonaceous residue after combustion.

The thermal degradation curve of PCL generally corresponds to a single major step degradation profile typical of synthetic polymers. The main degradation temperature range is between 350-450°C, which aligns with the thermal stability of PCL. Rapid mass loss occurs due to the cleavage of ester bonds in the main chain of PCL. This is consistent with the literature, indicating that PCL degrades in a controlled manner without producing any by-products or additional degradation steps [164].

In PCL films containing pomegranate peel, the degradation temperature range of PCL (350-450°C) appears to be maintained. However, as the amount of pomegranate peel increases, the onset of mass loss is observed to shift slightly earlier (indicating a minor reduction in thermal stability). This can be attributed to the organic compounds in pomegranate peel slightly reducing the thermal stability rather than contributing to it.

After 450°C, as the amount of PoP increases (e.g., 15%), a greater amount of carbonaceous residue is observed. This suggests that the combustion of pomegranate peel leaves a carbon-rich residue even after thermal degradation. Figure 4.6 and Table 4.9 shows the TGA results of the pure PCL film, PoP and PCL films with PoP.

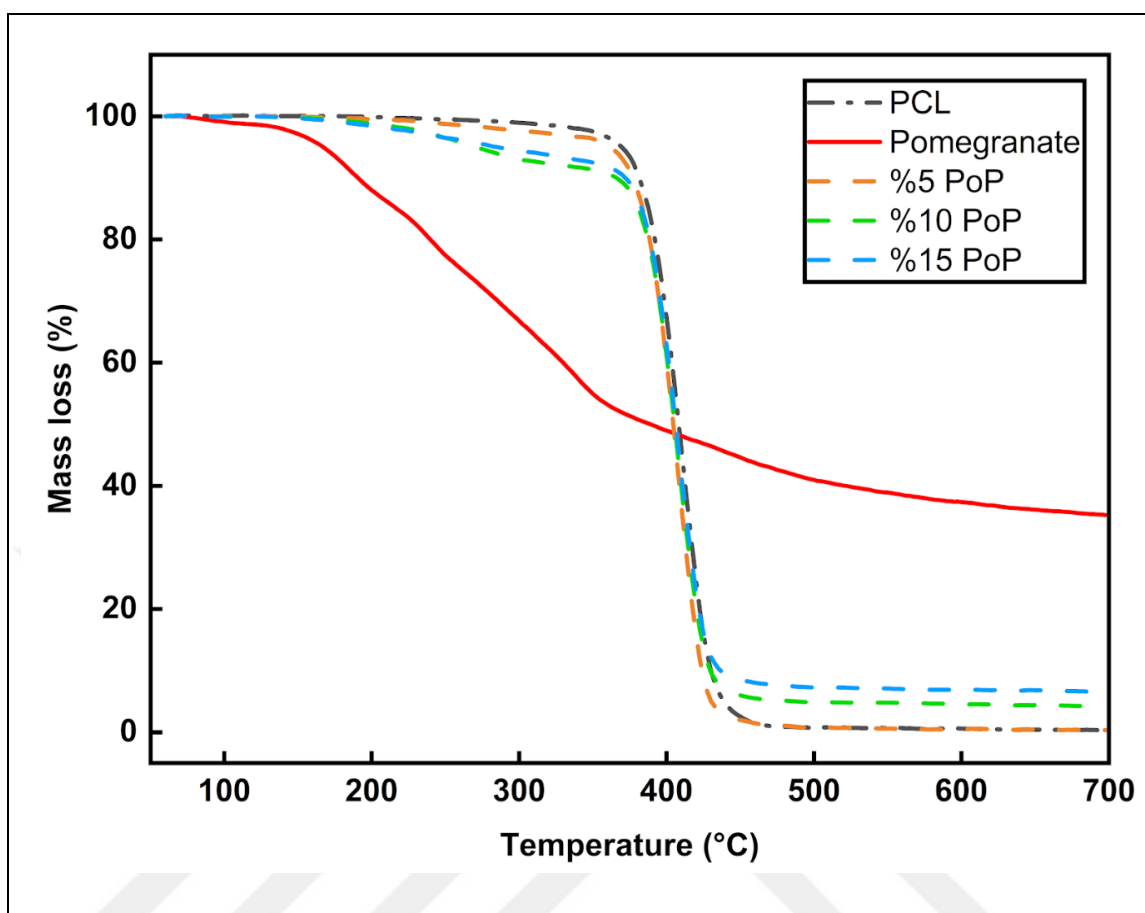


Figure 4. 6. TGA graph of the PCL films with PoP additive, pure PCL and PoP.

Table 4. 9. TGA results of the PCL films with PoP additive, pure PCL and PoP.

Sample	T at %1 Mass Loss (°C)	T at %5 Mass Loss (°C)	T at %10 Mass Loss (°C)
PCL	296.7	369.6	381.5
%5 PoP	240.5	361.7	377.2
%10 PoP	195.4	271.8	366.3
%15 PoP	182.8	285.8	372.3
PoP	143.3	174.3	196.7

4.3.4. DTGA Analysis of the Packaging Films

For pomegranate peels, the initial thermal event occurs at approximately 100 °C, where a small peak in the DTGA curve is observed. This peak is attributed to the evaporation of moisture and the concomitant loss of volatile organic compounds, including volatile oils and light phenolic substances present in the sample. As the temperature increases to the 300–400 °C range, a prominent peak becomes evident, corresponding to the thermal degradation

of the primary biopolymers found in the peel—namely cellulose, hemicellulose, and lignin. Notably, even at temperatures exceeding 500 °C, the pomegranate peel powder leaves behind a significant carbon residue, which indicates a high carbon content and the formation of a stable carbonaceous structure following combustion.

In contrast, pure PCL films exhibit their main thermal degradation within the 350–450 °C temperature range. Within this interval, a single, well-defined peak is observed, signifying that PCL undergoes a controlled thermal decomposition process primarily via the chain scission of ester bonds. The absence of any secondary peaks or abrupt mass losses in the DTG curve suggests that the degradation of PCL is homogeneous and occurs without the formation of significant by-products, a finding that is consistent with the literature.

In composite PCL films containing pomegranate peel, the primary thermal degradation range of PCL (350–450 °C) remains largely intact, indicating that the inclusion of pomegranate peel does not significantly alter this degradation interval. Beyond 450 °C, however, samples with higher pomegranate peel content exhibit an increased carbon residue; notably, composites with 15% pomegranate peel display a greater residue, which reflects the high carbon content inherent to the peel and its contribution to the residue following thermal decomposition. Additionally, minor peaks observed around 100 °C in the DTGA curves of pomegranate peel-containing samples suggest the evaporation of moisture and the release of volatile compounds—a phenomenon absent in pure PCL due to its non-volatile structure. Although the incorporation of pomegranate peel provides valuable organic contributions to the composite, it may slightly compromise the overall thermal stability of the films. Figure 4.7 shows the DTGA results of the pure PCL film, PoP and PCL films with PoP.

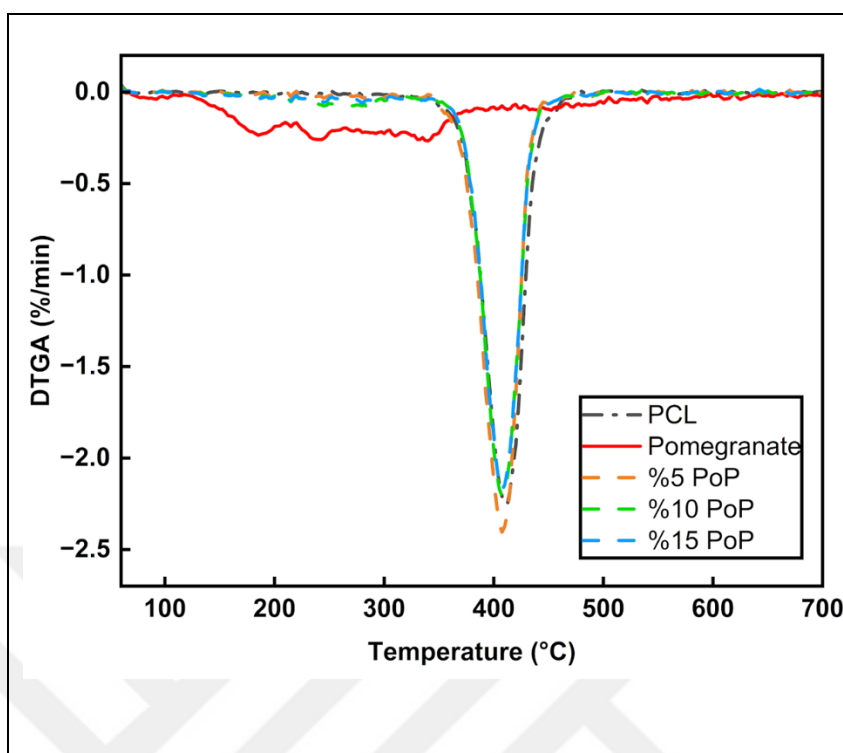


Figure 4. 7. DTGA graph of PCL films with PoP additive, pure PCL and PoP.

4.3.4. Color Test Results of the Packaging Films

Table 4. 10. Color Test of PCL films with PoP and pure PCL films.

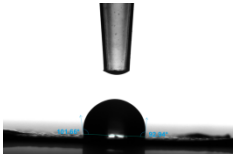
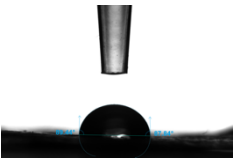
Sample	L*	a*	b*	C*	Hue°	Color
PCL	97.50 ± 0.53	1.12 ± 0.02	2.95 ± 0.12	3.15	69.27	
%5 PoP	95.04 ± 0.30	0.93 ± 0.03	4.71 ± 0.17	4.80	78.80	
%10 PoP	96.55 ± 0.34	1.27 ± 0.03	7.11 ± 0.05	7.22	79.84	
%15 PoP	93.56 ± 0.11	1.80 ± 0.03	9.92 ± 0.16	10.08	79.71	

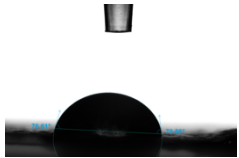
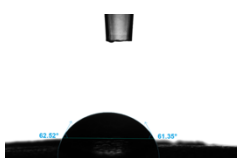
This table provides color measurement results for PCL films based on the L*, a*, and b* color space system. The L* value, which indicates the lightness of the sample, decreases as the PoP content increases, meaning the films become darker with higher PoP content. The a* values, representing the red-green axis, are all positive, indicating a red tint, and these values increase with more PoP, resulting in a more pronounced red hue. Similarly, the b* values, which indicate the yellow-blue axis, are positive across all samples, showing a yellow tint, with the intensity of yellow increasing significantly as PoP content rises. This is further reflected in the C* (chroma) values, which represent the saturation or intensity of the color, showing an increase with higher PoP content, suggesting more vivid colors. The hue

angle, represented by the Hue° values, increases slightly with PoP, indicating a shift toward yellow. The color column represents a visual depiction of these changes. Overall, the addition of PoP to the polymer leads to darker, yellow, and more intense colored films due to the intrinsic color properties of pomegranate peel. These measurements are important for evaluating the films' aesthetic and functional properties, especially in applications like food packaging, where color and appearance are significant factors. The pronounced darkening and shift toward warm hues observed with increasing PoP content present both advantages and limitations for food-packaging applications. On the one hand, richer yellow and red tones can provide effective light-blocking protection for UV-sensitive foods, helping to prevent photo-induced spoilage. On the other hand, reduced transparency and intense coloration may detract from consumer appeal in “pack-in-view” formats—such as fresh produce or beverages—where product visibility is essential. Consequently, films with high PoP loadings are well suited for semi-opaque or opaque packaging layers (e.g., barrier films or pouches for light-sensitive items) but are less ideal for fully transparent packaging. When designing PCL–PoP films for food packaging, it is important to balance protective performance with the need for product visibility; this can be achieved by selecting moderate PoP concentrations or by placing the PoP-rich layer within the interior of a multilayer structure [165].

4.3.5. Water Contact Angle Measurements of the Packaging Films

Table 4. 11. Contact angle of the films.

Sample	Water Contact Angle (°)	Images
PCL	101.66	
5% PoP	89.44	

10% PoP	76.61	
15% PoP	62.52	

Polycaprolactone (PCL) is known for its hydrophobic nature, primarily due to its semi-crystalline structure and the absence of polar functional groups such as hydroxyl ($-OH$) or carboxyl ($-COOH$) on its surface. This structural attribute limits its affinity for water, resulting in a relatively high water contact angle. In agreement with the literature, the contact angle for pure PCL was measured to be approximately 115° , confirming its strong hydrophobic character [166].

Upon the incorporation of pomegranate peel powder (PoP), a progressive decrease in water contact angle was observed across the samples, indicating enhanced surface hydrophilicity. As shown in Table 4.11, the contact angle for PCL-5% PoP was measured at 91.15° , approaching the conventional boundary of 90° used to distinguish between hydrophobic ($CA > 90^\circ$) and hydrophilic ($CA < 90^\circ$) surfaces. Therefore, it can be concluded that the PCL-5% PoP film is still marginally hydrophobic, whereas the films containing 10% and 15% PoP exhibit clearly hydrophilic behavior.

This change in wettability is also supported by FT-IR analysis (Figure 4.6), which demonstrated a notable increase in the intensity of $-OH$ stretching vibrations in the range of $3200\text{--}3600\text{ cm}^{-1}$ as the PoP content increased. These hydroxyl groups, originating from phenolic compounds in the pomegranate peel, contribute to hydrogen bonding with water molecules, thereby reducing the contact angle and enhancing surface wettability. The correlation between increased hydroxyl absorption and reduced contact angles supports the conclusion that PoP loading effectively modifies the surface chemistry of the films.

While hydrophilic surfaces are not typically preferred for general food packaging applications due to potential issues such as moisture uptake and microbial growth, they can be beneficial in certain use cases. In addition, the suitability of hydrophilic films in food

packaging depends on the specific moisture dynamics of the packaged product. In cases where the food naturally releases moisture—such as baked goods—hydrophilic films may absorb small amounts of vapor, reducing internal condensation and helping to maintain texture. Nevertheless, excessive moisture absorption may lead to accelerated microbial spoilage and degradation of the film's physical integrity. Therefore, the application of hydrophilic films requires careful consideration based on the product type, storage conditions, and overall moisture management strategy [167].

In summary, the incorporation of pomegranate peel powder into PCL films introduces hydrophilic functional groups, as evidenced by FT-IR spectroscopy, resulting in a systematic reduction in water contact angles. This effect can be tailored depending on the intended application and required barrier properties.

4.3.6. Antibacterial Test Results of the Packaging Films

The antibacterial activity of the produced PCL–PoP films was evaluated against two common foodborne pathogens, *Staphylococcus aureus* ATCC 6538 (Gram-positive) and *Pseudomonas aeruginosa* ATCC 15442 (Gram-negative), using the inhibition zone method. The results revealed a progressive increase in antibacterial activity with higher pomegranate peel (PoP) content. Films containing 5% PoP did not show any measurable inhibition against either bacterium. At 10% PoP loading, limited activity was observed against *S. aureus*, whereas no effect was noted for *P. aeruginosa*. In contrast, 15% PoP films exhibited antibacterial effectiveness against both bacteria, with more pronounced inhibition for *S. aureus*.

This is consistent with the well-established understanding that Gram-negative bacteria, due to their complex outer membrane, exhibit greater resistance to antibacterial agents. From a food packaging perspective, the observed inhibition zones at $\geq 10\%$ PoP concentration suggest that natural additives can confer a certain level of antimicrobial protection to packaging films. However, compared to data reported in the literature, the zones measured in this study were of moderate size. For instance, Almeida et al. (2024) [169] reported inhibition zones of approximately 18 mm against *S. aureus* for films containing 10% PoP extract, highlighting the potential benefits of using extract forms or enhanced dispersion techniques to boost antibacterial efficacy [168].

Although higher PoP contents (20–30%) could theoretically enhance antimicrobial activity further, such increases were not feasible in practice due to material limitations. At these concentrations, aggregation of PoP particles within the PCL matrix led to reduced homogeneity, compromised film elasticity, and surface roughness [108]. These issues underline the need to balance antimicrobial effectiveness with film processability and mechanical integrity.

Consequently, the 15% PoP loading was identified as optimal within the scope of this study, delivering effective antibacterial activity—especially against Gram-positive strains—while maintaining film functionality. Future work may explore strategies such as combining particulate and extract forms of PoP or applying surface modifications to enhance the bioavailability of phenolic compounds and achieve higher efficacy even at lower filler ratios.

Table 4. 12. Antibacterial test results of PCL films.

	5% PoP	10% PoP	15% PoP
Pseudomonas ATCC 6538 (Gram-positive bacterium)	-	-	11.77 mm
Staphylococcus ATCC 15442 (Gram-negative bacterium)	-	12.7 mm	14.88 mm

5. PUBLICATIONS

In the scope of this thesis study, several academic and scientific outputs have been generated, including a peer-reviewed journal article, a conference presentation, and a patent application. These contributions not only disseminate the findings of the thesis but also demonstrate the broader scientific and industrial impact of the research. The details are provided below:

Article: Çelebi, N., Aral, N., & Taştan, Ö. (2024). Development and characterization of pomegranate peel powder and waterborne polyurethane-coated fabrics. *Journal of Coatings Technology and Research*, 1–14.

Conference Presentation: Çelebi, N., Aral, N., & Uslu, Ö. (2024). Biodegradable and Antibacterial PCL Films Containing Pomegranate Peels for Food Packaging. 22nd International Metallurgy and Materials Congress, September 19, 2024, Istanbul, Turkey.

Patent: Aral, N., Tüysüzoğlu, İ., Çelebi, N., & Taştan, Ö. (2023). A synthetic leather containing bio-based raw materials and a method for its production. Turkish Patent Application No: 2023/012608. YUGEN Biological and Chemical Technologies Industry and Trade Inc.

CONCLUSION

In this thesis, the use of pomegranate peel powder—a natural bioadditive derived from agricultural waste—was investigated in the fabrication of both textile coatings and biodegradable packaging films by incorporating it into two different biodegradable polymer matrices: waterborne polyurethane (WPU) and poly(ϵ -caprolactone) (PCL). Although these two applications serve distinct industrial sectors, they were evaluated not only as separate case studies but also as complementary platforms for addressing shared environmental challenges. Data collected across a wide range of parameters, including microstructure, surface characteristics, thermal stability, and antibacterial activity, were analyzed individually and comparatively.

The incorporation of pomegranate peel powder significantly influenced surface and barrier properties in both systems. In packaging films, the incorporation of pomegranate peel powder led to a gradual decrease in water contact angle values, indicating an increase in surface hydrophilicity. This trend was consistent with FTIR results, which showed a more pronounced –OH absorption band with higher PoP loading, confirming the presence of phenolic groups responsible for increased polar character on the film surfaces. This enhanced hydrophilicity is advantageous for developing active packaging systems, especially for products that benefit from controlled moisture exchange. Additionally, changes in film color and increased opacity suggested a potential for light-protective packaging applications, particularly for UV-sensitive products. However, these visual and barrier changes must be carefully evaluated according to the specific requirements of the target product.

Only the powdered form of pomegranate peel was used in this study, and the effects of variables such as additive concentration and particle size on material properties were systematically examined. Antibacterial tests revealed that the pomegranate peel powder exhibited pronounced activity against *Staphylococcus aureus* ATCC 6538, and that this effect became more significant with higher additive loading. These findings demonstrate the bioadditive's potential as a functional component in both food packaging and hygienic textile products.

In the textile applications, the additive caused noticeable changes in fabric coloration, imparting a naturally tinted appearance. This visual differentiation may be particularly valuable in markets that emphasize eco-consciousness, such as in eco-textiles, where natural aesthetic features can enhance product appeal and brand perception. Mechanical testing indicated that the additive had a limited effect on tensile strength, whereas SEM analysis revealed a more uniform and cohesive coating layer.

While the study yielded encouraging results, several limitations must be acknowledged. For instance, only the powdered form of PoP was utilized, and challenges related to dispersion and agglomeration were observed at higher additive loadings. Additionally, although phenolic content contributed to functional improvements, achieving a balance between visual quality, surface hydrophilicity, and antibacterial efficiency remains a critical challenge. Future work should focus on evaluating the effects of pomegranate peel extracts, improving homogeneity through advanced mixing techniques, and expanding the range of characterization to include abrasion testing and long-term stability assessments.

In conclusion, this study demonstrates that pomegranate peel powder is a promising bioadditive with the potential to enhance multiple performance aspects of biodegradable materials in both textile and packaging applications. Its use aligns with circular economy principles and supports the development of more sustainable material systems, yet further optimization is necessary to fully unlock its functionality in commercial applications.

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