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Review

The Journey of Plastics: Historical Development, Environmental Challenges, and the Emergence of Bioplastics for Single-Use Products

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Abstract: This paper explores the historical development of conventional plastics, tracing their evolution from early forms to their pervasive use in modern society. Its observations include the rise of mass plastic production during World War II and the post-war development, showcasing plastics' economic and societal impact. The environmental repercussions of plastic pollution have led to increased global awareness and calls for sustainable alternatives. The emergence of bioplastics is investigated, including their classification, properties, applications, and challenges in scaling. This paper emphasises the urgency of adopting bioplastics for a sustainable future and discusses efforts towards homogenisation and standardisation across global markets.

Keywords: plastic; bioplastic; plastic pollution; environmental

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1. Introduction to the History of Plastics

1.1. Historical Development of Conventional Plastics and Their Varieties

Plastics are integral to modern society, but their environmental impact is significantly harmful. Biobased and biodegradable plastics from renewable resources offer promising replacements by reducing CO_2 emissions during production and providing improved end-of-life management opportunities [1]. These innovations can pave the way for a more sustainable future, helping mitigate conventional plastics' undesirable effects. The assortment of plastic materials in use today is extensive, with several types, including polyethene terephthalate (PET), high-density polyethene (HDPE), polyvinyl chloride (PVC), low-density polyethene (LDPE), polypropylene (PP), and polystyrene [2]. This list further extends from thermoplastics to thermoset polymers such as polyurethane (PU) and polychlorinated biphenyls (PCBs) [3]. Each type has distinguishing properties and applications, contributing to plastics' versatility and inescapable use across various industries, as seen in Figure 1. In agriculture, these polymers are applicable in forming nursery pots regarding HDPE and PP; LDPE is employed in irrigation tubing. PS is used for trays, PVC is primarily applied in home and computer cabling [3], and PU is commonly used in insulation for construction [4]. Many of the thermoplastics mentioned—PP, LDPE, HDPE, PET, and PS—are utilised in toy manufacturing and by the food packaging industry regarding the use of films and beverage bottles [4]. These polymers are valued for their performance in various thermal conditions. PVC has impressive thermal stability up to 60–70 °C. LDPE is favoured for its good shock resistance at low temperatures, and materials created from this polymer can be used up to 60 °C, and HDPE performs well at higher temperatures up to 80–100 °C. PP is similar to high-density polyethene, offering increased thermal stability [5]. All these factors contribute to plastic's appeal and broad utilisation across various applications on a global scale.

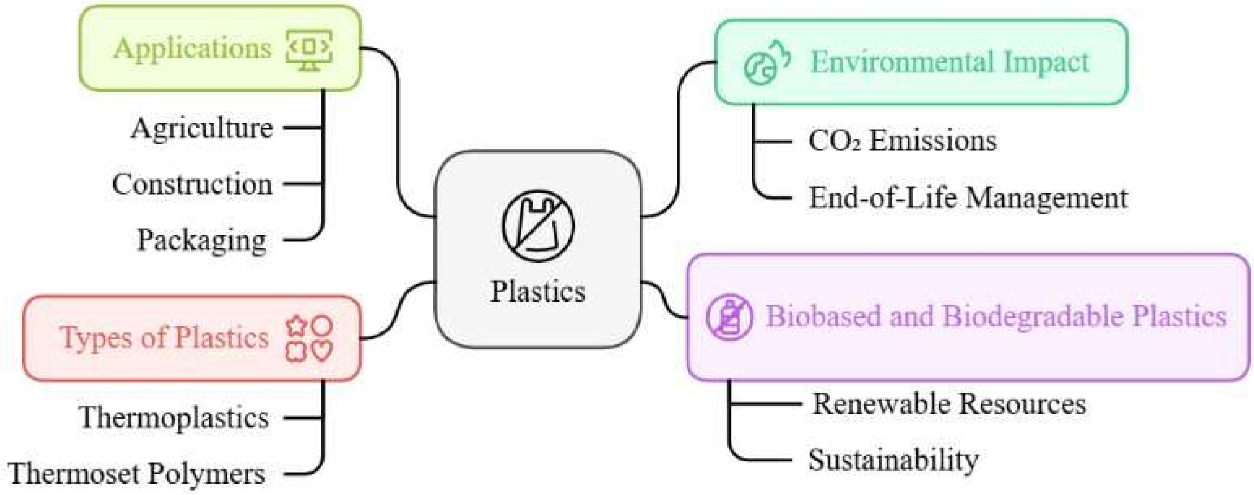

Figure 1. Illustrates the application of different conventional plastics.

1.2. The Early History of Plastics

The origins of plastics began with naturally occurring polymers, such as rubber and shellac. These crude materials were forerunners to synthetic alternatives, with cellulose playing a pivotal role [6]. The innovation of the first synthetic plastic, Parkesine, by Alexander Parkes in 1862 marked a momentous milestone. This material, derived from cellulose treated with nitric acid, allowed for versatile moulding and shaping [7]. The groundwork for future innovations in the plastic industry was laid with this invention. In the early 20th century, Belgian chemist Leo Baekeland generated Bakelite, the first fully synthetic plastic, in 1907. Bakelite was made from phenol and formaldehyde, which showcased unique, non-conductive and heat-resistant properties, making it invaluable in electrical applications, particularly within the flourishing automotive and electrical sectors [8]. This discovery catalysed a surge in plastic production and drew attention to the potential for synthetic polymers to replace traditional materials like wood, glass, and metal [9].

1.3. From Mass Production and World War II to Post-War Expansion and Consumerism

The advancements in polymer chemistry during the 1930s and 1940s were a turning point for the plastics industry, and notable developments included nylon, polystyrene, and polyethene. Wallace Carothers created nylon in 1935 at DuPont, marking the first prominent synthetic fibre production [10]. Initially used as a silk substitute in stockings and parachutes, nylon became vital during World War II when the supply of natural fibres declined [11]. World War II considerably accelerated the mass production of plastics, as the war effort demanded lightweight, durable, and easily mass-produced materials [6]. Polymers like polyethene and polytetrafluoroethylene (PTFE) were essential for military applications involving insulation for radar cables and aircraft components [9]. By the war's end, plastics became ingrained in industries ranging from defence to consumer goods, setting the stage for a post-war plastics production escalation [12]. The demand for lightweight and durable materials during World War II catalysed the rapid advancement of synthetic plastics, which were initially used for military applications [13]; this period established a foundation for post-war consumer demand for plastic products, setting the stage for widespread adoption.

The post-war era ushered in a new age where plastics became tantamount to consumer products. The 1950s and 1960s saw an exponential rise in plastic usage across packaging, household items, and textiles, driven by innovations in new polymers such as polypropylene [6]. These materials offered cost-effectiveness and versatility, leading to widespread implementation amidst numerous sectors [9]. Key advancements in the 1950s, particularly the discovery of high-density polyethene (HDPE) and low-density polyethene (LDPE), revolutionised food and beverage packaging due to their lightweight and moisture-resistant characteristics [14]. Polyethene terephthalate (PET), invented in 1941, also gained recognition in the 1970s for beverage bottle production [13]. Using single-use plastics in the 20th Century marked a pivotal shift in consumer behaviour, as items like plastic bags and straws became universal due to their convenience and low cost [15]. This consumer movement significantly increased plastic waste, leading to enhanced environmental concerns. The late 1980s and 1990s saw growing awareness of the ecological distress of plastic pollution, as seen in Figure 2, exemplified by the discovery of the Great Pacific Garbage Patch, which emphasised the scale of plastic waste in marine environments [16].

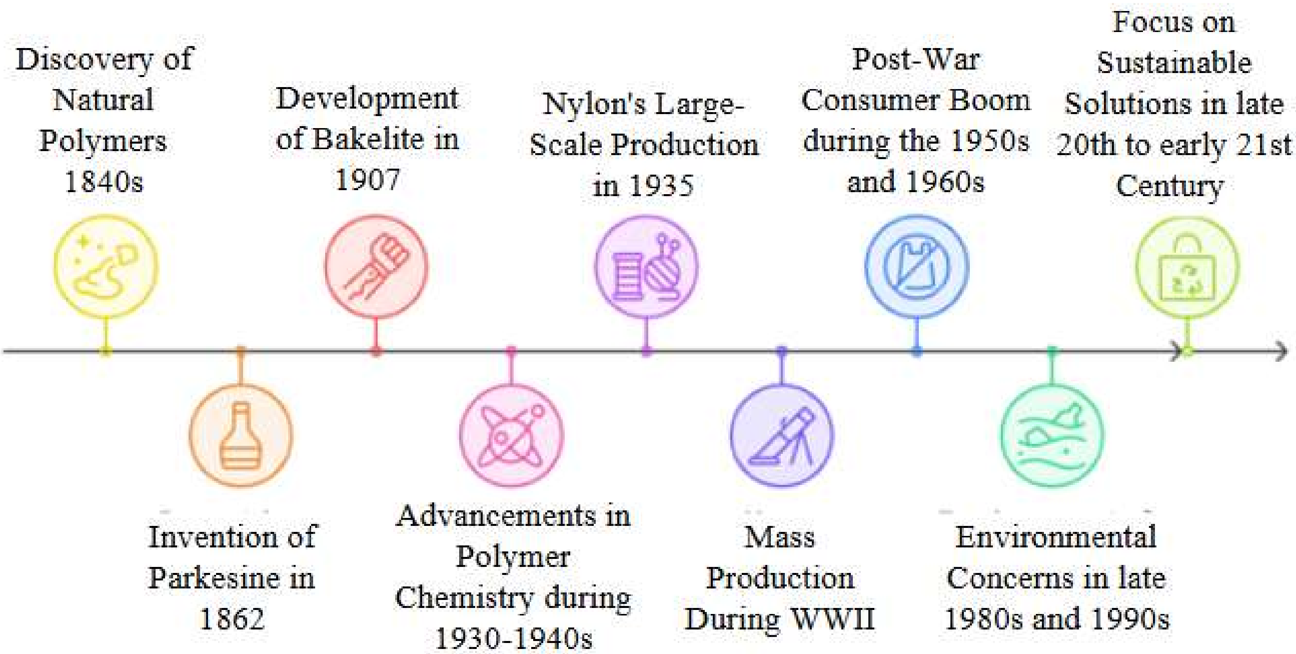

Figure 2. Displays the historical timeline of plastics from discovery to modern versions focused on sustainability.

1.4. The Role of Plastics in Modern Society

Today, plastics permeate nearly every aspect of life, influencing healthcare, transportation, electronics, and construction sectors. Their remarkable strength, durability, and chemical resistance have made them essential for manufacturing medical devices, automotive components, and packaging materials [9]. In developing countries, plastics provide low-cost, high-impact solutions, enhancing technology and quality of life [17]. Despite their advantages, the swift expansion of the plastics industry has raised considerable environmental concerns. The characteristics that make plastics durable also create challenges in waste management, predominantly regarding marine pollution and the accumulation of non-biodegradable waste [18], Figure 3. In response, the industry increasingly states its eagerness to give precedence to developing bioplastics and progressive recycling technologies to mitigate environmental impacts [19]. This focus on sustainable solutions signifies the next frontier in plastic innovation as society seeks to balance the benefits of plastic materials with their ecological effects [20]. The historical trajectory of plastics reflects a narrative of novelty driven by societal needs and technological advancements. From early natural polymers to the rise of artificial plastics and the consumer boom, plastics have played a dynamic role in various applications. While their contribution to modern life is undisputable, addressing the environmental challenges correlated with plastic waste is imperative for their sustainable future. As research continues into biodegradable and sustainable plastics, the next chapter in the story of plastics promises to be transformative, potentially reshaping the industry again [6,21].

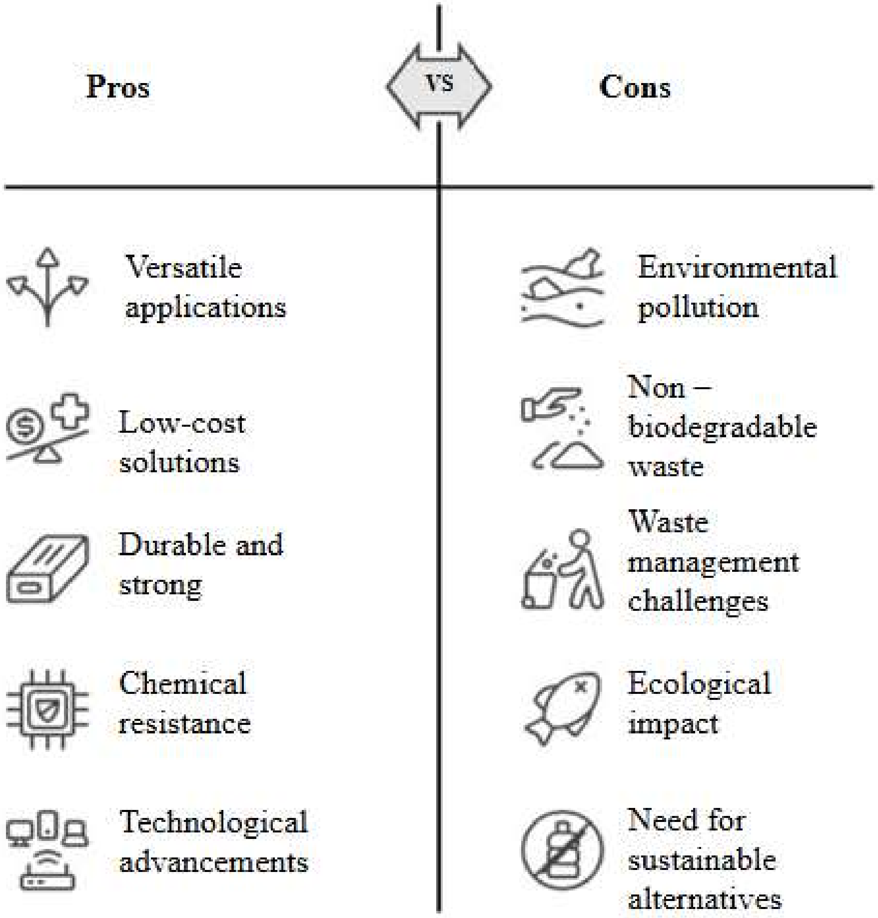

Figure 3. Pros and cons of petroleum-based polymers.

2. Pervasive Use in Society

The increasing reliance on plastic packaging and products is attributed to their appealing properties for manufacturers and consumers alike, including their lightweight, versatility, functionality, and cost-effectiveness. Notably, plastic bags' cost, design, and single-use nature have also significantly contributed to their global prevalence [22]. As a result, plastic consumption has surged over recent decades, raising concerns about its environmental impact. Plastic products can decompose for an average of 100 years, aggravating the plastic waste crisis [23].

The success of plastics in countless sectors stems from their low production costs and high necessity across diverse applications. However, their dependence on fossil fuels and non-biodegradability poses substantial environmental challenges [2]. The exponential rise in plastic use is intensely pronounced in the packaging industry, which has extensive negative implications for global ecosystems [24]. This increase can be credited to plastics' inherent versatility, excellent processability, and advantageous thermal and mechanical properties [25]. Despite the drawbacks, plastics remain in high demand due to their durability and proficiency in processing [26].

Additionally, plastics are resource-efficient during both their production and usage phases, which are crucial as energy consumption is highest during the use phase of products like houses, cars, and electronics. For instance, plastic insulation materials can save more than 140 times the energy needed for production throughout their service life [27]. Traditional plastic materials also play a vital role in protecting goods and food, reducing breakage and waste. Consequently, plastics are integral to many sectors, including packaging, construction, automotive, and healthcare [27].

2.1. Economic Contributions of the Plastic Industry and Environmental Repercussions

The European plastics industry recognises the economic significance of plastics, comprising raw material producers, converters, and machinery manufacturers. In 2015, the industry directly employed over 1.5 million people across nearly 60,000 companies, primarily small- and medium-sized businesses [27]. The sector generated a turnover exceeding EUR 340 billion and upheld a trade balance of over EUR 16.5 billion, representing its substantial economic footprint. Additionally, the industry contributed nearly EUR 27.5 billion to public finances and welfare in the same year, highlighting its importance in supporting social services [27].

Regarding its multiplier effect, the European plastics industry has a gross domestic product (GDP) multiplier of 2.4 and a job multiplier of almost three, positioning it alongside other vital sectors, such as pharmaceuticals [27]. In 2014 alone, over 7.5 million tonnes of plastic waste were collected for recycling, reflecting an industry beginning to acknowledge sustainability's importance [27]. By 2016, global plastic consumption reached 322 million tonnes, with Europe accounting for 58 million tonnes, further emphasising plastics' critical role in the economy and everyday life [27].

Many countries began implementing legislative measures to reduce plastic use in response to these environmental concerns. The European Union's directives on single-use plastics are prime examples of how regulations have been implemented to encourage more sustainable practices among member states [28].

The environmental impact of plastic pollution is overwhelming and far-reaching, where plastics are found in marine and terrestrial ecosystems, disrupting wildlife and food chains [29]. Despite these environmental challenges, the economic contributions of the plastic industry remain extensive. However, the costs of managing plastic waste, including clean-up and recycling, impose a financial burden on communities and governments. For instance, the United Nations Environment Programme estimates that marine plastic pollution alone incurs costs exceeding USD 13 billion annually, encompassing clean-up efforts and losses in tourism [30].

Despite these challenges, the rising awareness of environmental issues presents opportunities for innovative developments within the plastic sector to amend these problems. The push towards sustainable materials and practices fosters new markets for biodegradable plastics and recycling technologies.

2.2. Societal Awareness and Responsibility

Public awareness of plastic pollution has surged recently, driven by grassroots movements, where communities act as a basis for political changes and media campaigns. Initiatives such as "Plastic Free July" inspire individuals and communities to reduce plastic usage, highlighting the importance of personal responsibility in addressing this global epidemic [31]. Social media has played a pivotal role in amplifying these efforts, enabling the rapid dissemination of information about the harmful effects of plastic on the environment and human health. Educational organisations are also essential in shaping societal attitudes towards plastic use. Schools increasingly integrate sustainability and environmental education into their curriculum, promoting a generation more conscious of consumption habits [15].

Legislative responses to plastic pollution also highlight increasing societal fears of the adverse effects of plastics. Countries worldwide are implementing bans on single-use plastics to incentivise businesses to accept more sustainable practices. The European Union's Single-Use Plastics Directive aims to reduce the consumption of certain plastic products, encouraging member states to investigate alternatives and promote circular economy practices [28].

The pervasive nature of plastic in society presents a complex relationship of historical development, economic significance, environmental impact, and social responsibility. While the financial contributions of the plastic industry are substantial, they come with hidden costs that manifest as damage to the ecosystem and our communities. The growing public awareness and advocacy surrounding plastic pollution underline the necessity for a transition towards sustainable practices, not just as an environmental imperative but as a social and economic necessity. Addressing the plastic crisis requires a collaborative approach encompassing multiple dimensions, ensuring a sustainable future for coming generations.

3. Environmental Consequences of Plastic Pollution

3.1. Marine Ecosystems

Plastics significantly threaten marine ecosystems, with wildlife often ingesting plastic debris and mistaking it for food, leading to malnutrition, intestinal blockages, and fatalities [32]. For instance, sea turtles frequently consume plastic bags, believing they are jellyfish [33]. Microplastics, particles smaller than 5 mm, are particularly alarming due to their prevalence in marine environments and their predisposition to bioaccumulate within the food chain [34,35]. Beach clean-ups are a way to mitigate plastic pollution; they are government or individually led practices, such as one of the largest beach clean-ups in Mumbai, India [36]. In October 2015, two men, Alfroz Shan and 84-year-old neighbour Harbansh Mathur, were so frustrated at the appalling condition of Versova Beach that they felt strongly they had to do something [36]. They began doing the only option they had, to pick up the decomposing waste themselves, as Afroz, whose profession was a lawyer, knew the legal route would be an extensive and slow process [36]. Slowly, the rest of their community, over 70,000 adults and 60,000 students, began to join the clean-up with volunteers from slum dwellers, Bollywood stars, corporates, schoolchildren, and politicians [36]. So far, roughly 40 tonnes of waste have been removed from the beaching, Figure 4. The effects of this clean-up have not only revealed the natural beauty of the beach and removed the waste, thus reducing the plastic pollutants entering the ocean, but also created a clean environment for the Olive Ridley turtles to lay their eggs with at least 80 turtles, making their way into the Arabian Sea from these nests [36]. In this case, a locally organised group succeeded in such a successful operation, reclaiming their beach and mitigating the detrimental effect of waste on their environment. It is heartbreaking that such a scenic area was reduced to a seaside landfill. This is where certain bioplastics and swiftly implemented global policies could potentially alleviate this situation of the community having to act quickly to reverse the damage done to their home and that of flora and fauna in the area.

Figure 4. (**A**) portrays Versova Beach, India, before the clean-up occurred, and (**B**) shows the pristine sands of the beach after this enormous community clean-up [36].

3.2. Terrestrial Ecosystems

Plastic pollution also adversely impacts terrestrial ecosystems, such as overflowing landfills, leading to soil degradation and water contamination [37]. Microplastics, particularly, are of substantial concern for the agricultural sector as plastic mulching is common among farmers. The negative effects of this practice are predominantly soil health deterioration, leading to soil infertility, nutrient loss, and the release of toxic additives such as BPA into the soil [38]. Additionally, plastic waste in urban settings can block drainage systems, exacerbating flooding and creating health hazards by accelerating the spread of disease vectors [18], Figure 5.

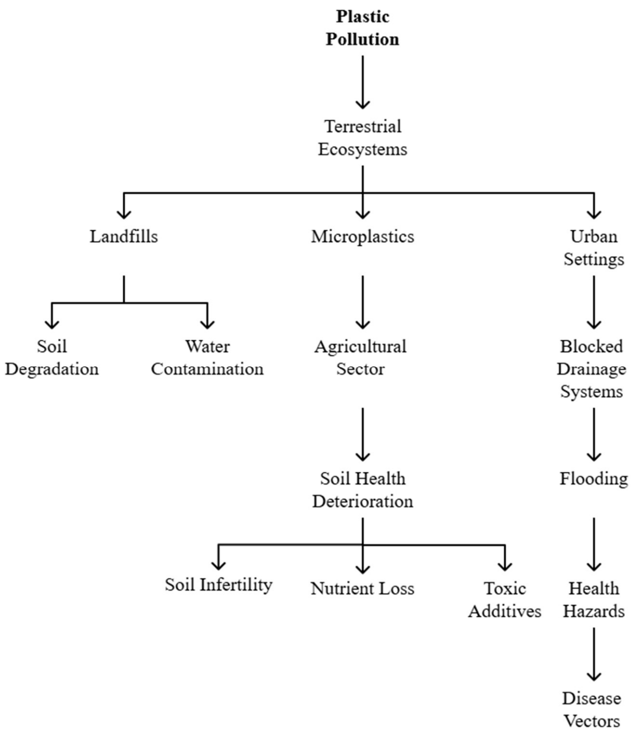

Figure 5. A breakdown of plastic pollution in the environment and its summarised consequences.

3.3. Human Health Implications

The effects of plastic pollution extend beyond wildlife to human health, particularly in the case of microplastics found in food and drinking water, raising concerns about their toxicity [39]. Chemicals linked to plastics, such as bisphenol A (BPA) and phthalates, are known endocrine disruptors and may lead to reproductive and developmental issues [40]. BPA is worryingly linked to cardiovascular disease, cancer, kidney disease, and birth defects. It has been found in the blood of pregnant women and placenta tissue, indicating foetal exposure to BPA, with feeding bottles being the primary exposure source for young children [41]. A study by [42] concerned with microplastics' effect on human health investigated how to quantify its presence in human blood with a subject group of 22 healthy people in the Netherlands. GC/MS was primarily used to identify the presence of several polymers—PP, PS, PE, and PET. This blood analysis concluded that 77% of donors contained quantifiable amounts of these plastics in their blood, with the authors stating a need for further investigation to enlighten everyone on the health implications of microplastics [42]. This situation draws attention to the need for comprehensive studies to assess the short- and long-term risks associated with microplastic exposure, as Figure 6 represents.

Figure 6. Illustrates the effects of microplastics on the human body and the need for more in-depth research.

3.4. Significance of the Topic

Addressing plastic pollution is crucial, as the United Nations has recognised it as a global crisis necessitating immediate action. In 2018, the UN Environment Assembly passed a resolution urging member states to combat plastic pollution [30]. The economic consequences are also significant, with clean-up efforts costing billions annually. For example, the European Union estimates plastic pollution costs the fishing industry approximately EUR 1.5 billion yearly [43]. Efforts to alleviate plastic pollution include promoting alternative materials, enhancing recycling technologies, and implementing policies to reduce plastic production and consumption. Innovations in bioplastics resulting from renewable resources present promising sustainable alternatives, though widespread implementation remains limited [44]. The most effective way to mitigate and reduce the detrimental repercussions of plastic pollution is through implementing legislation and policies at the national and international levels. China's announcement in 2017 on a ban on importing plastic waste from first-world countries, predominantly Europe and North America, is an example of an effective way to force others into progressing their own plastic management systems [41]. Implementing this ban by the Chinese government, known as the 'green fence' and 'blue sky' programs, caused direct and indirect problems for European and North American countries, pushing them to start improving their own plastic waste management systems [41]. It is valid to note that the plastic waste trade continued with other countries such as Indonesia and Turkey [41], but this ban caused a significant reduction in plastic waste in Europe and increased plastic waste management, with levels in European countries now stabilised.

3.5. The Urgency of Sustainable Alternatives

The dependence on fossil fuels in plastic production contributes to increased atmospheric CO_2 levels, exacerbating the greenhouse effect and contributing to climate change. This has led to more frequent extreme weather events and rising global temperatures, motivating international environmental policies aimed at reducing CO_2 emissions and protecting ecosystems [45]. The widespread use of petrochemical plastics substantially threatens biodiversity and human health due to their pollution [46], Figure 7. Despite their versatility, traditional plastics are non-biodegradable, leading to extensive environmental accumulation in landfills and oceans and ultimately entering the food chain [47]. Disposable plastic packaging, another major contributor to plastic waste, is consistently discarded in landfills, ultimately breaking into microplastics and polluting the environment. With 300 million tonnes of plastics produced annually, only 10–13% are recycled, highlighting the precarious need for innovative materials that imitate plastic's utility while being biodegradable [26].

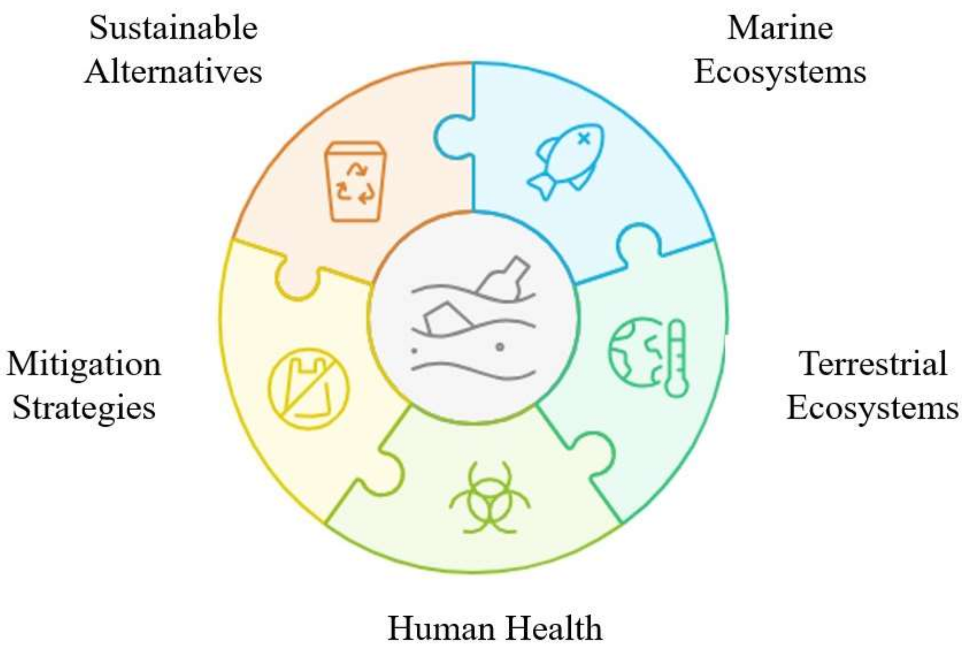

Figure 7. Portrays the 5 main topics related to plastic pollution.

Conventional plastics used in food packaging contribute to waste and threaten ecosystems due to their slow decomposition rates, presenting risks to wildlife and human health [48]. While these materials effectively preserve food, they are derived from fossil fuels and can leach harmful compounds into food products, necessitating a shift to sustainable alternatives [49]. The leading cause of plastic pollution is single-use plastics, which account for a significant portion of the estimated 380 million tonnes of plastic produced globally annually. Unfortunately, most of the population remains in the environment due to the stable bonds in their chemical structures, leading to prolonged degradation that contributes to environmental pollution [25]. Moreover, incinerating plastics generates substantial CO_2 emissions, further contributing to air pollution and climate change [25]. In response to the growing crisis, countries like China have executed stricter regulations on plastic waste imports, signalling a global call to action [50]. The European Union is also taking steps to address plastic waste. Commissioner Günther Oettinger has labelled it an ecological challenge, advocating for bans on specific single-use plastics and increased consumer education. Proposed measures include a plastic waste tax to incentivise member states to reduce plastic waste [51].

3.6. The Ongoing Crisis and Future Directions

Each year, an estimated 7.8 to 8.2 million tonnes of plastic enter the oceans, complicating waste management efforts and threatening land resource production. The hazardous substances released during plastic degradation contribute to serious environmental and health issues [52]. The entire lifecycle of plastic—from extraction to production—carries ecological consequences. The prevalence of plastic in marine environments is alarming, with an estimated 5 trillion plastic particles floating in the world's waters and around 12.7 million metric tonnes of plastic waste entering the ocean annually [2].

Public concern about plastic pollution is rising, as shown by a Eurobarometer Survey indicating that 88% of Irish participants and 87% of Europeans worry about the environmental impact of plastic products, [53]. The increasing volume of packaging waste, particularly in Europe, has reached an all-time high of 173 kg per capita [54]. Despite significant economic growth, packaging waste generation has outpaced GDP growth, highlighting the urgent need for sustainable solutions. Two critical factors contributing to increased plastic use are the high levels of avoidable packaging and the rising consumption of single-use plastics [54].

Although trends suggest a decline in reusable packaging, there are opportunities to influence growing consumer awareness and initiatives promoting zero-waste practices. Encouraging alternative, biodegradable materials, such as bioplastics, is critical for reducing plastic waste [24]. The environmental ramifications of plastic pollution are widespread, affecting ecosystems, wildlife, and human health. Historical developments have shaped the plastic industry and underscored the urgent need for action. As awareness of plastic pollution grows, governments, industries, and individuals must cooperate on innovative solutions to mitigate plastic waste and its impacts. Increased investment in biodegradable alternatives and a comprehensive examination of recycling strategies will be crucial in addressing this global crisis and protecting our environment and future generations.

4. The Evolution of Bioplastics: Definition, Classification, and Significance

Bioplastics have emerged as a sustainable alternative to traditional petroleum-based plastics in material science. The alarming increase in plastic pollution and the urgent need for environmental conservation have accelerated bioplastic research and development. This section explores the definition, classification, significance, and historical milestones that influenced the bioplastics industry.

4.1. Definition of Bioplastics

Bioplastics comprise a diverse family of materials characterised by their renewable biological origins or designed biodegradability. According to [45] a material qualifies as bioplastic if it is either biobased, biodegradable, or possesses both features. The term "biobased" refers to materials derived from plants, such as corn, sugarcane, or cellulose, whereas "biodegradable" denotes materials that can decompose into natural substances through microbial action without requiring artificial additives. This decomposition can produce harmless end products like carbon dioxide, water, and compost [45]. Bioplastic classification is further problematic because biobased materials are not inherently biodegradable. For instance, a material can be 100% biobased yet non-biodegradable, depending on its chemical structure, while some biodegradable materials may not originate from biological sources [45]. Therefore, 'bioplastics' is an umbrella term, and understanding the nuances of bioplastic definitions is crucial for both industry stakeholders and consumers. An organisation looking at creating bioplastics as 'drop-in' polymers is NautreWorks Ingeo, using plants to capture CO_2, transforming it into sugar molecules, which are then fermented to produce lactic acid, the primary component in their material [55]. They evaluated the global shift towards biopolymers and the potential to make their own stand in this race to create a versatile range of bioplastics. Ingeo Bioplastic produces coffee capsules, cups, packaging, electronics, and filaments for 3D printing [55].

4.2. Classification of Bioplastics

Bioplastics can be broadly categorised into two groups: biobased plastics and biodegradable plastics.

1. Biobased plastics: These are plastics derived from renewable resources that may be entirely or partially biobased. Common examples include polylactic acid (PLA) and polyhydroxyalkanoates (PHA), which are recognised for their excellent mechanical properties and potential to reduce reliance on fossil fuels [2]. PLA, for instance, is widely used in packaging and single-use items and is produced from fermented plant starch, typically corn. Bioplastics are not a single material but rather encompass a diverse family of materials, primarily categorised into two major groups. The first group comprises biobased plastics derived from renewable natural polymers such as starch and cellulose. These polymers are often from agricultural products like corn, potatoes, and sugarcane. An interview with Coca-Cola's global R&D, Dana Breed, in [56] discussed Coca-Cola's bioplastic bottles, PlantBottle™. This product first appeared in 2009, formulated with 30% mono ethylene glycol (MEG) derived from sugarcane residue and 70% terephthalic acid (PTA) derived from oil-based sources. The formulation was further improved by altering it to use plant-based paraxylene (bPX), made using corn sugar [56]. The company's spokesperson elaborated on why the company created this product with the aim of sustainability and recyclability of the biopolymer in support of the World Without Waste vision. The bPET material was compared to its petroleum counterpart, PET, and no drawbacks were found in its mechanical and recyclable abilities [56].
2. Biodegradable plastics: This category includes biodegradable plastics, which can degrade through microbial activity, breaking into water, carbon dioxide, and biomass under suitable environmental conditions. PLA is a prominent example, synthesised from fermented plant sugars, primarily sourced from crops like corn and sugarcane [57]. PLA is widely used in packaging, medical devices, and 3D printing applications. Mater-Bi, created by Novamont, is a commercialised bioplastic with biodegradable and compostable properties [58]. The organisation aims to develop a polymer to aid in tackling the environmental problems of plastics. Their products consist of starches, cellulose, vegetable oils, and combinations of these raw materials that produce the desired product [58]. All of their Mater-Bi products are certified in accordance with international and European standards. The applicability of this polymer is extensive, as it is used in food packaging, mulching films, cutlery, and carrier bags [58]. While some biodegradable plastics are also biobased, others may be petroleum-based; poly-

butylene adipate terephthalate (PBAT) is an example of a biodegradable plastic that is not biobased but is a bioplastic used in various applications [49].

A notable classification system by [45] divides bioplastics into three main groups, as seen in Figure 8:

- Biobased or partially biobased non-biodegradable plastics (e.g., biobased polyethene, polypropylene, or polyethene terephthalate).
- Biobased and biodegradable plastics (e.g., PLA and PHA).
- Petroleum-based biodegradable plastics (e.g., PBAT).

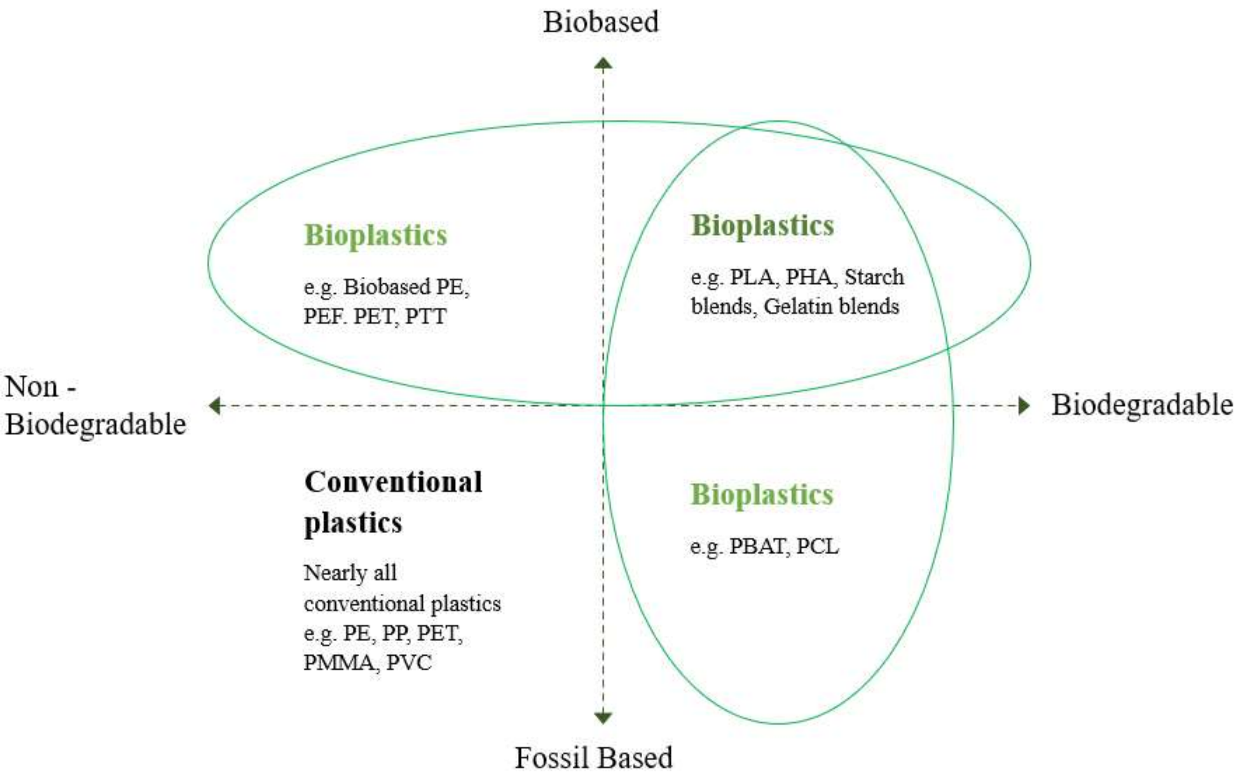

Figure 8. Illustrates how bioplastics are categorised depending on their biodegradability and material origin.

Significance of Bioplastics

The significance of bioplastics lies in their potential to relieve environmental issues associated with regular plastics. The production and consumption of plastics contribute to increasing greenhouse gas emissions, plastic waste accumulation, and reliance on fossil fuels. Substituting petroleum-based plastics with bioplastics is a promising prospect to reduce environmental footprints significantly.

Bioplastics not only hold the potential for environmental benefits but also present economic advantages. Their development can create jobs in the expanding green economy and stimulate innovation across various sectors, including packaging, agriculture, and consumer goods [1]. In 2018, the global market for biodegradable plastics was evaluated at approximately USD 3.02 billion, and it is expected to grow to USD 6.73 billion by 2025, emphasising the increasing demand for sustainable materials [1]. Moreover, bioplastics can enhance the sustainability of numerous industries by providing alternatives that do not compromise functionality or performance. The flexibility and adaptability of bioplastics enable them to be used in various applications, from food packaging to medical devices [26].

4.3. Key Events Shaping the Bioplastic Industry

Several key events have significantly influenced the journey of bioplastics:

1. The launch of PLA: The commercial introduction of PLA in the 1990s marked a pivotal moment in the bioplastics sector. As one of the first commercially successful bioplastics, PLA has paved the way for further advancements and applications in packaging and disposable products [2]. The company NatureWorks bioplastic Ingeo range, whose materials origin is from PLA, is a real-world example of PLA bioplastics in commercial use [55].
2. Establishment of the European Bioplastics Association: Founded in 2007, this association has been detrimental in advocating for the interests of the bioplastics industry in Europe. It has played a significant role in raising awareness, driving policy changes, and promoting the sustainable use of bioplastics [45].
3. Regulatory developments: Establishing regulations favouring biodegradable materials has accelerated growth in the bioplastics sector. Notably, the European Union's directives to reduce single-use plastics have spurred demand for bioplastics as worthwhile alternatives [49].
4. Market expansion and investment: The increasing investment in bioplastic research and development has led to advances in material properties and applications. The market for bioplastics has expanded, driven by consumer demand for sustainable products and corporate commitments to reduce environmental impact [24]. Avantium is a Dutch company trying to broach the bioplastic market with its biobased PEF (polyethylene furanoate) bottles [59]. The primary aim of this company is to replace conventional plastics and offer a sustainable alternative. Avantium's bioplastic consists of biobased substances such as maise, sugar, wheat, or beets in the formulation [59]. The bottles are designed to completely degrade in a composter within a year and a few years if littered into the environment, but the company plans to primarily recycle these products. Attracting larger companies is ideal for them to increase their investment and, in turn, the production of the bottles [59].

4.4. The Future of Bioplastics

As the world grapples with the pressing challenges of plastic pollution and the environmental crisis, the role of bioplastics is likely to become increasingly prominent. With advancements in technology and materials science, bioplastics are expected to develop and offer even more sustainable solutions across various applications. The demand for bioplastics will continue to grow, particularly as consumers become more environmentally conscious and industries seek sustainable alternatives. Bioplastics also promise to align with global sustainability goals, particularly in climate change mitigation and resource conservation [46]. The development and demand for bioplastics presents a critical opportunity to address the environmental challenges posed by conventional plastics. Understanding bioplastics' definition, classification, and significance is detrimental as society moves towards a more sustainable future. With continued research, innovation, and policy support, the bioplastics industry is poised for substantial growth, providing viable alternatives contributing to global sustainability efforts.

5. Concepts That Support Using Bioplastics as an Alternative

In recent years, increasing concerns over the environmental impact of petroleum-based plastics have fuelled interest in developing bioplastics as a sustainable alternative. Derived from renewable sources such as plant-based materials, bioplastics propose promising solutions to reduce carbon footprints and address the plastic pollution crisis. They also present supplementary waste management options, such as industrial composting, presenting a more comprehensive approach to sustainability [60]. Nestlé developed biobased lids and scoops made from sugar cane and its byproducts for infant and child nutrition products [61]. As the indirect ingestion of plastics from food products is of growing concern, it is vital that food companies like Nestlé address this potential problem. Nestlé Nutrition's NAN infant formula was first introduced to the Hong Kong market in 2020 and is scheduled to be sold in other global markets. The lids and scoops are made of 66% and 95% sugar cane and certified as plant-based polymers. This change by the company is expected, as stated in an interview conducted by [61] about how Nestlé is a founding member of the Bioplastics Feedstock Alliance, which aims to encourage the production of bioplastics in a responsible and viable environmentally.

Advancements in bioplastics, particularly in bio-polyethylene, bio-polypropylene, and bio-poly (ethylene terephthalate), demonstrate the material's capacity to mimic the properties of conventional plastics while lowering environmental impact. These biobased alternatives reduce dependency on fossil fuels and mitigate the environmental damage caused by plastic pollution. Policies such as the Single-Use Plastics Directive, the European Green Deal, and the Circular Economy Action Plan have further fast-tracked the adoption of bioplastics [60]. Coca-Cola's 100% biobased bottle [47] exemplifies bioplastic advancements as companies evolve their approach to comply with directives and circular plans.

The primary building blocks of biopolymers have been extensively studied for countless applications, from packaging to healthcare. Natural biocomposites, such as those derived from sugarcane and curauá fibre, have shown great promise as alternatives to non-renewable, fossil-based materials. These green composites contribute to a more sustainable future by leveraging high-performance raw materials with a reduced environmental footprint [62,63]. The versatility of bioplastics, particularly in food packaging, has been recognised as a viable solution to address the environmental concerns encompassing single-use plastics [60].

Environmental sustainability is a significant factor driving interest in bioplastics, as conventional plastics from non-renewable fossil fuels contribute heavily to greenhouse gas emissions during their lifecycle. In contrast, bioplastics derived from renewable resources like corn and sugarcane have notably lower carbon footprints. Lifecycle assessments have shown that bioplastics consume less energy and produce fewer emissions, making them a more sustainable alternative for resource recovery and recycling efforts [17]. Adopting bioplastics could promote a circular economy by reducing reliance on limited resources and encouraging the reuse of materials [52]. BASF is a company that is utilising the increased interest in bioplastics by manufacturing a variety of biopolymers with multiple applications. Their renewable BDO (1, 4-Butanediol) one-step fermentation process based on sugars, which holds a patent, is used to produce biodegradable plastics [64]. Elastollan® is the brand name for BASF's thermoplastic polyurethane (TPU), which has the capacity to be extruded or injection moulded into cable sheathing, films, and belts [64]. With the success of these polymers, a circular economy with the reduction in petroleum-based plastics is possible.

The use of renewable biological materials sets bioplastics apart from traditional plastics. For instance, PLA, one of the most common bioplastics, is derived from fermented plant starches and is used in applications ranging from packaging to medical devices. This reliance on renewable resources has the added benefit of creating carbon-neutral production processes as plants absorb CO_2 during their growth cycles [17,29]. Biodegradability is another significant advantage of bioplastics, as many can decompose under specific conditions, helping to alleviate the global plastic pollution crisis. Conventional plastics can persist for centuries, causing extensive environmental damage, while biodegradable bioplastics like PLA and PHAs break down into non-toxic components. However, not all bioplastics are biodegradable, and those often require industrial composting facilities to decompose fully, stressing the need for new infrastructure and standards to realise their full potential [17]. Mater-bi products [58] offer biodegradability and composability properties, meeting European international standards as a well-established bioplastics producer.

Bioplastics have applications in various sectors, including packaging, agriculture, and healthcare. In packaging, they are used to create biodegradable food containers, bags, and utensils, offering a sustainable alternative to traditional plastic products. In agriculture, bioplastics are utilised in biodegradable mulching films, improving soil health by eliminating the need to remove plastic residues after harvest [65]. Bioplastics are used in medical implants, sutures, and drug delivery systems, where their biodegradability is especially advantageous [9]. The benefits of bioplastics extend beyond environmental considerations as they also possess desirable barrier and mechanical properties that make them suitable for industries like food packaging, where sustainability is increasingly prioritised. By implementing bioplastics, industries can help reduce the environmental impact of single-use plastic goods in alignment with global policy initiatives [45].

6. Bioplastic Type, Properties, Applications, and Sustainability

The increasing concern over plastic pollution has garnered global awareness, driving a strong interest in bioplastics as an alternative to plastics. Traditional plastics, predominantly derived from petrochemical sources, have been a cornerstone of modern manufacturing and consumer products for decades. However, these materials have persisted in the environment for centuries, gathering in landfills and oceans and creating an ever-growing waste management crisis and environmental degradation. This issue has led to a significant demand for materials that are not only functional but also eco-friendly. Bioplastics, derived from renewable resources such as starch, cellulose, and proteins, offer a sustainable alternative to conventional plastics [66]. The critical difference lies in their ability to degrade more rapidly under appropriate conditions, unlike petrochemical-based plastics, which are resistant to microbial degradation.

Due to their long-lasting nature, traditional plastics contribute extensively to environmental pollution. Recent estimates suggest that millions of tonnes of plastic waste enter the oceans annually, causing harm to marine life and ecosystems. Bioplastics, on the other hand, present an answer that may alleviate some of these concerns. By incorporating renewable raw materials, bioplastics can reduce dependence on fossil fuels and mitigate the environmental footprint of plastic production. Furthermore, they consider end-of-life concerns by being compostable and biodegradable under controlled conditions [67]. This paper delves into the fundamental concepts supporting bioplastics as a sustainable alternative to plastics. It concentrates on their composition, environmental benefits, properties, challenges, and prospects for large-scale adoption.

6.1. Defining Bioplastics: Composition and Types

Biobased and biodegradable starch-based polymers and blends have gained traction in the bioplastic race to replace conventional plastics. When mixed with plasticisers, starch-based bioplastics have garnered significant attention due to their favourable properties, such as their flexibility, transparency, and strength [21]. These properties make them suitable for various applications, from packaging to agricultural films [68]. Starch is a plentiful and inexpensive biopolymer source, which makes it attractive for sustainable material development [69]. Other biopolymers like proteins, PHAs, and cellulose are also being explored, each offering unique advantages based on their chemical structures and mechanical properties [60,66].

In addition to their renewable composition, bioplastic production processes are often more sustainable than conventional plastic manufacturing. Plastics require significant amounts of fossil fuels to extract raw materials and energy-intensive production processes, leading to excessive greenhouse gas emissions. In contrast, the production of bioplastics generally requires less energy and results in lower carbon dioxide emissions and other greenhouse gases [21]. Despite these environmental benefits, several challenges still hamper the widespread adoption of bioplastics, such as high production costs and restrained scalability due to the availability of raw materials.

6.2. Environmental Impact: Reduction in Plastic Pollution

One of the most substantial advantages of bioplastics is their potential to mitigate the plastic pollution crisis. Conventional plastics are notorious for their persistence in the environment, where they can remain for hundreds of years, breaking down into microplastics that contaminate ecosystems and harm wildlife. Conversely, bioplastics are designed to degrade under appropriate conditions, reducing their long-term environmental impact. Biodegradable films made from starch, PLA, or other natural polymers have been shown to break down into organic matter under composting conditions, returning valuable nutrients to the soil without leaving harmful residues [17].

Compostable bioplastics are particularly attractive for applications in food packaging, where the need for materials that can decompose quickly and safely is of significant interest. Industrial composting facilities can break down these materials within months, significantly reducing the volume of plastic waste sent to landfills [66]. Research on PLA and starch/PLA composites [70,71] demonstrates their capacity for degradation in seawater, suggesting a reduced environmental impact contrasted to persistent conventional plastics. While the specific degradation rates and conditions fluctuate depending on factors like polymer composition and environmental factors, the biodegradability of these materials positions them as a promising solution for single-use applications in marine environments, including packaging, utensils, and straws [72]. However, it is important to note that even biodegradable plastics require specific conditions for optimal degradation, and their overall environmental impact needs further evaluation, considering factors like production processes and end-of-life management [73,74]. Additionally, research on seawater-degradable polymers [71] highlights the ongoing efforts to develop materials specifically designed to break down in marine environments, further supporting the potential of bioplastics to address the challenge of plastic pollution in oceans.

Bioplastics also hold promise in reducing plastic waste in other environments. For instance, [75] discusses biodegradable mulch film made of starch-coated paper and its effects on soil. The authors of [76] also state that bioplastics derived from starch are used in agricultural applications such as mulch films. The authors of [77,78] discuss biodegradable films and coatings as alternatives to traditional petroleum-based mulching films, supporting decreasing agricultural plastic waste.

6.3. Bioplastic Properties: Performance and Applications

While the environmental benefits of bioplastics are well established, their implementation in various applications is critical to their general adoption. It is important to clarify that the discussion here focuses primarily on applications such as packaging, agricultural films, and consumer single-use products where biodegradable and compostable properties are a vital function of the polymers. Bioplastics might not meet the requirements for permanent structures in industries like construction or aerospace, and their physical properties may hinder their desired purpose in these specific scenarios [79]. A review by [80] discussed the use of biopolymers as aggregates in concrete mixtures, where it was stated that while biopolymers such as expanded polylactic acids (EPLAs) might be utilised for lightweight concrete, the addition of this biopolymer was found to reduce the compressive strength and elastic modulus. These same observations were seen in [81], where the bioplastics used in construction were reviewed, and studies found that they lacked fire resistance for building envelopes.

Starch-based bioplastics, for example, exhibit passable mechanical properties, making them suitable for packaging, agricultural films, and disposable products [17]. A key challenge for bioplastics is their sensitivity to environmental conditions, primarily moisture and temperature [82]. Starch-based materials, for example, are susceptible to moisture absorption, which can compromise their strength and durability. Researchers are actively exploring strategies to enhance bioplastic barrier properties and mechanical performance by including additives and nanomaterials [83].

Protein-based bioplastics, derived from sources like soy protein, whey, and gelatine, offer distinctive properties that make them attractive for specific applications. These bioplastics are known for their flexibility and biodegradability, making them suitable for packaging and biomedical applications [84]. Protein-based materials exhibit good biocompatibility, essential for medical applications such as drug delivery systems, wound dressings, and tissue engineering scaffolds. The use of proteins in bioplastic production is an evolving field, with ongoing research to improve their mechanical and thermal characteristics. It is crucial to emphasise that these bioplastics are best suited for applications prioritising biodegradability and eco-friendliness rather than features requiring extreme mechanical strength and an extensive lifespan.

6.4. The Challenges of Scaling Bioplastics

Despite the many benefits of bioplastics, significant challenges still need to be deciphered in terms of cost and production scale. Bioplastics are more expensive than petroleum-based plastics, primarily due to the limited availability of raw materials and the relatively small scale of bioplastic manufacturing [17]. The high cost of bioplastics is a barrier to their pervasive adoption, particularly in industries where cost is a significant consideration, such as packaging and consumer goods. Biotechnology and green chemistry offer promising possibilities for improving bioplastic production's commercial viability and scalability [76]. Alternative feedstocks like agricultural waste and non-food biomass can significantly ease production costs and promote sustainable sourcing [85,86]. These approaches, coupled with research on optimising biopolymer extraction and modification techniques [87], can contribute to a circular economy by diminishing waste and reusing resources [57]. This reduces reliance on food crops and makes bioplastics a more competitive and environmentally sound alternative to conventional plastics [88]. Another challenge facing bioplastics is ensuring that they biodegrade swiftly. While many bioplastics are designed to degrade under specific conditions, such as those in industrial composting facilities, they may not break down as effectively in natural environments like oceans or forests [62]. This highlights the need for more precise standards and improved infrastructure to manage bioplastic waste, ensuring that these materials are correctly composted or recycled.

6.5. Future Prospects: Bioplastics and the Circular Economy

Bioplastics are well positioned to play a significant role in transitioning to a circular economy, where resources are reused and waste is minimal. The shift from a "take-make-dispose" model to a "cradle-to-cradle" approach requires innovations in recycling and composting technologies, as well as the advancement of bioplastics that can be more easily integrated into existing waste management systems [88]. As bioplastics become more widely adopted, improvements in recycling infrastructure and composting facilities will be fundamental for closing the loop on plastic waste. The development of novel biopolymer blends is another area of significant interest. Blends could lead to bioplastics that match traditional plastics' performance and exponentially better sustainability and environmental impact [84]. Bioplastics demonstrate potential beyond packaging, with research exploring applications in medical devices, automotive parts, and construction materials [76]. These developments suggest that bioplastics could play a transformative role in creating more sustainable businesses [57].

7. Homogenisation and Standardisation of Bioplastics Across Europe and Globally

The bioplastics industry has witnessed extraordinary growth in recent years, fuelled by rising consumer demand for sustainable and eco-friendly alternatives to conventional petroleum-based plastics. Bioplastics, derived from renewable biomass sources such as vegetable fats, oils, corn starch, or microbiota, provide a practical solution to the environmental challenges posed by traditional plastics. Nevertheless, the harmonisation and standardisation of bioplastic policies and regulations across Europe and global markets remain complicated and continuously evolving. The transition to a bioeconomy has intensified the demand for sustainable materials, particularly bioplastics. Bioplastics reduce plastic pollution and decarbonise industries as essential components of a circular economy. Despite their advantages, significant obstacles in regulatory frameworks, certifications, and market acceptability obstruct the progress of bioplastics, especially in achieving standardisation. Research indicates that the growth of the bioplastics sector is closely linked to the implementation of bioeconomy standards and labels by national governments [17]. Supportive policies, such as incentives, tax credits, and research funding, play a decisive role in propelling the adoption of bioplastics, further boosted by increasing concerns over the environmental impact of conventional plastics [60].

7.1. Bioplastics in the European Market: Current Landscape

Europe has made significant strides to integrate bioplastics into the broader bioeconomy. The European Union (EU) has implemented various policy frameworks to endorse bioplastics as part of its environmental strategy, including the European Green Deal and the Circular Economy Action Plan (CEAP). These initiatives are designed to reduce plastic waste and encourage sustainable resource use [89]. Central to these policies is authenticating clear standards governing bioplastic production, use, and disposal to cultivate a sustainable bioeconomy. One of the principal regulatory standards currently used in Europe is EN 13432 [90], which defines the requirements for recoverable packaging through composting and biodegradation. Despite such standards, the enforcement and adoption of bioplastics regulations must be more coherent across EU members [91]. For instance, some countries enforce strict rules regarding the biodegradability and composability of bioplastics, while others need to implement such guidelines, resulting in a fragmented internal market. This regulatory inconsistency challenges businesses aiming to scale their bioplastic products across Europe. Moreover, the complexity of bioplastics, which encompasses biodegradable, compostable, and biobased plastics, complicates the establishment of uniform standards. Notably, not all biobased plastics are biodegradable, and not all biodegradable plastics are compostable under standard industrial conditions [92]. Consumers often need to understand this distinction, further thwarting the efforts to create unified labelling and disposal systems, Figure 9. The European Commission acknowledges this challenge and is actively working to initiate more explicit definitions and labelling requirements to bridge existing gaps in understanding [93].

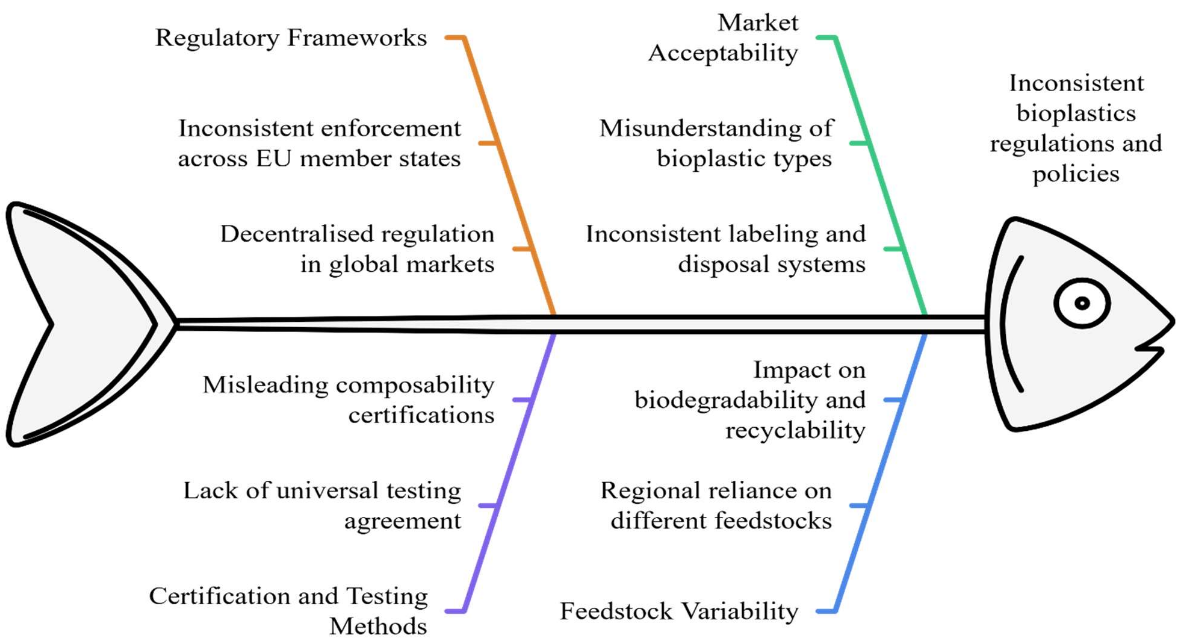

Figure 9. Shows a fishbone diagram of the challenges of standardising bioplastics.

7.2. Global Markets: Differences in Standardisation

Globally, the bioplastics market exhibits significant variations in regulations and policies. For example, there is no federal standard for bioplastics; regulation often occurs at the state level. This decentralised approach has resulted in various laws that complicate market entry for bioplastic manufacturers [92]. States like California have implemented strict regulations mandating that products labelled as biodegradable must meet specific composability standards, Figure 9. In contrast, other states lack rigorous requirements, allowing products to claim eco-friendliness without undergoing precise testing. In Asia, countries such as Japan and China have adopted policies promoting bioplastics to mitigate plastic pollution [94]. Japan, for instance, has implemented the "Plastics Resource Circulation Strategy", which mandates using biodegradable plastics in specific applications [95]. However, as in Europe, the definitions and standards for bioplastics vary across Asian markets, leading to inconsistencies that impede international trade. China has emerged as a significant producer of bioplastics, primarily driven by its policy focus on reducing plastic pollution. Nevertheless, the country's bioplastic industry faces disapproval for prioritising quantity over quality, often producing materials that must comply with international biodegradability standards [17,28]. Consequently, bioplastics manufactured in China may not be recognised or accepted in regions with stricter environmental regulations, such as Europe or North America [93]. This scenario underlines the necessity for global harmonisation in bioplastics standards to facilitate international trade and ensure environmental performance.

7.3. Challenges to Homogenisation

The varied range of feedstocks utilised in bioplastics production presents a considerable challenge to standardisation, Figure 9. Different regions rely on locally available feedstocks, affecting the resulting bioplastics' properties. For instance, European bioplastics are typically produced from agricultural waste and non-food biomass, whereas starch-based plastics derived from corn or cassava are more common in Asia [96]. This variation in raw materials results in differences in biodegradability, composability, and recyclability, necessitating localised standards for bioplastics. Furthermore, the testing methods for assessing the environmental impact of bioplastics need more universal agreement. Many certifications emphasise composability under specific industrial conditions, which may not accurately reflect real-world environments, such as soil or marine ecosystems [92]. For instance, a bioplastic product may receive certification as compostable under industrial conditions but could take significantly longer to degrade in natural settings, such as oceans. This inconsistency must be clarified for consumers and complicates efforts to establish universal bioplastic standards [28]. The absence of well-defined guidelines for bioplastic disposal presents another significant obstacle. While some bioplastics are designed for composting, industrial composting facilities are only widely available in some regions. Consequently, bioplastics may end up in landfills, negating their environmental benefits. With appropriate waste management infrastructure and consistent labelling, bioplastics can avoid becoming a source of pollution rather than a solution [28].

7.4. Efforts Towards Homogenisation

Despite these challenges, concerted efforts to standardise bioplastics are underway, with the International Organisation for Standardisation (ISO) and the European Committee for Standardisation (CEN) collaborating to develop globally recognised bioplastic standards. For example, ISO 17088 [97] outlines principles for determining the composability of bioplastics, providing a reference point for manufacturers and regulators alike [73]. These standards ensure that bioplastics perform consistently across diverse regions and environmental conditions. At the policy level, the European Union is engaging with international organisations and other regions to harmonise bioplastics standards. The EU has introduced measures to encourage the adoption of unified labelling systems that differentiate between biodegradable, compostable, and recyclable bioplastics [89]. This proposal is crucial for enabling consumers to make informed choices and preventing greenwashing, wherein products are marketed as environmentally friendly without adhering to stringent standards. Additionally, the Paris Agreement's focus on reducing global carbon emissions has strongly encouraged many countries to consider bioplastics as a solution to plastic pollution. This trend has fostered increased collaboration between governments, industries, and research institutions to develop standard guidelines and policies for bioplastics production and waste management [17,28]. As part of this initiative, the United Nations Environment Programme (UNEP) has advocated for a global framework that aligns bioplastics policies with broader sustainability [92].

7.5. Future Directions

The future of bioplastics hinges on the successful harmonisation of standards and the establishment of a satisfactory waste management infrastructure. As production continues to rise, there is an increasing need for clear regulations defining the biodegradability and composability of these materials, as displayed in Figure 9. Governments must collaborate to align their policies with international standards, ensuring that bioplastics can be utilised and disposed of to amplify their environmental advantages. Simultaneously, enhanced investment in bioplastic research and development is crucial. Innovations in feedstock selection and processing technologies will progress bioplastics' performance and minimise their environmental impact. Furthermore, public awareness campaigns are essential for educating consumers on the benefits and limitations of bioplastics, thereby driving demand for products that meet the utmost environmental standards [28].

7.6. Conclusions

Harmonising bioplastics standards is pivotal for successfully integrating these materials into the global economy. While Europe has made notable advancements in developing supportive bioplastic policies, the global market remains fragmented, with significant variations in regulations and certifications. These challenges necessitate international collaboration among governments, industries, and standardisation bodies. By establishing unified standards and enhancing waste management infrastructure, bioplastics can become integral to the transition to a sustainable bioeconomy. Additionally, clarity through standardisation will regulate any unintentional greenwashing and bring bioplastics closer to a green circular economy. An important focus should be placed on developing highly applicable bioplastic products for areas like packaging, where biodegradability and composability are primarily sought properties.

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