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EXECUTIVE SUMMARY

Biobased, biodegradable, and recyclable packaging, made from materials such as plant-based polymers and agro-food waste, offers an eco-friendly alternative and is the focus of the "Plant-Based Antimicrobial and Circular Packaging for Plant Products" (PLAMINPACK) project, funded by the Partnership for Research and Innovation in the Mediterranean Area (PRIMA). The shift toward sustainable packaging is driven by the growing consumer preference for environmentally friendly products, as well as by companies aiming to enhance their brand image while reducing environmental pollution. Thus, this document analyses the market context for biobased, biodegradable, and recyclable packaging, considering economic trends, social aspects, innovations related to the proposed packaging, and potential barriers. It also examines the regulatory framework and the unique characteristics of the Mediterranean region. The full analysis aims to gather insights that will support effective communication, dissemination, exploitation, and outreach of the PLAMINPACK objectives and results.

1. Introduction

The biobased and biodegradable packaging demand has been increased in recent years, driven by a combination of environmental, regulatory, and social factors. As long as companies increasingly have recognized the relevance of sustainability in their own products, the push for eco-friendly packaging solutions has gained significant interest [1]. One of the primary drivers of this demand is the growing concern over environmental pollution, particularly from plastic waste. In fact, fossil plastic packaging contributes significantly to landfill waste and ocean pollution, harming both wildlife and ecosystems [1].

The gradual replacement of fossil-based plastics with bioplastics marks an important step toward sustainability. Bioplastics, made from renewable biological resources, can help reduce reliance on fossil fuels and lower greenhouse gas (GHG) emissions. Most bio-based plastics are currently derived from crops like sugarcane and corn. However, second-generation feedstocks, such as switchgrass and forest residues, provide additional benefits, including more sustainable cultivation practices and minimal competition with the food industry [2].

The global biodegradable packaging market is expected to reach USD 218.13 billion by 2024, with a projected annual growth rate of 5-6%, leading to a market size of USD 352.73 billion by 2034. As environmental concerns rise, there is increasing demand for sustainable packaging solutions. Biodegradable packaging, made from materials like plant-based polymers, starch, and recycled paper, offers an eco-friendly packaging alternative. This shift toward sustainable packaging is driven by growing consumer preference for environmentally friendly products, as well as by companies aiming to enhance their brand image while reducing environmental pollution. Additionally, stringent government regulations around the world are further boosting the demand for biodegradable packaging solutions [3].

The present document is investigating market context about biobased and biodegradable packaging, regulation framework and peculiarities of the Mediterranean area, to support the exploitation strategies of the PLAMINPACK project.

2. Market context about biobased packaging

2.1 Economic trends

Companies and corporations are increasingly incorporating sustainability into their core business strategies, with many brands setting ambitious goals to reduce their environmental footprint, including and adopting biodegradable packaging. Multinational companies, such as Unilever and Nestlé, have committed to make all their packaging recyclable, compostable, or biodegradable by 2025. These commitments are driven by the need for regulatory compliance, consumer demand, and the understanding that sustainable practices can result in long-term cost savings and enhanced operational efficiency [1]. The dynamics of the biodegradable packaging market are also changing. Advances in biodegradable packaging technology have made it more cost-competitive with traditional plastic options. Furthermore, economies of scale, driven by increased production and the growing availability of raw materials, have further reduced costs. The global biodegradable packaging market is projected to reach $140.6 billion by 2029, growing at a compound annual growth rate (CAGR) of 5.97% from 2024 to 2029. This growth highlights the expanding market opportunities for businesses that invest in biodegradable packaging solutions [1].

The future growth of bioplastic production will be significantly influenced by fluctuations in the prices of conventional plastics. Additionally, technological advancements, economies of scale, and raw material costs will play key roles in shaping this evolution. Policies supporting sustainable alternatives to fossil fuel-based plastics could further boost demand for bioplastics. As a result, when making quantitative projections of market development, it is essential to use a model that incorporates these diverse factors. Based on this approach, Dohler et al. [4] estimated an average annual growth rate of 4.98% for global production capacities between 2018 and 2030.

The work of Ocicka et al. [5], focusing on the Polish market, leads to similar conclusions. The shift to biobased and compostable plastics for packaging relies on external factors like economic conditions, legal frameworks, and technical standards, as well as internal factors such as advancements in waste management infrastructure, corporate environmental responsibility, environmental education, and improvements in bio-packaging properties. Stakeholders influencing the bio-packaging market include internal groups like raw material suppliers, bioplastics manufacturers, packaging companies, distributors, business clients, consumers, and waste management organizations. Among these factors, cost currently plays the most critical role in determining the competitiveness of bio-packaging. The bio-packaging market involves a diverse range of entities varying in size, scale, and activity levels, making integration and collaboration for value co-creation challenging. Interactions among market players are mostly transactional and governed by formal contracts. Collaboration in activities like designing and commercializing bio-packaging, sharing production capacities, and outsourcing remains minimal. This is due to factors such as intense competition, lack of trust, and concerns over intellectual property protection. Consequently, relationships between stakeholders are fragmented, preventing the formation of a unified value system aligned with Circular Economy (CE) principles and hindering the creation of a

sustainable bio-packaging lifecycle. International Fast-Moving Consumer Goods (FMCG) corporations and retailers are adopting strategies focused on circular supply chain management, with some leading players forming cross-sector partnerships rooted in shared values. Meanwhile, start-ups led by younger generations (Y and Z) are creating responsible business models centred on eco-innovation.

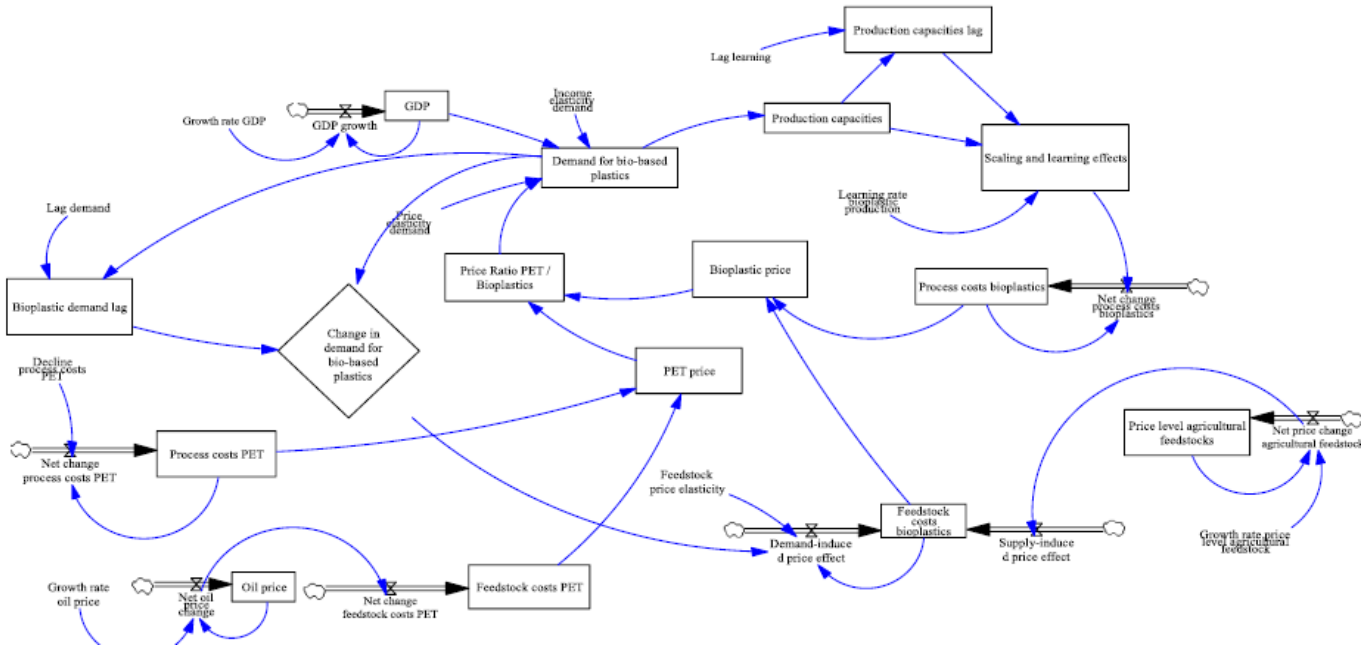

Figure 1: *Stock and flow diagram adopted in ref [4] to study the market of biobased plastics.*

In Poland, the bio-packaging market offers products with varying ecological qualities, such as biodegradability. However, limited environmental awareness and responsibility have led to widespread greenwashing, with some stakeholders engaging in this practice knowingly or unknowingly. The absence of effective regulations and shared ethical standards allows unethical practices to persist. To address this, there is a pressing need for formalized bio-packaging standards and waste management regulations.

Standardizing bio-packaging would streamline waste management, enhance circularity, and promote the integration of biomaterials into the economy. Consumers, as key drivers of the bio-packaging market, influence its development through their purchases of bio-packaged goods, including food. Although interest in packaging types and quality is growing, many consumers remain uninformed about bio-packaging's features.

Rising demand in both business-to-business (B2B) and business-to-consumers (B2C) markets presents an opportunity to strengthen and expand the bio-packaging regime. However, challenges persist, including insufficient waste segregation and limited recycling scalability, which hinder alignment with Circular Economy (CE) principles despite the existence of guidelines for regime actors. A recent study [6] in Germany, involving 485 consumers, revealed that price and product origin were more influential than packaging in purchasing decisions. Consumers displayed a clear preference for unpackaged produce over packaged options, favouring the ability to see and select items themselves. This trend applied to both

durable fruits, like apples, and more delicate ones, like tomatoes, though consumers acknowledged that packaging could offer protective benefits.

When it came to bio-based plastic packaging for fresh produce, consumers showed little interest, likely due to a lack of awareness and understanding of its benefits and characteristics. These findings highlight the challenges of promoting renewable and compostable materials. Sustainability spans environmental, social, and economic dimensions, aiming at a more sustainable future. Increasingly, consumers are encouraged to adopt sustainable behaviors, starting at home with recycling, reducing food waste, and minimizing single-use plastics. However, barriers such as affordability, lack of knowledge, limited time, insufficient information, and task complexity can hinder compliance [7].

Key drivers like environmental concern, perceived recyclability, task-specific benefits, and convenience may help foster consumer engagement. Food packaging, which serves various functional purposes and uses diverse materials (plastic, glass, metal, paper/cardboard), poses significant disposal challenges. Ensuring that packaging incorporates sustainable materials and encourages responsible consumer behavior is a critical global challenge for both companies and consumers.

Uncertainty, inconsistency, and varying infrastructure related to food packaging contribute to consumer confusion, underscoring the need for further research to develop consumer-focused messaging and inform future policies. Consumers' expectations for sustainable packaging are evolving, with an increasing preference for cost-saving behaviors (e.g., repairing, buying second-hand, or choosing durable products) and convenience features like extended shelf life, resealable, re-closable, and easy-to-open designs.

Improving packaging waste collection is crucial to closing the circular economy loop. However, significant variations within and between countries in waste collection systems and consumer preferences highlight the need for better infrastructure and tailored strategies. Cross-country research can help identify key factors, account for cultural differences, and inform targeted approaches [8].

Global food brands play a pivotal role in driving packaging innovation. Their efforts must align with diverse consumer expectations and adapt to varying recycling systems across different countries to ensure effectiveness and sustainability.

Transitioning to a circular bioeconomy offers a viable solution to environmental challenges, requiring a shift from a technology-centered approach to an economic value-based perspective that evaluates the societal costs and benefits of circularity. Five key strategies [9] are proposed to guide this transition:

1. **Support Technological Advances:** Public investment in research and development is critical to enhancing technologies that compete with conventional methods while balancing economic interests with societal benefits. Emerging tools like digital twins and artificial intelligence, paired with high-resolution agricultural data, can transform agriculture into a manageable pollution source. These innovations enable precision agriculture, supply chain transparency, and environmental impact assessments, improving sustainability and cost efficiency.
2. **Regulatory Incentives**: Moving beyond traditional conservation programs, market-based policies like carbon taxes, nitrate taxes, and pollution trading schemes are needed to align product pricing with social and environmental costs. Institutional reforms, including environmental reporting,

labelling requirements, and removing barriers for bio-based technologies, can mitigate risks and facilitate the adoption of circular practices.

3. **Promote Markets for Circular Products**: Establishing voluntary markets with credible certification, branding, and measurable indicators fosters trust and enables premium pricing for sustainable goods. Tools like blockchain and digital twins can verify practices, ensure compliance with sustainability standards, and boost transparency and market access. Such frameworks encourage businesses to adopt circular models while educating consumers about the environmental benefits of their purchases.
4. **Investing in Public Education**: Consumer education on ecosystem services provided by circular products can increase willingness to pay, create demand, and build political support for circularity. Public understanding is vital for fostering long-term sustainability and market growth for bioeconomy goods.
5. **Monitor and Promote Equity**: Equity must be embedded in the circular bioeconomy to ensure fair distribution of benefits, especially for marginalized groups. Measures like anti-trust standards, compensation mechanisms, and workforce reskilling initiatives are essential to mitigate higher production costs and prevent market concentration. Inclusive governance and targeted safety nets can address distributional impacts and support those negatively affected by the transition.

This comprehensive framework balances technological innovation, regulatory reform, market development, public awareness, and equity to create a sustainable and inclusive circular bioeconomy.

2.2 Social aspects

Consumer awareness about environmental issues has also been a significant factor in the rise of biodegradable packaging. Today's consumers are more aware and concerned about the environmental impact of their purchases. A 2023 survey by McKinsey & Company found that 50% of U.S. consumers are willing to pay more for products with sustainable packaging. This shift in consumer preferences has pressured companies to adopt biodegradable packaging solutions to meet the demand for eco-friendly products and enhance their brand image [1].

Students and young generation opinion. A recent study [7] explored food packaging challenges and preferences among students in Europe and Asia to inform tailored support, such as targeted education, to promote sustainable practices. The findings revealed that food packaging significantly influenced product choices, highlighting the importance of enhancing sustainability-related knowledge to address disposal barriers. Key insights include:

- Opportunities for Change: Fresh produce like meat, fish, fruits, and vegetables (UK, India, France) and snacks or baked goods (China) were identified as priorities for sustainable packaging improvements.
- Disposal Challenges: Issues with mixed-material packaging were prominent in the UK, France, and India, while glass posed challenges in China.
- Barriers to Sustainable Practices: Common concerns included unclear information, limited sustainable options, excessive packaging, and inadequate infrastructure (e.g., a lack of bins at home or in public).

- Information Dissemination: Students rarely sought out packaging information. To increase engagement, accessible formats like infographics or short videos focusing on recyclability were recommended.

Colleges and universities emerged as effective platforms for disseminating targeted information, improving students' knowledge and awareness. Encouraging sustainable disposal practices at the individual level could collectively reduce climate change impacts.

While students represent future change-makers, the study cautioned against generalizing their behaviors and attitudes to entire generations, as these can vary significantly across countries.

Figure 2: *Overview of the key themes (blue: UK; red: France; Green: India; yellow: China) [8]*

Consumers preferences

Consumers rely on a variety of cues when evaluating packaging [8]. These cues include: **Structural cues**: such as material, size, and shape; **Visual cues**: like eco-labels, color, and images; **Informational cues**: both numerical and verbal details provided on the package. **Sensory cues**: such as the tactile feel of the packaging. Research highlights that labels are often a key cue for consumers. A 2018 study found that consumers in Germany, France, and the United States frequently referred to eco-labels on packaging. However, a general lack of understanding about these labels reduces their effectiveness. Simple and clear labels can help consumers quickly and easily assess packaging options without much effort. In addition to eco-labels, elements like logos, images, and the material of the packaging often signal environmental friendliness. French consumers in the study prioritized packaging materials, particularly their color, while consumers in Germany and the United States tended to focus on reading detailed information on the package or seeking additional details online.

According to industry experts, bio-based plastics are considered the third-best solution to address the environmental challenges of plastic packaging. The top-ranked solution is recycling-focused approaches, followed by replacing single-use plastic packaging with non-plastic alternatives. Despite this, a recent study revealed that 40% of brand owners have set specific production goals for incorporating bio-based materials in packaging. Interestingly, experts highlight a significant gap between consumer perceptions and the actual benefits of bio-based packaging. While 74% believe it enhances the public image of plastics, only 42% think it will genuinely reduce packaging's environmental impact.

Circular and biocircular economy diffusion by "Industry 4.0" and "small wins". It is evident that on the social point of view the circular economy has attracted the attention of consumers. Rejeb et al. [10] examined the knowledge diffusion in the CE context. According to their results, circular economy research focuses on six primary research themes: CE and sustainability, bioeconomy, CE practices, lifecycle assessment and industrial symbiosis, construction activities, and waste management. In addition, the study demonstrated that the circular economy literature has recently focused on Industry 4.0 technologies and their contribution to the circular economy.

The circular bioeconomy (CBE) combines the principles of the circular economy and the bioeconomy. One of the key drivers of transformative change within the circular bioeconomy is the implementation of circular initiatives with tangible outcomes, often referred to as 'small wins' [11]. These small wins play a crucial role in sustaining transformation by deepening, broadening, and spreading their impact. Focusing on the dynamics and mechanisms underpinning the development of small wins offers valuable insights into how they can support continuous transformative change. The transformative development of small wins involves the ongoing (re)activation of energizing mechanisms and the logic of attraction through their spreading, deepening, and broadening, while preserving these advancements. By doing so, initiatives not only continue to evolve but also challenge additional aspects of the linear economy. Understanding the non-linear dynamics between these mechanisms and the positive feedback loops they generate can help ensure that initiatives maintain their momentum. Furthermore, it can accelerate the overall learning process, benefiting the CBE and all stakeholders involved.

Diffusion of horticulture. The integration of circular economy principles into agriculture has led to sustainable innovations in food production, particularly within horticulture [12]. Circular horticulture, an emerging research field, is gaining significant traction, with Europe, particularly Spain, Italy, and Belgium, at the forefront. Institutions like the University of Almería and researchers such as Bart Vandecasteele and Jane Debode are leading contributions in this area.

Key research areas in circular horticulture include bioeconomy, urban agriculture, nutrient recovery, soilless farming, biochar, fertigation, and desalination. Studies have largely focused on fruits and vegetables, with circular strategies concentrating on biowaste recovery and water reuse. Various biowastes, such as those from animals and crops, have been explored for use as biofertilizers or alternatives to traditional substrates. Significant advancements in water management include wastewater treatment, hydroponic systems, and automated technologies. Progress has also been made in greenhouse technologies, integrating sustainable materials and bioenergy sources to enhance microclimate management.

Despite these advancements, there are gaps in implementing the One Health approach, which advocates for interdisciplinary methodologies addressing the health of ecosystems, animals, and humans. Engaging groups like children, students, and the elderly in horticulture could be a powerful tool for spreading awareness about the WEFE Nexus (Water-Energy-Food-Ecosystem Nexus) and promoting innovative, sustainable packaging solutions for perishable fruits.

2.3 Smart and sustainable products for perishable fruits

Fruits and vegetables are among the most commonly lost or wasted foods post-harvest, with losses ranging from 6% to 20% between harvest and retail, excluding crops left in the field [13]. Additionally, another 17% of food is wasted in households, food service, and retail settings [14-15].

The fresh produce industry relies heavily on polyethylene-based films and plastics, as these materials provide essential barriers against oxygen and water transmission, helping to extend shelf life. Prior to the COVID-19 pandemic, there was growing interest in bio-based packaging materials or reducing packaging altogether. However, during the pandemic, consumer demand for packaging fluctuated based on concerns about food safety. With upcoming EU regulations set to address packaging requirements in 2023, demand for innovative packaging solutions is expected to rise.

Researchers are focusing on integrating biobased and compostable materials into packaging for ready-to-eat food supply chains, with a strong emphasis on more eco-friendly packaging options. The direct inclusion of bioactive compounds within packaging materials could offer new opportunities for food diversification, enable smart applications, and help reduce waste. Moreover, creating food channels to repurpose food by-products can redirect them into other marketable areas.

Interestingly, plant breeding could also reduce the need for packaging. For instance, tomatoes that lack an abscission zone remain attached to the raceme even when ripe [16], allowing them to be sold in compact clusters without the need for additional packaging. Teplinsky et al. suggested that significant progress in extending the shelf life of fresh foods, particularly fruits and vegetables, can be made by advancing plant genetics, studying plant-microbe interactions, and using innovative materials [17].

The use of agricultural by-products in packaging can be perceived as an interesting innovation for consumers [10]. Industrial and municipal food waste processing offers modest economic advantages over agricultural waste processing due to its low market value. However, factors such as logistics, storage, and operational capacity play a critical role in determining the economic viability of a biorefinery. For a biorefinery to be economically sustainable, it must operate as a multi-feedstock plant. This approach helps overcome challenges like raw material seasonality and ensures a constant supply of biomass, which is essential for maintaining consistent operations and profitability. Therefore, in regard to the biorefinery concept, the processing of agri-food waste and by-products has been considered a promising, economically viable, and sustainable approach to produce biomaterials for food packaging [10].

A significant portion of food waste occurs due to inefficiencies in the supply chain, as well as damage during transport and handling. Innovations in packaging design and materials present real opportunities

to minimize food waste across the supply chain. Additionally, the growing demand for fresh, high-quality, minimally processed, ready-to-eat foods with extended shelf lives must meet stringent and evolving food safety regulations. In this context, precise monitoring of food quality and spoilage is critical to reducing health risks and food waste.

Improved barrier and surface properties, along with active materials for food preservation, are essential in maintaining food freshness. Similarly, intelligent and smart packaging systems are gaining importance, particularly biobased sensor technologies developed using 3D printing. These systems allow for real-time monitoring of food quality, helping to reduce waste and enhance safety [18].

Furthermore, key factors influencing the design and production of fully biobased packaging include the reuse of byproducts, waste reduction, recyclability, biodegradability, and other end-of-life options. These factors must be considered to ensure the overall sustainability of the product/package system, reducing environmental impacts and promoting circular economy practices. Despite their limitations, the biodegradable materials are valuable for creating more sustainable packaging for organic products. They are particularly promising because they are biobased, biodegradable, and mostly derived from food industry waste [19].

Research into biobased and biodegradable packaging solutions, especially for perishable foods in the Mediterranean area, is increasingly relevant due to environmental concerns and a growing demand for sustainable food packaging. A variety of bioplastics, such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch-based plastics, are gaining traction for their ability to replace traditional plastics. These materials are renewable, biodegradable, and less harmful to the environment [20-21].

One innovative approach involves the development of active bio-based packaging coatings to extend the shelf life of Mediterranean foods, including ready-to-eat options. These coatings often incorporate food-grade, biodegradable components like natural antioxidants and antimicrobials. They are derived from by-products of the food industry, contributing to circular economy principles. Additionally, these coatings are designed to reduce food waste by improving the preservation of perishable Mediterranean foods.

Some of the biodegradable materials commonly used in food packaging include cellulose films and starch-based plastics. These options provide good barrier properties and are already in use for packaging fresh products and snacks. Moreover, edible coatings, which are becoming more popular, help reduce packaging waste by allowing the film to be consumed with the food. This trend is aligned with the move toward cleaner labels and sustainability [22-23].

These developments suggest that the Mediterranean region is well-positioned to adopt and benefit from biobased and biodegradable packaging, contributing to both environmental sustainability and the preservation of traditional food systems.

Recent patents in the field of biodegradable and bio-based packaging for perishable fruits, including those from the Mediterranean region, focus on sustainable materials like cellulose, silk, and seaweed.

1. Silk-based packaging: One notable patent proposes using silk films as a coating for biodegradable or bio-based packaging, which can extend the shelf life of perishable foods like fruits by regulating oxygen and moisture [24].
2. Seaweed-based packaging: Another patent focuses on seaweed-based biodegradable packaging, designed to naturally degrade within months. This packaging can be used for perishable items, providing a flexible and eco-friendly alternative to traditional plastic [24]

These innovations reflect growing interest in sustainable solutions for packaging perishable produce.

2.4 Barriers

A major challenge for biodegradable packaging has been replicating the barrier properties of traditional plastics, which are essential for protecting products from moisture, oxygen, and contaminants. However, recent technological advancements have made significant strides in improving the barrier properties of biodegradable materials. For example, nanocomposites and multi-layered biopolymer films are being developed to enhance the protection and shelf life of packaged goods. These innovations are especially beneficial for biodegradable food packaging, where maintaining product freshness is critical for reducing waste and ensuring quality. These advancements hold promise for making biodegradable packaging a viable alternative to conventional plastics in food packaging and other applications [1].

Food packaging serves multiple functional purposes and involves a range of materials, including plastic, glass, metal, and paper/cardboard, which contribute to significant disposal challenges. Ensuring that food packaging uses sustainable materials and encourages responsible end-user behavior is crucial. This is a major global challenge for both companies and consumers. Additionally, increasing the collection of packaging waste is vital to closing the circular economy loop. However, significant variations exist within and across countries, emphasizing the need for improved waste collection systems and management practices. Addressing these differences can have a considerable impact while also catering to variations in consumer preferences and values. [7].

The European Commission, in its Plastics Strategy, highlights the limited market share of bio-based plastics as a concern. One key challenge is the unclear environmental performance of bio-based packaging materials. It should be clarified that integrating renewability, compostability, and recyclability represents the optimal approach for packaging. This combination can help counterbalance climate change through the use of carbon-neutral materials, improve soil quality, promote circularity, and enable long-term carbon storage.

Simple and easy-to-understand labels could empower consumers to assess packaging solutions without requiring significant time or effort. However, as seen with other products, an overabundance of labels can confuse rather than assist consumers. Producers could address this by making the "bio-based" nature of materials more perceptible. A consumer study revealed that features such as "visible grains and fibers" evoke a sense of naturalness among buyers. Product and material designers could intentionally leverage this insight when developing new products from bio-based materials.

Pricing also plays a crucial role in the adoption of bio-based plastics. High production costs, driven by limited economies of scale and persistent technological challenges, are the primary factors keeping prices elevated. Addressing these barriers could significantly accelerate the diffusion of bio-based plastics in the market [8].

Research into the circular bioeconomy remains fragmented, focusing on relatively isolated dimensions of the transition. Analysis that seeks to link different geographic dimensions or sectoral and value-chain-based foci is rare. This also means that the identification of barriers takes place in different spheres, failing to link aspects related to the incumbent regime with the challenges of emerging technologies and industries [9].

Several challenges related to the recovery of agri-food waste and by-products are critical to the sector's growth [25]. One issue is that some biorefineries struggle to process large volumes of feedstock due to the seasonality of certain products. Additionally, there is a lack of studies identifying the most efficient way to centralize waste management. Biorefineries may be reluctant to invest in logistics if the costs exceed the added value of the biomass, leading the agroindustry to dispose of waste through incineration or landfills.

Implementing a circular bioeconomy model could address these issues by revaluing food waste, by-products, and biomaterials produced by biorefineries, thereby reducing waste and promoting sustainability. However, current methods for processing and producing biomaterials from food waste at a laboratory scale show low yields. To make bioproducts viable for large-scale production and commercialization, these yields must be improved. Enhancing processing and production techniques is one common approach to achieving better results. Additionally, a possible solution to offset the lower yield is to integrate production within a multi-feedstock biorefinery model, allowing for the simultaneous production of various bioproducts from the same feedstock.

3. Regulation framework related to biobased packaging

In response to the environmental concerns associated with fossil plastic use, Europe and many other countries and regions have introduced strict regulations to reduce plastic waste and promote the use of biodegradable alternatives. One notable example is the EU's Single-Use Plastics Directive, which came into effect in 2021. This directive has accelerated the shift toward biodegradable packaging by banning certain single-use plastic products and encouraging the adoption of more sustainable materials. These regulations aim to reduce plastic pollution, foster innovation in biodegradable packaging, and drive a more sustainable approach to product packaging across industries [1].

The European Commission is deeply committed to addressing issues related to plastic production and waste management. Plastic plays a pivotal role in advancing circular economy models [26]. Through the Circular Economy Package and the European Strategy for Plastics, efforts are being made to enhance sustainability across the plastic value chain—from production to waste recycling. The Directive on Single-Use Plastics, awaiting formal publication, sets strict targets for reducing environmental impacts, focusing on the ten most commonly littered plastic products. The European Strategy for Plastics demands significant efforts from the plastics industry to transition from unsustainable practices, reducing the environmental harm caused by fossil-based products. While existing packaging laws have encouraged sustainable practices, the Directive on Single-Use Plastics promotes collaboration among policymakers, industry leaders, trade associations, and consumers. Although Member States had two years to implement the Directive, many European-wide industrial initiatives were already in progress. Major brands, which contribute significantly to plastic pollution, are forming alliances, joint ventures, and associations. However, effective coordination across these efforts required improvements in internal management to align with European expectations. Such changes could impact supply chains, processes, marketing, and waste management, requiring integrated skills and innovation to maintain competitiveness. Notable examples are companies that embraced circular economy principles by transforming their supply chain into a closed-loop system, where waste becomes a resource. By decoupling value creation from purely economic growth, these companies established a competitive advantage in green markets, demonstrating how sustainable practices can drive differentiation and success. Small and medium enterprises (SMEs) are also encouraged to prioritize sustainability investments to foster innovation, seize new market opportunities, and bolster European leadership in sustainable markets. Collaboration between policymakers and industry stakeholders is essential. The European Commission engaged with stakeholders to implement measures aimed at meeting ambitious environmental targets. Efforts included regulating the production and consumption of plastic bags and packaging, particularly food packaging, to align with the new directives. Additional market restrictions have spurred industry responses, such as forming alliances, joint ventures, and creating a more integrated value chain. A case study highlights a successful closed supply chain as a model for sustainable practices.

To reduce waste, it is essential to combine legal measures with efforts to improve production processes, develop longer-lasting products, and encourage consumers to choose eco-friendly, durable options. Experience from European Union member states shows that economic incentives, the spread of best practices, changes in consumer habits, and other social shifts significantly contribute to waste reduction [27].

Global bioplastics production is projected to grow from 2.417 million tonnes in 2021 to 7.593 million tonnes by 2026, more than tripling current capacities. To manage this growth effectively, it's crucial to address challenges and barriers related to bio-based and biodegradable plastics. These include macroeconomic, regulatory, technological, and social factors [27].

Proper waste management for bio-based plastics requires separate collection and treatment under controlled conditions. However, there are currently no legal provisions for separate collection, leading to these plastics being mixed with hazardous waste, conventional plastics, or municipal waste.

An effective strategy for managing bio-based and biodegradable plastics must align with broader plastic waste management practices, emphasizing standardizing waste collection systems and creating a unified infrastructure. This approach would improve sorting and treatment processes, supporting efficient waste management.

The degradation of biodegradable plastics, such as in marine, soil, and freshwater environments, depends on the polymer's chemical composition and the characteristics of the environment. However, degradation rates are generally very slow. For instance, PLA blends can take 4–5 years to break down in soil and up to 12 years in aquatic environments. This highlights the need for bio-based and biodegradable plastics to be collected and treated separately, primarily under controlled and regulated conditions.

In 2022, the European Commission introduced a policy framework focused on the sourcing, labelling, and use of biobased, biodegradable, and compostable plastics. Announced as part of the European Green Deal, Circular Economy Action Plan, and Plastics Strategy, the framework aims to support a sustainable plastics economy by clarifying where and how these materials can offer environmental benefits under specific conditions and applications. It also ensures they meet the same high standards as other materials [26].

Although no specific EU law currently regulates bioplastics, existing legislation, such as the EU Taxonomy, Single-Use Plastics Directive, Plastic Carrier Bags Directive, and Packaging and Waste Framework Directives, addresses some aspects of their use. While the framework itself is non-legislative and not legally binding, it outlines the Commission's perspective and will shape future EU policies on topics like green claims, sustainable product design, carbon removal, and microplastics [25].

In January 2024 Bioplastics Europe published a booklet based on its research project activities [28], including the following policy recommendations:

- **Educate and Inform Consumers:** Enhance education and communication efforts to raise awareness among end-users about the benefits of bio-based, biodegradable, and compostable plastics, as well as proper disposal methods.
- **Boost Research**: Promote in-depth research across the entire bio-based material value chain—from production to disposal—to address existing technical and economic challenges.
- **Conduct Rigorous Testing**: Implement thorough toxicity and ecotoxicity assessments for bio-based and biodegradable materials, including additives and their combinations, to evaluate risks to human health and the environment.

- **Improve Material Testing:** Encourage plastic industry companies to perform advanced material tests, such as degradation tests and rapid degradation evaluations, to study material behavior during breakdown processes in waste facilities and natural environments.

In the same period the association of companies European Bioplastics has published a Policy Manifesto, including recommendations related to the harmonization of regulations, incentivising access to sustainable biomass, enhancing financial support to technological innovation, closing infrastructure gaps and incentivising access to food waste collection, increasing market uptake and increasing consumers awareness [29].

Incentives to promote the use of bioplastics include policy measures like subsidies for bioplastic production and taxes on fossil-based plastics. The study of Dokl et al. [2] highlights how this combination of taxes and subsidies can enhance the economic viability of bioplastics. Additionally, investments in technology are critical for improving the efficiency of agricultural feedstocks and minimizing land use. Advances in biorefinery technologies, particularly those utilizing non-food feedstocks like algae or agricultural residues, are essential to reduce competition with food production and enhance overall sustainability [2].

Projections in this study indicate that global plastic production will steadily rise from 464 million tons (Mt) in 2020 to between 735.4 Mt and 884.0 Mt annually by 2050, depending on the estimation method. Despite anticipated improvements in recycling rates, the volume of plastic waste is expected to double by 2050.

Proactive policy measures are critical to addressing challenges in plastic production and waste management. Intervention analysis emphasizes the benefits of policies combined with complementary actions such as decarbonizing energy systems, expanding bio-based plastics production, leveraging power-to-X technologies, and implementing comprehensive recycling strategies.

Regional analyses show that strict environmental policies—like bans on single-use plastics, plastic taxes, and extended producer responsibility—significantly reduce plastic waste. Countries with stringent policies, coupled with industrial innovations, have been more successful in minimizing plastic waste, serving as models for others. The findings underscore the importance of continued policy development, collaboration within the industry, and consumer education to advance sustainability goals effectively.

In the Moroccan context, the law Dahir n°1-10-145 prohibits the manufacture of non-degradable or non-biodegradable plastic bags for the local market, as well as their import, holding for sale, offering for sale, sale or distribution free of charge.

4. Peculiarities of the Mediterranean area

The Mediterranean region is a diverse and dynamic area, both culturally and ecologically. Its food systems, including the Mediterranean diet—recognized as an intangible cultural heritage by UNESCO in 2013—and its rich biodiversity make it a global hotspot. However, it is also one of the most vulnerable regions to global environmental changes, particularly soil degradation and water scarcity.

Mediterranean farming landscapes have evolved over millennia through interactions between humans and varied geographical, soil, and climatic conditions, forming archetypal social–ecological systems. Traditional agriculture in the region is characterized by agro-silvo-pastoral mosaic systems, which occupy about 23% of the land. These systems integrate agricultural, pastoral, and forestry components, fostering efficient resource use, high biodiversity, diverse products, and valuable ecosystem services, making many Mediterranean farming systems multifunctional and of high ecological value.

The region also experiences striking contrasts: southern Mediterranean areas face growing land-use pressures and competition, particularly in fertile plains, while northern Mediterranean regions, especially less productive mountainous areas, are seeing land abandonment. Socioeconomic challenges, including demographic shifts, political instability, and economic disparities, further shape the region's agricultural and social landscapes. These dynamics make the Mediterranean an ideal case study for examining diverse food systems and agricultural practices within a complex social–ecological framework [30].

Food waste management and circular economy strategies are crucial for building sustainable food systems. In the Mediterranean region, food security is at risk due to limited natural resources, dependency on food imports, and unstable global trade. Adopting a circular economy approach to food waste helps retain the value of food, nutrients, and resources for longer by minimizing resource usage and repurposing waste and by-products.

The Mediterranean region's diversity across sub-regions, countries, and communities requires tailored approaches to waste management. To address this, a guidebook provides a flexible framework and practical tools for local municipalities to develop custom zero waste strategies. Adopting a zero-waste approach can help Mediterranean regions tackle their unique challenges. Such strategies can play a central role in local climate mitigation plans, establish efficient and cost-effective waste management systems, and significantly reduce waste generated by residents and visitors. They also enable municipalities with both urban and rural areas to address their distinct needs. Furthermore, zero waste practices promote waste prevention through reuse, repair, and product redesign, integrating sustainability into daily community life [31].

Municipalities can address waste prevention effectively by implementing measures at various levels and ensuring these efforts complement one another. Key strategies include policy improvements, public awareness initiatives, and promoting sustainable practices within the community.

Actions at policy level are:

- **Public Commitments:** Municipalities can demonstrate their commitment by joining initiatives like the Plastic Free Community, formal zero waste programs with clear targets, or the Ellen MacArthur Foundation’s New Plastics Economy Global Commitment.
- **Local Incentives:** Introducing local certifications, labels, public challenges, or competitions can encourage residents and businesses to adopt waste-reducing practices.
- **Regulatory Advocacy:** Municipalities should not only adjust local policies but also advocate for changes to restrictive regional or national legislation. For example, adopting green public

procurement policies that prioritize waste reduction, sustainable sourcing, and packaging minimization.

- **Economic Incentives:** Provide rewards or penalties to motivate citizens and businesses to minimize waste.

Actions of Education and Community Engagement:

- **Awareness Campaigns:** Focus on promoting concepts like reuse, repair, and refusal of unnecessary items. Highlighting traditional, low-waste practices, such as using tap water instead of bottled water, can encourage behaviour change.
- **Self-Sufficiency:** Support gardening and food self-sufficiency programs to reduce packaging and food waste.
- **Inspiring Change:** Create a community culture that views waste reduction as a collective challenge, motivating individuals to adopt sustainable habits.

With over 70% of the Mediterranean population living in urban areas, cities play a significant role in shaping food consumption patterns. Urban areas can transition from being waste endpoints to becoming innovation hubs, transforming food by-products into valuable materials. Local governments can integrate food systems into urban plans by prioritizing food waste management and circular practices.

Collaborative efforts among local governments, civil society, research institutions, the private sector, international organizations, and investors are essential to shift from a "take-make-waste" model to a circular economy [32]. Education and awareness campaigns at the local level can help reshape perspectives and behaviors, while city-to-city exchanges and twinning programs enable sharing best practices and fostering innovation. To succeed, increased investments are needed in infrastructure and technologies for waste upcycling, alongside the revival and promotion of traditional food preservation methods. Several international networks are already advancing these initiatives, demonstrating the potential for cross-city knowledge transfer and sustainable development [33].

The 2015 FAO report on global food insecurity highlighted that most Mediterranean countries, including those in Southern Europe, the Middle East, and North Africa, have largely eliminated severe food insecurity. However, over the past 50 years, adherence to the traditional Mediterranean diet has significantly declined. This diet has been replaced by eating habits characterized by increased consumption of animal-based and ultra-processed foods and reduced intake of plant-based foods, reflecting a shift toward Western dietary patterns.

This dietary transition has resulted in poorer nutrient intake and higher risks of obesity and diet-related non-communicable diseases for those adopting the Western diet. Key factors driving this shift include the widespread availability of processed, calorie-dense, and nutrient-poor foods, facilitated by transnational food corporations, trade liberalization policies, and, in some cases, government subsidies [19].

Alongside dietary and nutritional shifts, the Mediterranean region is experiencing significant environmental challenges, including land degradation, water scarcity, pollution, biodiversity loss, and climate change. Studies also indicate that the Western-style diet prevalent in the region has a substantial environmental impact.

Although the Mediterranean has historically been a major food-producing area with rich agro-biodiversity, these environmental changes threaten the capacity of local food systems to maintain food and nutrition security. To address these challenges, it is essential to promote and implement sustainable diets across various contexts, including industrialized and transitioning countries, with a focus on preserving food security and quality in the Mediterranean region.

In the food chain, the production phase—particularly meat and dairy production—has the most significant environmental impact. Other critical factors include transportation, packaging, and food loss or waste. Key contributors to these impacts are greenhouse gas (GHG) emissions, water depletion, and extensive land use for agricultural production and occupation. These practices lead to biodiversity loss, soil degradation, and diminished soil quality, exacerbated by the use of harmful chemicals like pesticides on farmland.

The study by Bouranta et al. [21] explored and compared consumer perceptions of food safety in Greece, Italy, and Spain. Using a structured questionnaire, the survey focused on issues such as food characteristics, labeling of systems like Quality Management Systems (QMS) and Food Safety Management Systems (FSMS), consumer trust in the food supply chain, and the perceived illusion of food control. Data was collected from 2,664 respondents across the three countries, which share similar cultural and dietary traits. The findings revealed significant differences in food safety perceptions. Spanish consumers exhibited the highest trust in the food supply chain and the strongest illusion of control over food safety. Italian consumers rated food characteristics and QMS-FSMS labeling higher than their Spanish and Greek counterparts. This study highlights the diverse food safety concerns among consumers in these Mediterranean nations [21].

By 2024, the European Commission plans to evaluate a new framework for sustainable labeling. Clodoveo et al. [34] proposed the introduction of the Mediterranean Index (Med Index), a labeling system designed to encourage adherence to the Mediterranean diet, a healthy and sustainable eating pattern. The system promotes physical activity aligned with meal energy intake and motivates producers to create healthier, more sustainable foods. It incorporates 27 criteria across three key areas: nutritional, environmental, and social sustainability. The Med Index is envisioned as a comprehensive, front-of-pack label that is practical for food producers, relying on measurable and widely accepted criteria typically used independently by various stakeholders.

5. Perspectives for PLAMINPACK

The PLAMINPACK project aims to develop innovative food packaging for perishable fruits in the Mediterranean region.

The global biodegradable packaging market is projected to grow at a compound annual growth rate (CAGR) of 5-6% from 2024 to 2029. This growth underscores the expanding market opportunities for businesses investing in biodegradable packaging solutions.

Food packaging has a significant impact on product choices, especially among younger generations. As a result, colleges and universities have become effective platforms for disseminating targeted information, improving students' knowledge and awareness. Encouraging sustainable disposal practices at the individual level could collectively help reduce the impact of climate change.

A notable gap still exists between consumer perceptions and the actual benefits of bio-based packaging, requiring stronger engagement in outreach activities. The effectiveness of replacing fossil plastics with renewable, biodegradable, and recyclable materials to address waste management, pollution, and climate change concerns should be communicated more widely.

The structure and outcomes of PLAMINPACK can serve as tangible examples of the effectiveness of a circular bioeconomy approach, where plant waste residues are recovered and used to create smart, innovative, and sustainable packaging. The dissemination of agricultural knowledge and practices to younger generations can effectively communicate the need for better integration of materials derived from agricultural residues for food preservation.

The Mediterranean region is well-positioned to adopt and benefit from bio-based and biodegradable packaging, contributing to environmental sustainability and the preservation of traditional food systems. The Mediterranean diet, as well as the need to protect the region's biodiversity in the face of climate change, is closely connected to the innovative circular packaging model promoted by PLAMINPACK. Initiatives linking this healthy diet with advanced, "biomimetic" packaging for perishable products can enhance the effective use of project results.

Position papers resulting from PLAMINPACK's implementation and networking activities can serve as a valuable methodology to proactively influence policy in the Mediterranean region, considering not only specific political actions but also the importance of education and community engagement.

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