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Review

Cellulose-Based Materials as a Sustainable Alternative to Plastics: Mitigating Environmental Pollution Through Biodegradability and Reduced Toxicity

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ABSTRACT

This review examines the potential of using cellulose materials for overcoming environmental issues such as pollution, microplastics, and ecological toxicity as sustainable alternatives to petroleum-based plastics. Unlike plastics which persist in the environment and break down into microplastics, cellulose materials readily degrade into non-toxic organic compounds, thus reducing pollutants in soil and water. The review outlines the relatively low environmental impact of cellulose production from renewable materials such as timber, agricultural waste, and non-timber flora. Cellulose, unlike petroleum-based polymers, is produced with lower energy inputs, greenhouse gas emissions, and greater carbon capture during plant growth. Sustainably harvested and farmed cellulose strengthens its circular economy relationship clocking in boastful compostability, and in some instances, recyclability. The described processes, including the manufacture of nanocellulose, chemically and mechanically treated the cellulose, improving its strength, flexibility, moisture resistance, and expanding its application in packaging, biocomposites, textiles, and medical devices. There are still some disadvantages such as high costs, lack of industrial composting, and absence of enabling legislation. The review calls for greater advocacy of policy change, technological improvements, and public awareness campaigns aimed at promoting the use of cellulose. Most importantly, it demonstrates why these materials are needed to reduce pollution inflicted by plastics, protect biodiversity, enhance sustainability, and manage waste through responsible consumption.

INTRODUCTION

The origin of plastics dates back to the early 20th century, when they were introduced as substitutes for natural materials like ivory, horn, and tortoiseshell (Andrady & Neal 2009; Gilbert 2017). With the invention of synthetic polymers such as Bakelite in 1907 and the development of petroleum-based plastics in the 1950s, plastics quickly became integrated into modern society due to their moldability, durability, lightweight, and cost-efficiency (Thompson *et al.* 2009; Geyer *et al.* 2017). Today, plastics are indispensable across various sectors, including packaging, electronics, textiles, automotive, and healthcare. Global plastic production has grown from 2 million tonnes in 1950 to over 390 million tonnes in recent years, underscoring their widespread acceptance and utility (PlasticsEurope 2021). Their chemical resilience and ability to meet specific functional needs at low costs have made plastics central to modern industrial and consumer applications.

However, the rapid proliferation of plastics has created far-reaching environmental, health, and socioeconomic consequences. Plastics are primarily derived from non-renewable fossil fuels and are largely non-biodegradable, persisting in ecosystems for hundreds of years (Jambeck *et al.* 2015). Each year, approximately 8 million metric tonnes of plastic waste enter the oceans, contributing to global environmental degradation (Lebreton *et al.* 2017). Approximately 79% of plastic waste is in landfills or the natural environment, while only 9% is recycled (Geyer *et al.* 2017). Weathering and degradation processes fragment plastics into microplastics (<5 mm), which are now detected in marine organisms, soils, food, water, and even human tissues (Jambeck *et al.* 2015). Furthermore, plastics can leach toxic additives such as phthalates and bisphenol A (BPA), which are associated with endocrine disruption, developmental abnormalities, and increased risks of cancer and reproductive disorders in humans and wildlife (Godswill & Godspel 2019). In food systems, plastics compromise safety by leaching into food products, especially under high temperatures or acidic conditions (Groh *et al.* 2019; Obuzor & Onyedikachi 2023). Despite these well-documented risks, global responses remain inadequate. Many policy interventions are still nascent or inconsistently enforced, while sustainable alternatives have yet to achieve widespread adoption (Giacovelli 2018).

In light of these concerns, cellulose—a naturally abundant, biodegradable polymer derived from plant cell walls—has attracted renewed attention as a viable substitute for petroleum-based plastics. Sourced from wood, agricultural residues, and lignocellulosic biomass, cellulose is the most prevalent biopolymer on Earth (Klemm *et al.* 2005; Mujtaba *et al.* 2023). Unlike synthetic polymers, cellulose and its derivatives are compostable, less toxic, and derived from renewable resources (Maraveas 2020a). Technological advancements have significantly enhanced the material properties of cellulose. For instance, nanocellulose—produced via mechanical or chemical disintegration of cellulose fibres—exhibits superior strength, barrier properties, and flexibility, making it suitable for packaging, biomedical devices, and composites (Dufresne 2013; Shaghaleh *et al.* 2018). Additionally, specific chemical changes like acetylation have resulted in derivatives such as cellulose acetate, which improves resistance to water and durability, therefore broadening its application scope in coatings, films, and fibres (Habibi *et al.* 2010; Shaghaleh *et al.* 2018). Recent studies underscore the environmental advantages of cellulose-based alternatives, particularly in reducing microplastic generation, toxic leachates, and carbon footprints associated with plastic lifecycle emissions (Foroughi *et al.* 2021; Jing *et al.* 2024).

This review analyzes the possibilities of cellulose-containing materials as substitutes for plastics of environmental impact, characteristics of materials, technologies for processing materials, and economic aspects. It highlights current innovations, identifies the regulatory and market challenges impeding widespread adoption, and provides a comparative assessment of biodegradability, toxicity, and life cycle sustainability. The findings are relevant to stakeholders such as scientists, policymakers, business professionals, and eco-organizations targeting the shift towards sustainable materials. This review is distinctive in its holistic evaluation of cellulose-based biomaterials as potential substitutes for plastics. Beyond characterizing the materials, it assesses the recent technological developments, biodegradation, toxicity, and life cycle impacts of cellulose-based plastics. Moreover, the review examines regulatory, market, and economic obstacles that inhibit widespread adoption—these factors are often neglected by other studies. With this integrative approach, it enhances cross-sectoral efforts to propose meaningful innovations, policies, and marketing strategies aimed at harnessing cellulose composites to alleviate plastic pollution.

2. ENVIRONMENTAL PERSISTENCE AND BIODEGRADABILITY

2.1. Functional Comparison of Plastics and Cellulose-Based Materials Across Industrial Applications

Plastics and cellulose-based materials serve as two distinct material classes—synthetic and fossil-derived, the other natural and bio-based—yet both have played transformative roles in industrial development. An integrated overview of their applications and functions aids in understanding the material shift currently in relation to environmental sustainability (Table 1. Due to their ease of use, cost-effectiveness and barrier properties, plastics form the bulk of the packaging industry (Wu *et al.* 2021). Polypropylene (PP), Polyethylene (PE), and polyethylene terephthalate (PET) are popular for food containers, films and bottles owing to their gas and moisture impermeability, which preserves the product's quality (Wu *et al.* 2021). However, the long-lasting durability of these materials results in waste. On the other hand, paper, nanocellulose films, and cellulose acetate are more cellulose-based materials that are increasingly being researched for use in packaging (Romão *et al.* 2022; Yekta *et al.* 2023; Ren *et al.* 2024). Though traditionally limited by poor moisture resistance, recent coatings and chemical modification innovations have significantly enhanced their barrier properties, making them competitive in short-lifespan applications.

Due to their strength and chemical resistance, plastic materials like PVC and polystyrene are used in piping, insulation, and fittings (Revuelta 2021). Cellulose-based boards and bio-composites are gaining traction as eco-friendly alternatives in interior cladding, insulation, and lightweight construction panels (Saini & Ledwani 2024). While not yet mainstream for heavy-duty infrastructure, modified cellulose offers advantages in biodegradability, indoor air quality, and renewable sourcing.

Plastics reduce vehicle weight, enhancing fuel efficiency. ABS, nylon, and composites are used in vehicle interiors, exterior trims, and under-hood components (Gupta & Singhal 2022). Cellulose-reinforced composites (e.g., nanocellulose-polymer blends) are emerging as substitutes in dashboards, door panels, and insulation layers (Karak 2024; Carvalho *et al.* 2024). Though still under development, they provide comparable mechanical strength with significantly reduced environmental footprints.

Plastics are vital in healthcare for sterile, disposable items such as syringes, IV bags, and diagnostic equipment (Greene *et al.* 2022). Biocompatible and biodegradable cellulose is used in wound dressings, drug delivery systems, and biosensors (Khan *et al.* 2024). Nanocellulose hydrogels and scaffolds are being actively researched in tissue engineering (Tamo, 2024). However, challenges remain in ensuring sterility, mechanical strength, and cost-competitiveness for wide clinical deployment.

Plastics are used in greenhouses, mulch films, irrigation systems, and silage wraps (Maraveas 2020b). While effective, their disposal contributes to soil and microplastic contamination. Biodegradable cellulose-based films and coatings derived from agricultural waste are being developed to support controlled release, moisture retention, and compostability, thus offering circular economy advantages (Giordanengo 2024; Riseh 2024).

Synthetic fibres like polyester and nylon dominate textiles, offering strength and flexibility but contributing significantly to microplastic pollution. Cellulose-based alternatives, such as lyocell, modal, and viscose, are already commercialized and provide renewable, biodegradable options (Wang *et al.* 2021). These materials are widely used in fashion, upholstery, and hygiene products, though water and chemical use in production must be optimized.

Table 1: Comparison of Typical Plastic Applications and Corresponding Cellulose-Based Alternatives.

Application Sector	Typical Plastic Materials	Cellulose-Based Alternatives	Remarks
Packaging	PE, PP, PET, PS	Cellulose films, nanocellulose coatings, cellulose acetate	Improved barrier properties through functionalization/coating
Textiles	Polyester, Nylon, Acrylic	Lyocell, Modal, Viscose	Derived from regenerated cellulose; biodegradable but chemical-intensive
Healthcare	PVC, PP, PET, ABS	Cellulose hydrogels, nanocellulose scaffolds, biofilms	Suitable for wound dressings, drug delivery; sterility remains a challenge
Construction	PVC, Polystyrene, Polycarbonate	Cellulose composites, fiberboards, insulation panels	Offers renewable alternative for interior applications
Automotive	ABS, PP, Nylon, composites	Cellulose-reinforced composites, nanocellulose-polymer hybrids	Emerging use in lightweight panels and trims
Electronics	ABS, PC, HIPS	Transparent nanocellulose films, flexible substrates	Early-stage development; potential in green electronics
Agriculture	PE films, PP containers	Biodegradable cellulose mulch films, coated cellulose packaging	Supports compostability and moisture retention
3D Printing & Bioplastics	PLA blends, ABS	Cellulose-PLA composites, cellulose acetate filaments	Enhancing printability and biodegradability in additive manufacturing
Cosmetics & Personal Care	Microbeads in gels, PE containers	Cellulose microbeads, molded pulp packaging	Replacing banned plastic microbeads; improving sustainable packaging

2.2. Biodegradability of Plastics and Cellulose-Based Materials in Different Environments

Plastic and cellulose-based material degradation rates vary greatly by environment (Table 2). Traditional petroleum-derived plastics like polyethylene and polypropylene can persist in landfills for years due to their resistance to microbial activity and climatic conditions (Raddadi & Fava 2019). Due to photodegradation, UV radiation converts these plastics to microplastics without mineralizing them, slowing their breakdown in marine settings (Gewert *et al.* 2015). Certain plastics, including polyvinyl chloride (PVC), withstand environmental deterioration and degrade slowly in soil (Hopewell *et al.* 2009).

Cellulose degrades faster than plastic (Yaradoddi *et al.* 2020). The cellulose breaks down within weeks to months under certain conditions (Azwa *et al.* 2013). According to Erdal & Hakkarainen (2022), cellulose breaks down in composting in three to six months. Briassoulis *et al.* (2019) found that bacteria may destroy cellulose sheets in seawater after a few months. Abiotic degradation of cellulose occurs in the soil as bacteria and fungi transform cellulose into glucose, subsequently converting it into carbon dioxide and water (Datta 2024).

Cellulose breakdown is generally facilitated by enzymes and bacteria. Bacteria and fungi synthesize cellulases and hemicellulases that decompose cellulose polymers into smaller units such as cellobiose and glucose (Lynd *et al.* 2002; Datta 2024). In rich soil and compost, these bacteria break down cellulose into organic molecules to synthesize necessary organic chemicals (Datta 2024). Zeghal *et al.* (2021) observed that marine bacteria and fungi increase cellulose degradation. By degrading cellulose into glucose, microbes get energy. Synthetic plastics decompose slowly in microbiological breakdown processes because they resist enzymatic activity (Gewert *et al.* 2015).

Studies have shown that cellulose degrades differently than plastics (Puls *et al.* 2011; Grzybek 2024). Slezak *et al.* (2023) found that cellulose-based biodegradable film degraded after six months when buried in soil, whereas plastic films did not after a year. Cellulolytic marine microorganisms break down cellulose-based materials fast, whereas plastics endure for years (Briassoulis *et al.* 2019). Polylactic acid (PLA) takes approximately twice as long to break down in composting as cellulose acetate (Tsuji 2013).

Cellulose is more biodegradable than conventional and certain bioplastics. Polar ice and deep-sea sediments contain microplastics, according to Thompson *et al.* (2004). Moreover, these microplastics do not degrade; instead, they fragment, leading to enduring pollution. Consequently, plankton, fish, and humans have ingested them, potentially posing health hazards and changing food chains (Rochman 2018). Conversely, cellulose-based products decompose into organic chemicals that are environmentally benign. Cellulose particles are quickly metabolized by bacteria, reducing their long-term build-up in ecosystems. Thus, cellulose is considerably less detrimental to natural ecosystems.

Table 2: Biodegradability Rates and Environmental Impact of Cellulose-Based vs. Petroleum-Based Plastics.

Material Type	Environment	Degradation Time	Influencing Factors	Environmental Impact	References
Traditional Petroleum Plastics	Soil	>500 years	Low microbial activity, slow photodegradation	High emissions, significant microplastic pollution	Andrady 2011; Gewert *et al.* 2015
Traditional Petroleum Plastics	Marine	>500 years	UV exposure, low biodegradation	High water use, no carbon sequestration	Thompson *et al.* 2004; Jambeck *et al.* 2015
Bioplastics (PLA)	Composting Facility	3-6 months	Elevated temperature, high microbial activity	Moderate environmental impact, reduced emissions	Tsuji 2013
Cellulose-Based Materials	Soil	1-3 months	High microbial activity, moderate moisture levels	Low emissions, positive carbon sequestration during growth	Skrzypczak *et al.* 2023; Salimi *et al.* 2024
Cellulose-Based Materials	Marine	1-3 months	Microbial degradation, moderate water conditions	No microplastic pollution, moderate water use	Briassoulis *et al.* 2019

2.3. Impact on Ecosystems (Terrestrial and Aquatic Organisms)

Plastics negatively impact terrestrial and aquatic ecosystems. In urban settings, terrestrial animals may consume or become ensnared in plastic waste, leading to damage or death (Gall & Thompson 2015). Plastics have been detected in the digestive systems of numerous species, including fish, birds, and mammals, within marine ecosystems (Lusher *et al.* 2013). The consumption of plastics might cause physical obstructions, malnutrition, and exposure to hazardous substances, resulting in population decreases (Awuchi & Awuchi 2019; Ghosh *et al.* 2023). Conversely, cellulose-derived compounds are biodegradable and pose negligible dangers to organisms (Erdal & Hakkarainen 2022). Upon introduction into terrestrial or marine habitats, they degrade into non-toxic organic molecules, thereby diminishing ingestion and entanglement hazards while alleviating chemical contamination. Moreover, cellulose decomposition facilitates nutrient cycling in soil ecosystems, fostering microbial proliferation and enhancing soil health (Zhan 2024).

The utilization of cellulose-based materials may substantially reduce the enduring environmental hazards associated with traditional plastics (Figure 1). Cellulose, owing to its biodegradable characteristics, does not contribute to microplastic pollution, establishing it as a sustainable alternative for packaging, fabrics, and disposable products. Shifting from petroleum-derived plastics to cellulose-based substitutes can diminish the buildup of enduring plastic waste in the environment, mitigating its detrimental impacts on ecosystems and human health (Klemm *et al.* 2005).

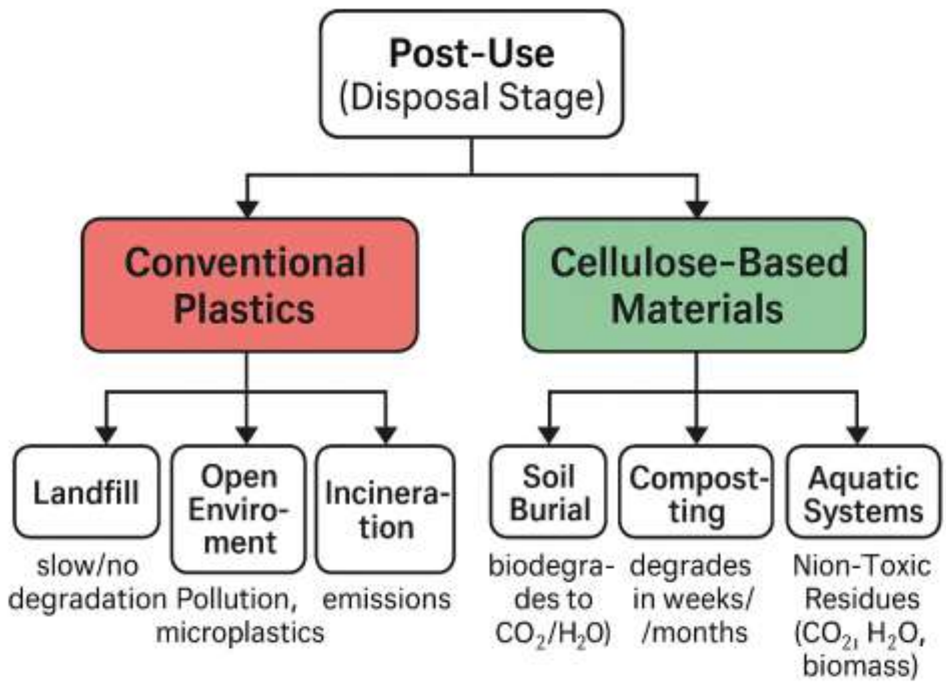

Figure 1: Environmental fates of plastics and cellulose-based materials

3. LIFECYCLE ANALYSIS OF CELLULOSE-BASED MATERIALS

3.1. Resource Extraction and Production

3.1.1. Impacts of Cellulose Sourcing from Wood, Plants, and Agricultural Residue

Cellulose, the most abundant organic polymer, comes from wood, plants, and agricultural waste. To manufacture cellulose fiber, trees, cotton, or post-harvest agricultural byproducts are pulped to eliminate lignin and other impurities (Klemm *et al.* 2005). Cellulose extraction can harm the environment depending on feedstock and methods. Sustainable Forest Management can reduce habitat loss, carbon emissions, and biodiversity loss from deforestation (Condé *et al.* 2022). Forest Stewardship Council (FSC) accreditation supports responsible forest management to prevent environmental deterioration from cellulose extraction from wood (Cashore *et al.* 2006). Instead of throwing away or burning sugarcane bagasse or straw, reusing them saves the environment. These leftovers add to greenhouse gas emissions and energy usage during transit and processing (Joshi *et al.* 2015). Cellulose extraction leaves less carbon footprint than petroleum-based polymers because it is ecologically benign and uses plant-based raw materials that store carbon during growth (Rajendran et al. 2025).

Compared to fossil-based plastics, cellulose extraction has a substantially lower carbon footprint (Foroughi et al., 2021). Producing 1 kg of bleached kraft pulp emits approximately 0.3–0.6 kg CO_2-eq, while polyethylene and polypropylene production emit 1.8–2.5 kg CO_2-eq per kg (Kim et al., 2022). Cellulose-based materials can also sequester 1.75–12.3 tons CO_2 per hectare per year through carbon storage during plant growth (Kim et al., 2022; Forfora et al., 2024).

3.1.2. Energy, water, and emissions comparison with petroleum-based plastics

Refining crude oil and natural gas produces polyethylene and polypropylene. Due to their energy usage, these activities increase greenhouse gas emissions and global climate change (Hopewell *et al.* 2009**).** Making plastic polymers from crude oil requires a lot of water and energy. Virgin polyethylene production consumes 80–90 MJ/kg primary energy, far exceeding the 30–50 MJ/kg required for cellulose-based products (Schirmeister & Mülhaupt 2022; Ritzen et al. 2024). However, cellulose manufacturing consumes less energy and emits fewer greenhouse gases. According to Van Schoubroeck *et al.* (2018), cellulose and other bio-based products have less impact on the environment in terms of non-renewable energy usage and global warming. However, processing cellulose in big pulping facilities may be energy and water-intensive. Kraft pulping can consume 30–60 m^3 of water per tonne of pulp, generating effluents that, if poorly treated, cause water pollution (Badar & Farooqi 2012; Latha *et al.* 2018).

3.2. Use Phase and Performance Comparison

3.2.1. Cellulose-based products: Durability, Performance, and Usability

Cellulose is used in construction, biomedical devices, textiles, and packaging (Felgueiras *et al.* 2021). Cellulose products are useful and frequently endure a long time, however, petroleum-based polymers may perform better (Wang *et al.* 2021). Cellulose-based packaging materials lack polyethylene in water resistance and tensile strength (Wang *et al.* 2021). Aziz *et al.* (2022) suggest synthesizing cellulose acetate or adding nanocellulose to make cellulose tougher, more flexible, and long-lasting than plastics. Cellulose acetate films exhibit tensile strengths of 60–1570 MPa, comparable to around 20 MPa in low-density polyethylene (Wang *et al.* 2021). Thereby, making cellulose-based materials to outperform petroleum-based ones. Consumer products and food packaging benefit from these lightweight, biodegradable, phthalate- and BPA-free plastic alternatives (Piergiovanni & Limbo 2016). Cellulose fabrics like rayon and lyocell are more breathable, absorbent, and comfortable than polyester or nylon (Ahmed & Akhtar 2017; Salleh *et al.* 2021). The Lyocell biodegrades within 6–8 weeks in soil, whereas polyester persists for decades or longer (Wang *et al.* 2021).

3.2.2. Packaging, textiles, and industrial uses compared to traditional plastics

In recent years, cellulose-based polymers have emerged as promising plastic substitutes for single-use goods including bags, wraps, and containers. Plastics protect against gases and moisture better than cellulose, although enhancing its water resistance and barrier qualities is difficult (Siró & Plackett 2010). Cellulose-based fibres like lyocell and viscose are replacing synthetics in textiles. Nanocellulose coatings can achieve oxygen permeability rates as low as 0.0006 to 0.009 $cm^3·\mu m/(m^2·day·kPa)$ under dry conditions, which is significantly lower than that of conventional PET films, typically ranging from 1 to 3 $cm^3·\mu m/(m^2·day·kPa)$. This superior barrier performance makes nanocellulose an attractive alternative for packaging applications requiring high oxygen resistance (Nair et al. 2014). In textiles, cellulose fibres achieve 90% biodegradation under aerobic conditions, compared to <5% for polyester and nylon (Egan & Salmon 2022). These materials offer higher moisture absorption, breathability, and biodegradability (Ahmad & Akhtar 2017). Bio-composites and the building sector are using cellulose-based goods more because they can replace petroleum-based materials like plastics and fibreglass. In the construction, aerospace, and automotive industries, cellulose nanofibers can strengthen and lighten bio-composites (Dufresne 2013; Hasan *et al.* 2020). Adding 5–10 wt% nanocellulose can enhance tensile modulus of composites by 30–60%, while reducing weight, making cellulose-based composites attractive for automotive, aerospace, and construction applications (Hasan et al. 2020).

3.3. End-of-Life Scenarios

3.3.1. Compostability, Recyclability, and Biodegradation Pathways

Cellulose-based polymers have considerable benefits compared to petroleum-based plastics in terms of end-of-life outcomes (Figure 2). Cellulose is naturally biodegradable, breaking down into organic molecules via microbial and enzymatic activities in natural settings, leaving no hazardous leftovers (Bisaria & Ghose 1981). Conversely, plastics can endure for decades, breaking down into microplastics that exacerbate environmental pollution (Thompson *et al.* 2009). The compostability of cellulose-based materials is a significant advantage. Numerous cellulose products, including paper-based packaging and cellulose films, are appropriate for composting in both industrial and domestic environments, decomposing into water, carbon dioxide, and biomass within months (Song *et al.* 2009). Cellulose-based packaging achieves approximately 90% mass loss within 180 days under simulated home composting conditions. Under industrial composting conditions, it meets EN 13432 standards by achieving >90% biodegradation within 12 weeks (Song et al. 2009). Cellulose acetate, a chemically modified cellulose derivative, exhibits significantly reduced biodegradability, especially when the degree of substitution is ≥2.5 (Yadav & Hakkarainen 2021). To degrade, chemically modified cellulose products like cellulose acetate may need high temperatures and microbial activity (Tsuji 2013). The recycling of cellulose-based materials is achievable yet complex. Although paper and cardboard are widely recycled, other cellulose products, like textiles and composites, necessitate specialized recycling methods due to chemical additives and heterogeneous ingredients. Paper and cardboard recycling achieves approximately 70–90% fibre recovery over 4 to 6 recycling cycles, depending on the process conditions and fibre quality (Belle et al. 2024). Improving the recyclability of cellulose-based products is a vital research domain that underpins the feasibility of a circular economy.

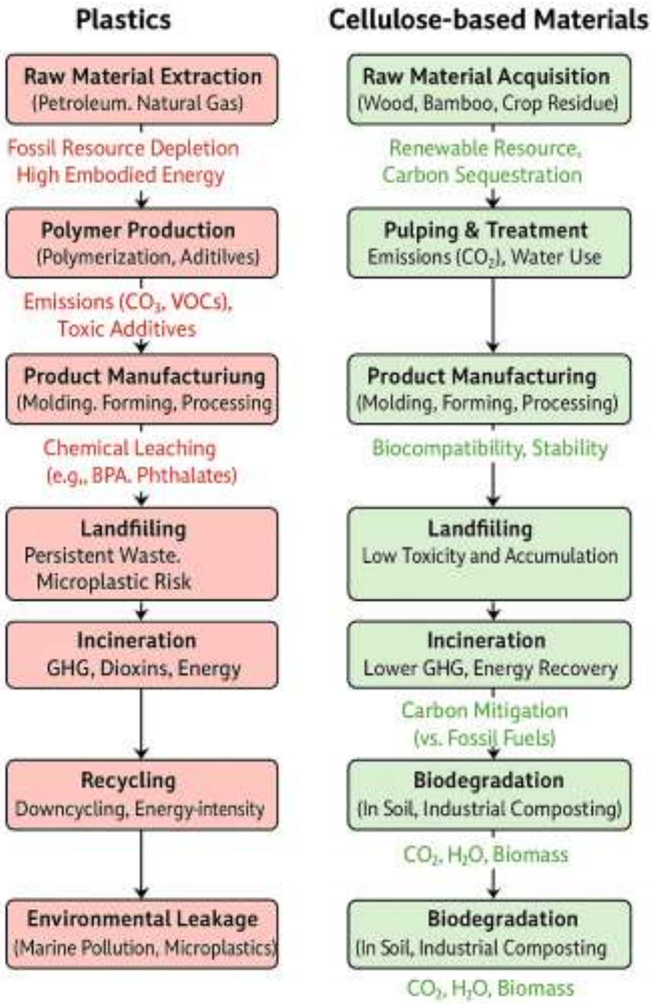

Figure 2: Life cycle assessment of plastics and cellulose-based materials.

3.3.2. Evaluating Circular Economy Potential: Reuse, Recovery, and Recycling Efficiency

The circular economy concept seeks to reduce waste by optimising material use via reuse, recycling, and recovery (MacArthur 2013). The biodegradability, recyclability, and renewability of cellulose-based materials render them very attractive in this context compared to plastic materials (Table 3). Cellulose elements in paper and cardboard can be recycled multiple times before becoming unusable, after which they can be composted or converted into energy (Thompson *et al.* 2009). Compared to virgin pulp production, paper and cardboard recycling reduces energy consumption by up to 60%, making it a more energy-efficient and environmentally sustainable option (Belle et al. 2024).

The extraction of nutrients from cellulose-based materials through industrial composting or anaerobic digestion can enhance regenerative farming methods (Tjeerdsma & Militz 2005). Furthermore, improvements in cellulose chemistry, particularly the synthesis of nanocellulose, facilitate the creation of high-performance products from recycled cellulose, thus diminishing dependence on virgin raw materials and prolonging product lifecycles

(Dufresne 2017). Nanocellulose produced from recycled paper retains over 80% of the tensile strength and modulus compared to that from virgin pulp, supporting its suitability for high-value reuse in circular material applications (Kargupta et al. 2023).

Table 3: Mechanical Properties, Applications, and Challenges of Cellulose-Based and Petroleum-Based Plastics.

Material	Tensile Strength	Water Resistance	Applications	Challenges	Proposed Solution	References
Cellulose Acetate	Moderate	Moderate	Packaging, film applications	Limited water resistance	Development of hydrophobic coatings	Moon *et al.* 2011; Klemm *et al.* 2005
Nanocellulose	High	Low	Bio-composites, medical devices	High production cost, scalability issues	Advancements in enzymatic processes, nanotechnology	Dufresne 2017
PLA (Bioplastic)	Moderate	High	Food packaging, medical use	Costly production, limited recyclability	Expansion of recycling infrastructure	Tsuji 2013
Polyethylene (Petroleum)	Very High	Very High	Industrial and consumer plastics	High microplastic pollution	None (non-biodegradable)	Siró & Plackett 2010
Cellulose Films	Low to Moderate	Low	Packaging, textiles	Low consumer awareness, high perceived cost	Public awareness campaigns on biodegradability	Verma *et al.* 2024
Polyvinyl Alcohol (PVA)	Low	Moderate	Food packaging, medical applications	Solubility in water limits applications	Blending with other biopolymers for strength	Sirviö *et al.* 2020
Polyhydroxyalkanoates (PHA)	High	Moderate	Biodegradable plastics, agricultural films	High production cost	Process optimization, policy support	Gewert *et al.* 2015
Starch-Based Bioplastics	Low	Low to Moderate	Single-use items, compostable bags	Weak mechanical properties	Blending with nanocellulose for strength	Garavito *et al.* 2024
Cellophane	Moderate	Low	Packaging, textile industry	Low durability in humid conditions	Surface modification for improved performance	Moon *et al.* 2011
Polycaprolactone (PCL)	High	High	Biomedical, packaging, compostable items	Limited scalability, high production costs	Scaling production, blending with other polymers	Dufresne 2017

4. TOXICITY AND MICROPLASTICS REDUCTION

4.1. Comparative toxicology of plastics and cellulose-based materials

Chemical additives frequently utilised in plastics, particularly those sourced from petroleum, can improve attributes such as flexibility, durability, and transparency. Bisphenol A (BPA) and phthalates, commonly found in polycarbonate plastics and polyvinyl chloride (PVC), present considerable issues. BPA acts as an endocrine disruptor, imitating oestrogen and disrupting hormonal activities in humans and wildlife, resulting in reproductive, developmental, and metabolic issues (Rubin 2011). Chemicals used to make plastic flexible, phthalates, can cause fertility problems, developmental disorders, and cancer (Meeker *et al.* 2009). Leachate studies show that plastics can release a wide range of hazardous compounds. or example, polycarbonate plastics can leach bisphenol A (BPA) in concentrations ranging from 0.036 to 1.1 mg/L under various conditions, while flexible PVC may release phthalates at levels up to 40% by weight, particularly during use involving contact with food or biological tissues (Hahladakis et al. 2023). Plastic leachates are released from various polymers such as PVC, PE, PP, PS, and PET through weathering, UV exposure, and microbial degradation (Omidoyin & Jho 2024). In marine environments, PBDE concentrations in plastics ranged from 0.3 to 9900 ng/g, while HBCD levels in expanded polystyrene fragments have been recorded as high as 14,500 µg/g (Hirai et al., 2011; Taniguchi et al., 2016; Jang et al., 2017). In freshwater systems like Taihu Lake, leachates include BPA (28–560 ng/L), nonylphenols (262–1443 ng/L), and OPFRs (~1097 ng/L) (Lu et al., 2011; Xiao-Ju et al., 2012; Yan et al., 2017). Soil contamination is also significant, with approximately 3905 tons of PAEs accumulated in Chinese soils from 1958 to 2019 (Bi et al., 2021) and up to 72% of DEHP from plastic products ending up in the soil (Wang et al., 2017). These data underscore the widespread of plastic leachate and its ecological significance across multiple environmental compartments. Conversely, cellulose-based products typically do not include these hazardous chemicals, as they are derived from natural, plant-based sources. Certain chemically modified cellulose derivatives, including cellulose acetate, may include additives; nonetheless, these are generally less toxic and pose lesser risks than synthetic plastics (Moon *et al.* 2011). Cellulose acetate films leached bisphenol A (BPA) at around 0.5 µg/L under standard use conditions. The leaching rate was significantly lower compared to conventional synthetic polymers. This level highlights the safer environmental profile of cellulose acetate in applications involving water contact (Islam et al. 2023). Cellulose derivatives employed in food packaging, textiles, and biomedical applications frequently obtain safety certifications from regulatory agencies such as the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA) (Klemm *et al.* 2005). Moreover, the biodegradability of cellulose materials mitigates accumulation in ecosystems, thereby diminishing long-term toxicological effects.

Microplastics are already pervasive in the environment and present considerable threats to both human and animal health. Plankton, fish, birds, and mammals in aquatic and terrestrial ecosystems eat microplastics. Microplastics can induce physical obstructions, reduced food consumption, and malnutrition in marine animals (Wright *et al.* 2013). Additionally, microplastics can absorb persistent organic pollutants (POPs) including PCBs and PAHs from the environment. Microplastics release monomers and additives such as bisphenol A (BPA) and phthalates, which are known to leach from plastic matrices and disrupt endocrine function even at very low concentrations (Prata et al. 2020). These leachates induce oxidative stress, evidenced by increased reactive oxygen species and lipid peroxidation in zebrafish and mice exposed to polystyrene particles (Lu et al. 2016; Deng et al. 2017). Exposure to 5–20 µm PS particles in mice led to significant accumulation in the liver and kidney, causing metabolic disruption and oxidative damage (Deng et al. 2017). Immunotoxic effects include suppressed dendritic cell activation and cytokine imbalances, while mussels exposed to microplastics showed altered immune gene expression and reduced immune competence (Saravia et al. 2014). Additionally, endocrine-disrupting compounds leached from plastics have been linked to hormonal imbalances and reproductive effects at low doses, highlighting the risk of chronic exposure through ingestion of up to 52,000 microplastic particles per person annually (Cox et al. 2019). Once in the food chain, these contaminants bioaccumulate and biomagnify (Rochman 2018). More individuals are afraid about eating microplastics from seafood, water, and air. Microplastics may cause oxidative stress, immune system disruption, inflammation, and other health issues, although researchers are still studying them (Prata *et al.* 2020). Microplastics can emit harmful chemicals like bisphenol A (BPA) and phthalates and harm the ecosystem. Cellulose-based products do not degrade into hazardous microplastics. Since microorganisms and enzymes break down cellulose, eating glucose and other naturally occurring components is harmless. This feature considerably reduces bioaccumulation and health concerns (Klemm *et al.* 2005).

4.2. The Role of Cellulose-Based Materials in Mitigating Microplastics in Ecosystems

Cellulose-based polymers reduce microplastic contamination better than petroleum-based plastics. Cellulose, a natural polymer, biodegrades in soil, rivers, and seas without leaving toxic residues. However, synthetic polymer breakdown microplastics can endure generations (Andrady 2011). Switching to cellulose-based cutlery, packaging, and straws can reduce coastal microplastic pollution. Biodegradable and compostable cellulose-derived products reduce microplastic pollution in aquatic habitats. Marine microbes may easily break down these toxins into non-toxic organic molecules, as reported by Song *et al.* (2009).

Multiple studies have proven prevalence of microplastics in aquatic ecosystems. Every year, 4.8–12.7 million metric tonnes of plastic debris enter the world's waters, contributing to microplastics (Jambeck *et al.* 2015). The Great Pacific Garbage Patch has dangerous quantities that are harming marine life (Eriksen *et al.* 2014). Briassoulis *et al.* (2019) compared cellulose-based film degradation in terrestrial and marine ecosystems to plastics. The study found that plastic films decay slowly whereas cellulose films breakdown entirely within months. This suggests that employing cellulose polymers instead of petroleum plastics might dramatically shorten microplastics' ecosystem time. A second Mediterranean Sea case study examined cellulose-based marine debris reduction alternatives. Biodegradable cellulose-based fishing gear and packaging may reduce plastic pollution by 30% over ten years if waste management is successful (Bergmann *et al.* 2015). These findings show that cellulose-based products not only prevent microplastic generation but also reduce exposure to toxic leachates and endocrine disruptors associated with conventional plastics. As such, cellulose-based alternatives contribute both to ecosystem health and to reduced chemical risks in the food chain.

5. REGULATORY AND ECONOMIC CONSIDERATIONS

5.1. Overview of International and National Regulations on Single-Use Plastics and Bioplastics

In recent years, some nations have established regulations to prevent plastic pollution, particularly single-use plastics. The EU's Single-Use Plastics Directive (2019) bans straws, cutlery, and polystyrene food containers. This law requires plastic bottles to have recycled material by 2025 and sets collection and recycling targets. As worries about plastic pollution in landfills and waterways have increased, Kenya, Canada, and India have banned or severely restricted single-use plastics. The 2019 Basel Convention modifications ban the transboundary movement of plastic waste; thus, governments must acquire authorisation before exporting non-recyclable plastic waste (Ahmed 2019). These restrictions aim to halt the flow of plastic waste from affluent to poor nations, where a lack of waste treatment infrastructure degrades the environment. Bioplastics and other eco-friendly materials are being promoted in numerous countries to decrease plastic waste. The EU's Circular Economy Action Plan (2020) aims to increase biodegradable material consumption and improve the bio-based product market. National governments, including the US and Japan, have provided financial incentives and research initiatives to create bioplastics and cellulose-based alternatives to conventional plastics (OECD 2018). Bioplastics are growing in popularity, yet cellulose-based products are still behind petroleum-based polymers. Government subsidies, tax cuts, and research grants are needed to promote cellulose-based alternatives. The European Bio-based Industries Joint Undertaking funds research and development of bio-based materials, primarily cellulose-derived polymers (Bio-based Industries Joint Undertaking 2022). Additionally, certain nations' public procurement regulations encourage biodegradable and compostable materials in public services and packaging, which expands these markets. The USDA BioPreferred Program in North America encourages bio-based goods, notably cellulose-based ones. This campaign encourages bio-based purchases and use through government procurement laws. After many public governments banned single-use plastics and required biodegradable or compostable alternatives, cellulose-based goods are becoming the standard. Table 4 outlines a chronological progression of key global regulatory actions targeting plastic pollution by promoting biodegradable alternatives.

Many developing nations face significant regulatory and implementation challenges. The global initiative to mitigate plastic pollution is affected by weak enforcement of bans on plastic materials, insufficient waste collection infrastructure, and ambiguous regulations concerning biodegradable plastics (Islam et al 2024). Capacities for enforcement and compliance monitoring do not exist in most countries that officially restrict single-use plastics (Islam et al, 2024); hence, these countries continue to consume plastic. Developing regions face an additional challenge of limited administrative capacity paired with fragmented governance structures. Inadequate infrastructure for managing waste stagnates the processes involved in properly collecting and sorting plastic wastes needed for recycling. Investment-related incentives are dampened due to logistical challenges and market uncertainty facing recycling systems (OECD, 2018; Gerassimidou et al. 2022). Furthermore, undefined and unenforceable rules concerning biodegradable plastics allow for the continued existence of harmful products meant to be regulated in nature without being entirely removed from ecosystems. Policy changes, infrastructure development alongside coordinated multilateral agreements, and defined international guidelines would help fill the noted gaps (Islam et al. 2024).

Table 4: Global regulations promoting biodegradable alternatives.

Year	Country/Region	Regulation/Initiative	Policy/Action	Reference
2002	Bangladesh	Plastic Bag Ban	First country to ban thin plastic bags due to drain blockage and flooding.	(UNEP 2018)
2015	USA	Microbead-Free Waters Act	Banned plastic microbeads in rinse-off cosmetics to prevent water contamination.	(NOAA 2015)

2016	Germany	Plastic Bag Tax	Introduced a voluntary agreement leading to ~60% drop in bag usage.	(DW 2016)
2017	Kenya	Plastic Bag Ban	Strictest penalties globally, including fines and jail terms for production/use.	(Griffin and Karasik 2022)
2018	Spain	Plastic Bag Charge	Mandatory charge for lightweight plastic bags; exemptions for very lightweight bags.	(European Commission 2019)
2019	European Union	Single-Use Plastics Directive	Ban on cutlery, straws, plates; targets for recycling and collection.	(European Commission 2019)
2020	France	Ban on Plastic Cutlery & Plates	Part of a wider anti-waste law banning disposable plastic items.	(Frontier Group 2023)
2021	China	Phased Plastic Ban	Gradual restrictions on plastic bags, straws, and delivery packaging.	(Library of Congress 2021)
2022	Colombia	Single-Use Plastics Prohibition	Law banning 14 single-use plastic products from 2022 to 2030.	(ADBioplastics, 2024)
2022	India	Single-Use Plastic Ban	Ban on manufacture, import, stocking, distribution, sale and use of listed plastic items.	(MoEFCC 2023)
2023	Canada	Single-Use Plastics Ban	Prohibits the sale and manufacture of plastic checkout bags, cutlery, straws, and other items.	(Government of Canada, 2023)
2025	European Union	Packaging and Packaging Waste Regulation (PPWR)	Requires all packaging to be recyclable or reusable by 2030; mandates compostability criteria.	(European Commission, 2025)
2023	France	Plastic Bottle Sales Reduction Target	Goal to cut single-use plastic bottle sales by 50% by 2030.	(Le Monde 2023)
2021	New Zealand	Single-Use Plastics Ban	Banned single-use plastic items such as cotton buds, drink stirrers, and fruit labels.	(Crux 2021)
2022	Nigeria	Single-Use Plastics Ban	Scheduled to ban single-use plastics, including plastic bags and straws, to combat environmental pollution.	(Sustainable Plastics 2024)
2024	United Arab Emirates	Single-Use Plastics Ban	Plans to ban single-use plastic food containers and cutlery to reduce plastic waste. The country aims to achieve zero plastic waste by 2030 as part of its larger environmental vision.	(UAE Stories 2024)

5.2. Economic Viability of Cellulose-Based Materials

Cellulose-based polymers are uneconomical because they cost more to make than petroleum-based plastics. Costs depend on delicate procedures involved in collecting and processing cellulose from premium sources like wood pulp or agricultural byproducts (Shen *et al.* 2010). However, economies of scale, well-established production techniques, and decreased raw material costs due to natural gas and crude oil abundance favour traditional plastics. Cellulose-based products must be mass-produced to be profitable. Improved production should lower per-unit costs. Dufresne (2017) suggests that nanocellulose production might save costs by improving extraction and refining efficiency. Moreover, escalating petroleum prices and heightened regulatory restrictions on plastic use may improve the economic viability of cellulose-based alternatives, particularly as the external environmental and social costs of plastic pollution are increasingly incorporated into market pricing.

Nonetheless, augmenting cellulose manufacturing entails numerous technical and economic obstacles. Industrial-scale operations necessitate significant investments in research and infrastructure, especially for sophisticated processing methods such as enzymatic hydrolysis and nanocellulose extraction (Klemm *et al.* 2005). Furthermore, the shift from small-scale niche production to mass manufacture must tackle technological challenges with product uniformity, performance, and integration with current manufacturing processes. For developing nations, economic barriers are particularly acute. High capital costs, limited technical expertise, and inadequate financial incentives constrain local production of cellulose-based materials.

Market adoption is also contingent upon consumer acceptance and willingness to invest in sustainable options. There is a growing consumer preference for environmentally friendly products in select markets, which could potentially boost demand for cellulose-based materials. Nonetheless, broad adoption will require further cost reductions and improvements in product performance to ensure competitiveness with the durability and functionality of conventional plastics in applications such as packaging and consumer goods (Siró & Plackett 2010).

5.3. Barriers to Widespread Implementation

Several technological and economic challenges impede the widespread adoption of cellulose-based materials (Li *et al.* 2024; Wang *et al.* 2024). Enhancing the properties of cellulose-derived products—such as moisture resistance, flexibility, and strength—requires continuous innovation (Zhao *et al.* 2021). For instance, cellulose films and packaging often lack the barrier properties inherent in petroleum-based plastics, rendering them less suitable for specific food packaging applications (Wang *et al.* 2018). Furthermore, modifying cellulose to improve its properties, such as conversion to cellulose acetate or nanocellulose, can increase costs, undermining its competitive edge. Economic challenges include the substantial initial investment required for new manufacturing processes and the limited availability of sustainably sourced raw materials on a scale. While cellulose is abundant, sustainable sourcing and industrial-scale processing can incur significant expenses (Wang *et al.* 2024). Additionally, cellulose-based materials must compete with established petroleum-based plastics, which benefit from extensive infrastructure investments and economies of scale.

Consumer behaviour also poses a challenge, as many consumers are unaware of the environmental benefits of cellulose-based alternatives or may hesitate to switch due to concerns about performance and cost (Filho *et al.* 2022). Addressing these behavioural barriers necessitates educational initiatives and improvements in the affordability and functionality of cellulose-based products (Filho *et al.* 2022). A critical barrier to the widespread adoption of cellulose-based materials is the insufficient infrastructure for recycling and composting (Parveen *et al.* 2024). While cellulose is biodegradable and compostable, numerous chemically modified or composite cellulose products necessitate certain conditions for efficient composting or recycling. Cellulose acetate, frequently utilized in packaging, often fails to disintegrate in home composting settings and generally requires industrial composting facilities for thorough degradation (Song *et al.* 2009). The current infrastructure, which is predominantly designed for conventional plastics, limits the recycling capability for cellulose-based products (Parveen *et al.* 2024). Enhancing this recycling infrastructure to include biodegradable and cellulose-based items will necessitate substantial expenditures in sorting technologies, industrial composting facilities, and consumer education. In developing nations, these infrastructure deficits are even more pronounced. Most waste management systems focus on landfill and informal recycling, with minimal capacity for industrial composting or specialised cellulose recycling. Unless these infrastructural inadequacies are rectified, the prospective environmental advantages of cellulose-based materials may remain unfulfilled.

6. FUTURE DIRECTIONS AND INNOVATION OPPORTUNITIES

6.1. Technological Innovations

Recent advances have made cellulose-based polymers a viable alternative to plastics. Researchers have transformed cellulose's nanoscale structure to boost its mechanical strength and flexibility (Ray *et al.* 2021). This is shown in nanocellulose, which contains cellulose nanocrystals -CNCs and cellulose nanofibrils -CNFs (Du *et al.* 2019; Dufresne 2019). Its high strength-to-weight ratio makes it ideal for packaging, coatings, and composites, and its mechanical qualities rival petroleum-based polymers (Dufresne 2017). Besides mechanical qualities, research on cellulose-based material water resistance has garnered a lot of interest. Due to its hydrophilic nature and rapid moisture absorption, natural cellulose is restricted in moisture-sensitive packaging. Acetylation and hydrophobic coatings boost the performance of water resistance, packaging, and food contact (Klemm *et al.* 2005). Cellulose and biodegradable polymers like polylactic acid have been combined to generate composite materials with increased moisture resistance and durability.

Modern cellulose processing uses ionic liquids and deep eutectic solvents to dissolve cellulose (Taokaew & Kriangkrai 2022). These safe solvents degrade cellulose without harsh chemicals, reducing its environmental impact (Sirviö *et al.* 2020). Enzymatic processing optimizes cellulose materials to reduce emissions and energy use compared to kraft pulping (Isikgor & Becer 2015).

Cellulose three-dimensional printing is novel. Cellulose-based additive manufacturing can mass-produce biodegradable, custom-shaped goods for building, medicine, and other industries (Chen *et al.* 2020). Nanocellulose-based 3D printing inks are expanding the use of cellulose materials in eco-friendly, high-performance manufacturing (Chauhan *et al.* 2024; Kim *et al.* 2024). Figure 3 presents a SWOT analysis of cellulose-based materials, highlighting their biodegradability and renewable origin as strengths while identifying scalability and competition from conventional plastics as key challenges.

Figure 3: SWOT Analysis of Cellulose-Based Materials as Alternatives to Conventional Plastics.

6.2. Policy and Industry Integration

To advance cellulose-based products, policymakers and industry stakeholders must work together. Restricting single-use plastics can accelerate the transition to biodegradable materials such as cellulose (OECD 2018). Comprehensive cellulose recycling and composting rules are needed to balance end-of-life management with environmental aims (Sikorska *et al.* 2021; Gadaleta *et al.* 2023). Collaboration between industry and research institutions is necessary for innovation and production scalability. Research and development are needed to improve the performance of cellulose-based materials and decrease their cost to compete with petroleum-based polymers. The packaging, textile, and consumer products sectors want sustainable solutions (Siró & Plackett 2010). Companies in these areas should integrate cellulose-based goods into their supply chains. Public-private partnerships (PPPs) can help innovate cellulose-based products. This type of partnership accelerates technology development and commercialization by pooling expertise, assets, and finance. The EU Bio-based Industries Joint Undertaking (BBI JU) funds cellulose product development projects. Industries, academic institutions, and governments should collaborate on this endeavour to tackle commercial and technical problems. PPPs may also align industry practices with regulations by boosting green production and waste management. Government incentives or co-investments may assist cellulose-based material producers in developing and embracing new technologies. PPPs can speed cellulose-based product development and deployment by fostering cross-sector collaboration.

6.3. Research Gaps and Prospective Investigations

Cellulose-based materials have advanced, but further study is needed to enhance their environmental advantages. Comprehensive lifecycle assessments (LCAs) are used to examine the environmental implications of cellulose-based products from extraction to disposal (Foroughi *et al.* 2021). Though renewable, cellulose extraction and processing have different environmental implications depending on feedstock and manufacturing procedures (Shen *et al.* 2010). More research is needed to improve these processes while reducing energy, water, and pollutants. The biodegradation of cellulose acetate and other chemically modified cellulose derivatives is crucial to study. Undamaged cellulose is biodegradable, although chemical changes may hinder it. Future research should aim to make modified cellulose materials biodegradable so they can break down in soil and water without leaving a deposit (Song *et al.* 2009). Cellulose-derived items in the bio-circular economy are a promising new research area. The bio-circular economy emphasizes waste reduction, renewable resources, and recycling (MacArthur 2013). Cellulose fits this paradigm since it's renewable, biodegradable, and recyclable. Effectively integrating cellulose materials into circular supply networks requires additional research. Research should focus on recycling composites and chemically modified cellulose, which are unsuitable for current procedures. New cellulose uses like bio-composites, and eco-friendly packaging can boost bio-circular economy performance. According to Tjeerdsma & Militz (2005), governments and companies must collaborate to provide composting, recycling, and reuse infrastructure for cellulose-based goods to contribute to a sustainable economy.

7. CONCLUSION

Cellulose-derived materials offer a promising pathway to mitigate plastic pollution due to their biodegradability, compostability, and lower greenhouse gas emissions compared to petroleum-based plastics. They naturally decompose in terrestrial and marine environments, avoiding the long-term persistence and toxic effects associated with microplastics. Despite these advantages, technical and economic barriers remain. Unmodified cellulose lacks sufficient water resistance and mechanical strength, while chemical modifications such as cellulose acetate and nanocellulose introduce additional costs and processing challenges. Scaling production and improving material performance are essential to enhance market competitiveness. Achieving a broader transition to cellulose-based materials requires coordinated action. Industry should invest in R&D to develop cost-effective and environmentally friendly production processes. Governments can support this shift through targeted legislation, tax incentives, and investment in recycling and composting infrastructure. Public procurement policies and consumer education will further drive demand and market growth. Future efforts must focus on overcoming affordability, scalability, and end-of-life management challenges. Advancing cellulose-based solutions through innovation, public-private collaboration, and informed policy will contribute significantly to a sustainable and circular economy. In addressing the global plastic crisis, cellulose-based alternatives represent a critical step towards a cleaner and more resilient future.

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