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# Bioplastics from Waste Biomass: Paving the Way for a Sustainable Future

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***Abstract: Bioplastics originating from waste biomass present a viable remedy to the environmental dilemmas associated with traditional plastics, thereby reducing dependency on fossil fuels and mitigating carbon emissions. This review investigates the utilization of diverse waste biomass sources, encompassing agricultural residues, food waste, industrial by-products, municipal solid waste, and forest biomass residues, in the synthesis of bioplastics. Technological innovations in feedstock pretreatment, bioconversion methodologies, and polymerization techniques have markedly enhanced the efficiency and material characteristics of bioplastics, establishing them as formidable alternatives to petroleum-derived plastics. Notwithstanding these advancements, obstacles such as feedstock inconsistency, scalability issues, technological limitations, and consumer acceptance persistently impede the extensive adoption of bioplastics. The ecological advantages of bioplastics, particularly concerning their diminished carbon footprint and potential for biodegradability, are underscored through life cycle assessments (LCAs). Government policies, the increasing market demand for sustainable products, and advancements in emerging technologies, including synthetic biology and AI-enhanced process optimization, are propelling the commercialization of bioplastics derived from waste biomass. The incorporation of bioplastics within a circular economy framework, coupled with considerations for long-term sustainability, positions them as a pivotal element in fostering a more sustainable and environmentally friendly future. This review offers a thorough examination of the present landscape, challenges, and future prospects of bioplastics production from waste biomass.***
***Keywords: Bioplastics, Waste biomass, Environmental Pollution, Polylactic acid (PLA), Polyhydroxyalkanoates (PHA)***

## I. INTRODUCTION

Bioplastics represent a promising alternative to conventional petroleum-based plastics, offering environmental benefits through biodegradability and reduced carbon footprints [1]. Bioplastics differ significantly from traditional plastics in their chemical composition and environmental impact [2]. Traditional plastics, such as polyethylene and polypropylene, are derived from fossil fuels and consist of synthetic polymers, which contribute significantly to environmental degradation due to their non-biodegradable nature, with over 8 million tons entering oceans annually [3]. According to a report by Our World in Data (2021), global plastic production has increased from 2 million tons in 1950 to 367 million tons in 2020 [4]. Of this, over 300 million tons of plastic waste are generated annually, and only 9% of this waste is recycled [4]. Additionally, recent studies show that microplastics are now found in drinking water, food, and even in human blood [5], [6], [7]. These particles pose health risks, as they can accumulate in organs and potentially disrupt biological systems. It is estimated that by 2050 traditional or synthetic plastics could account for up to 15% of global carbon emissions if current trends continue[8]. On the other hand, bioplastics can be fully or partially bio-based, derived from renewable resources like starch, proteins, and polyhydroxyalkanoates (PHA) [9]. They are usually categorized into biodegradable polymers, such as polylactic acid (PLA) and polybutylene adipate terephthalate (PBAT) [10], as illustrated in Fig. 1.

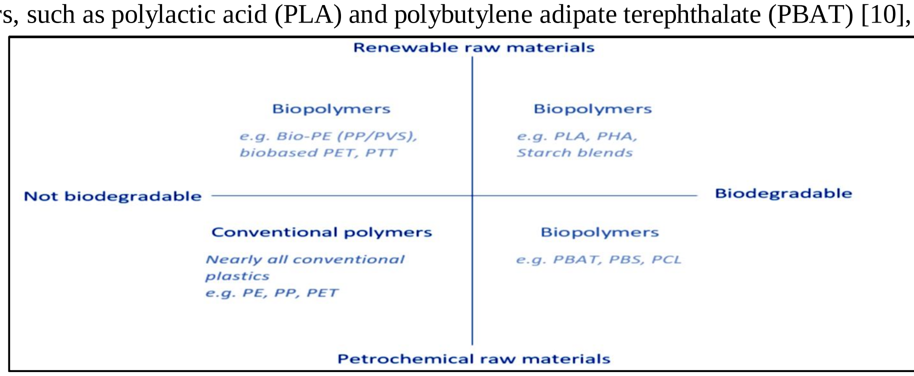


Fig. 1 Overview of the different types of bioplastics

Bioplastics derived from waste biomass sources present a sustainable alternative to conventional plastics, leveraging various agricultural, industrial by-products, municipal solid waste (MSW), and forest biomass residues [11]. The most promising sources include waste wood, corn stalks, microalgae, corncob residues, and fruit peels, each offering unique advantages [12]. It is estimated that the world generates around 5 billion tons of agricultural waste annually [13]. According to the Food and Agriculture Organization (FAO), approximately 1.3 billion tons of food waste is generated globally every year, this includes organic waste from households, restaurants, and food industries [14]. The forest industry generates about 1.2 billion tons of woody biomass residues, including bark, sawdust, and wood chips [15]. On a global scale, about 2.01 billion tons of MSW is generated annually, with organic waste biomass accounting for approximately 46%, which includes food scraps, yard trimmings, and paper products [16]. Industrial sectors like sugar production, palm oil, and paper mills contribute significantly to biomass waste. For example, the sugar industry generates about 279 million tons of bagasse (sugarcane waste) each year globally [17]. Bioplastics derived from waste biomass can decrease greenhouse gas emissions by 35% to 80% compared to conventional plastics [18]. In addition, fully biomass-derived films have demonstrated favorable degradation rates, contributing to reduced plastic pollution [19]. The use of waste biomass as a feedstock for bioplastics production presents significant environmental benefits compared to traditional fossil fuel-based methods [20]. This approach not only reduces reliance on non-renewable resources but also mitigates pollution and waste management issues [21].

The significance of bioplastics obtained from waste biomass is vital in the global initiative to mitigate plastic pollution and reduce reliance on fossil fuels [22]. Bioplastics, particularly those produced from waste biomass, present a sustainable alternative. For example, enterprises such as NatureWorks are manufacturing polylactic acid (PLA) bioplastics utilizing agricultural waste, thereby mitigating landfill accumulation and carbon emissions [23]. Furthermore, international initiatives, including the European Union's Circular Economy Action Plan, highlight the shift towards sustainable materials, which propels innovation in waste-derived bioplastics [24]. This methodology not only reduces environmental repercussions but also enhances the value of waste, in accordance with the tenets of a circular economy.

## II. TYPES OF WASTE BIOMASS FOR BIOPLASTICS PRODUCTION

Recent studies demonstrate that various waste biomass sources can yield bioplastics with desirable mechanical and physical characteristics.

### *A. Agricultural Residues*

Crop residues, such as corn stover, rice husk, and wheat straw, have gained attention as sustainable feedstocks for bioplastic production [25]. These residues are agricultural by-products that would otherwise go to waste or be burned, contributing to environmental pollution. Corn stover which consists of leaves, stalks, and cobs left after harvesting corn, rice husk, and wheat straw consisting of stems and leaves left after wheat harvesting are valuable agricultural residues for bio-based polyhydroxyalkanoates (PHA) and polylactic acid (PLA) production [26]. These agricultural residues are rich in cellulose, hemicellulose, and lignin, which can be transformed into biopolymers like PLA [26]. Companies like NatureWorks have been focusing on PLA production using corn-based feedstocks [27]. Research from Iowa State University is exploring ways to improve the efficiency of converting corn stover into PLA, enhancing yield and reducing production costs [28]. According to Brites et al., (2024), the Indian Institute of Technology (IIT) has developed bioplastic films from rice husk that are both biodegradable and cost-effective [29]. Rice husk is rich in lignocellulose, a complex of cellulose, hemicellulose, and lignin, making it a valuable resource for producing bio-based plastics. According to Sachan et al., (2024), in Europe, wheat straw has been utilized by companies like Bio-on to produce PHA [30]. Additionally, researchers at the University of York are working on converting wheat straw into sustainable biocomposite materials for packaging and automotive parts [31].

### *B. Food Waste*

Food waste, including fruit peels and vegetable scraps, is emerging as a promising feedstock for bioplastic production. Fruit peels and vegetable scraps are rich in cellulose, starch, pectin, chitin, chitosan, and lignin which can be converted into biopolymers [32]. Orange peels rich in cellulose have been utilized to create biodegradable plastic films that are transparent, flexible, and suitable for packaging [33]. Cellulose is extracted from orange peels and converted into cellulose acetate or other bio-based polymers. Potato peels rich in starch can be converted into thermoplastic starch (TPS), which is a biodegradable material widely used in packaging, disposable cutlery, and agricultural films and when combined with other biopolymers like PLA, it improves the material's mechanical properties [34].

Apple peels rich in pectin are used to produce bioplastic with good film-forming capabilities which can be used in food packaging [35]. Mushroom waste is being explored as a source of chitosan for bioplastic, when deacetylated, chitin becomes chitosan, a biopolymer used to create biodegradable films and coatings [36], chitosan has antimicrobial properties, making it ideal for food packaging. Tomato skins and other vegetable waste rich in lignin content can be used as a natural binder and reinforcing agent in bioplastic [37].

### C. Industrial By-products

Industrial by-products such as glycerol, lignin, and cellulose are increasingly being used as feedstocks in bioplastic production, contributing to more sustainable manufacturing processes. According to, Bio-on, an Italian company, glycerol can be used as a plasticizer in the production of polyhydroxyalkanoates (PHAs) and biodegradable polyesters [38]. Glycerol is a by-product of biodiesel production and oleochemical industries. It is abundant and inexpensive due to the rise of biodiesel production globally. Similarly, According to Chung, (2021), researchers from the University of Delaware have developed a lignin-based bioplastic that is fully biodegradable [39]. Lignin is a by-product of the paper and pulp industry and is one of the most abundant natural polymers. According to Tomani, (2017) the LignoCity project, in Sweden, lignin is converted into value-added bioplastic for use in packaging materials, replacing petroleum-based plastics with more sustainable alternatives [40]. These lignin-based materials are highly resistant to UV radiation, making them suitable for outdoor applications. According to Gruter and van Aken, (2021), Avantium, a renewable chemicals company, has developed cellulose-based PEF (polyethylene furanoate) as a replacement for PET in plastic bottles [41], cellulose is the most abundant natural polymer, derived as a by-product from the paper, textile, and agricultural industries.

### D. Municipal Solid Waste (MSW)

The organic fraction of Municipal Solid Waste (MSW), which includes kitchen waste (food scraps, vegetable peels, fruit wastes) and yard trimmings (grass clippings, leaves, branches), offers a valuable feedstock for producing bioplastic. Yard trimmings, rich in cellulose, have been used in processes where lignocellulosic material is hydrolyzed to produce fermentable sugars, which are then converted into biodegradable plastics like PLA [42]. According to Ventura and Venturs, (2024), a project in Finand is using yard trimmings to produce polyhydroxybutyrate (PHB), a type of PHA bioplastic [43].

### E. Forest biomass residues

Forest biomass residues, including bark, sawdust, and wood chips, are renewable and abundant sources of lignocellulosic material that can be used in bioplastic production [44]. This biomass is rich in lignin, cellulose, hemicellulose, and extractives (resins and tannins). Lignin found in bark, sawdust, and wood chips, can be extracted and used as a reinforcing agent or even chemically modified for use in bioplastic [45]. Cellulose and Hemicellulose are abundant in wood biomass, they can be broken down into sugars that are fermented into bio-based monomers, which are then polymerized into biodegradable plastics like PLA or PHA [46]. Extractives such as resins, tannins, and other chemical compounds found in bark and wood can be used as additives or precursors in bioplastic formulations [47].

## III. TECHNOLOGICAL ADVANCEMENTS IN BIOPLASTICS PRODUCTION FROM WASTE BIOMASS

Technological advancements in bioplastics production from waste biomass have significantly improved the efficiency, sustainability, and scalability of bioplastics as an alternative to petroleum-based plastics.

### A. Novel feedstock pretreatment techniques

Before converting waste biomass into bioplastics, it must be pretreated to break down complex lignocellulosic structures, such as cellulose, hemicellulose, and lignin, into simpler components. Novel pretreatment techniques for converting complex waste biomass into simpler components are delineated in Table 1.

Table I Novel pretreatment methodologies aimed at the transformation of complex waste biomass into simpler components.

| Pretreatment Technology | Description | Advantages | Feedstock Examples | Recent Advancements | Example Application | References |
|---|---|---|---|---|---|---|
| Steam Explosion | Uses high-pressure steam | Energy-efficient and | Corn stover, | More effective at releasing | Utilizes steam explosion for | [48] |

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| | to break down the lignocellulosic structure of biomass. | scalable for industrial use | wood chips, wheat straw | fermentable sugars. Lower energy consumption | breaking down straw into sugars for bioplastics production. | |
| Ionic Liquids | Advanced solvents are used to dissolve biomass and extract cellulose. | High-efficiency and recyclable solvents | Corn stover, rice husks, and other agricultural residues | Reduced waste. Sustainable recycling of solvents | Ionic liquids are used to dissolve lignocellulosic biomass into simple sugars for biopolymer synthesis. | [49] |
| Deep Eutectic Solvents (DES) | A new class of green solvents with low toxicity and environmental impact is used to break down biomass. | Environmentally friendly and low in toxicity | Wood chips, agricultural residues, forest biomass | Improved lignocellulosic breakdown. Lower ecological impact compared to ionic liquids | DES is applied in the pretreatment of forest biomass for sustainable bioplastics production. | [50] |

### *B. Advancement in bioconversion technologies*

Bioconversion, through enzymatic hydrolysis and microbial fermentation, is at the heart of bioplastics production from waste biomass [51], [52]. New developments in these areas focus on increasing efficiency and yield while reducing costs.

#### *1) Recent advancements in microbial fermentation*

Microbial fermentation uses microorganisms (bacteria, yeast, and fungi) to break down biomass and produce bio-based monomers like lactic acid, which are used to synthesize polymers such as Polylactic Acid (PLA), or directly produce Polyhydroxyalkanoates (PHA) [51]. Recent developments in the microbial fermentation of waste biomass utilized in the synthesis of bioplastics are delineated in Table 2.

Table II Recent advancements in microbial fermentation of waste biomass utilized in the synthesis of bioplastics

| Microorganism | Biomass Feedstock | Product | Advancement | References |
|---|---|---|---|---|
| *Lactobacillus spp.* | Food waste, agricultural residues | Lactic Acid (for PLA) | Improved fermentation efficiency and yield | [53] |
| *Cupriavidus necator* | Waste glycerol, forest residues | Polyhydroxybutyrate (PHB) | Genetic engineering for enhanced PHB production | [54] |
| *Pseudomonas putida* | Lignocellulosic biomass | Polyhydroxyalkanoates (PHA) | The strain was engineered to convert sugars from food waste into PHA at a yield of 45 g/L. | [54] |

#### *2) Recent advancements in enzymatic hydrolysis*

Enzymatic hydrolysis involves breaking down complex carbohydrates (like cellulose and hemicellulose) in biomass into simple sugars, which can then be fermented or chemically processed into monomers like lactic acid for bioplastics [52]. Recent developments in the enzymatic hydrolysis of waste biomass utilized in the synthesis of bioplastics are delineated in Table 3.

Table III Recent advancements in enzymatic hydrolysis of waste biomass utilized in the synthesis of bioplastics

| Enzyme | Biomass Feedstock | Monomer/Polymer | Advancement | References |
|---|---|---|---|---|
| Cellulases | Agricultural residues (corn stover, wheat straw) | Glucose (for PLA) | Enhanced enzyme efficiency at lower temperatures | [55] |

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| Xylanases | Food waste, forest residues | Xylose (for PHA) | Cost-effective enzyme production methods | [56] |
| Laccases | Lignin-rich biomass (bark, wood chips) | Lignin derivatives (for biocomposites) | Improved lignin breakdown and valorization | [57] |

*a) Enzyme Optimization*

- Thermostable Enzymes: These enzymes can operate at higher temperatures, speeding up the hydrolysis of lignocellulosic biomass, reducing energy costs, and increasing sugar yields [58].
- Cocktail Enzymes: New enzyme mixtures, such as those combining cellulases, hemicellulases, and laccases, improve the breakdown of biomass by targeting multiple components simultaneously [59].
- Efficiency enhancements in the process of new enzyme-cocktail-based hydrolysis for the production of bioplastics are delineated in Table 4.

Table IV Efficiency improvements in new enzyme-cocktail based hydrolysis for bioplastics production

| Feedstock | Traditional Hydrolysis Yield | New Enzyme Cocktail Yield | References |
|---|---|---|---|
| Corn Stover | 60% | 85% | [60] |
| Wheat Straw | 55% | 80% | [61] |
| Rice Husk | 50% | 78% | [62] |

The process of microbial fermentation, which involves the metabolic activities of microorganisms such as bacteria and yeast, operates through the anaerobic breakdown of organic substrates, thereby producing energy-rich compounds like ethanol and organic acids, while enzymatic hydrolysis entails the utilization of specific enzymes to catalyze the degradation of complex polysaccharides into simpler sugars, which can subsequently be fermented or further processed into desired end products. A detailed examination and analysis of the contrasting methodologies of microbial fermentation and enzymatic hydrolysis reveal significant differences in their mechanisms, efficiencies, and overall applications in the conversion of biomass into valuable biofuels and bioproducts (Table 5).

Table V Comparison of Microbial Fermentation and Enzymatic Hydrolysis in Bioconversion

| Parameter | Microbial Fermentation | Enzymatic Hydrolysis | References |
|---|---|---|---|
| Feedstock Type | Organic waste, sugars | Lignocellulosic biomass | [63] |
| Product Yield (g/L) | 30-50 g/L | 20-40 g/L | |
| Process Temperature (°C) | 30-40°C | 50-60°C | |
| Primary Product | PLA, PHA | Monomers for PLA, PHA | |
| Environmental Impact | Low $CO_2$ emissions | Moderate, due to energy input | |
| Economic Feasibility | High for sugars-based feedstock | High with pretreatment improvements | |

*3) Combined Bioconversion Techniques*

Combining enzymatic hydrolysis with microbial fermentation maximizes the efficiency of converting waste biomass into valuable monomers or polymers for bioplastics. In this process, lignocellulosic biomass is first hydrolyzed using enzymes, and the resulting sugars are fermented by microorganisms to produce lactic acid or PHAs [64]. Combining both processes can increase the overall efficiency of the bioconversion process, as delineated in Table 6.

Table VI A comparative analysis of independent enzymatic hydrolysis and independent microbial fermentation versus the integrated approach of enzymatic hydrolysis coupled with microbial fermentation

| Bioconversion Technique | Description | Key Steps | Efficiency | Advantages | Example Application | References |
|---|---|---|---|---|---|---|
| Standalone Enzymatic Hydrolysis | Enzymes break down lignocellulosic biomass into simple sugars (e.g., glucose, xylose). | Biomass is pretreated and then. Enzymes hydrolyze cellulose into sugars. | Moderate | Simple process and suitable for various feedstocks | Lactic acid production from cellulose using cellulase enzymes. | [52] |

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|---|---|---|---|---|---|---|
| Standalone Microbial Fermentation | Microorganisms convert sugars (from biomass) into monomers such as lactic acid or PHAs. | Sugars are fermented by microbes into bioplastics precursors | Moderate | Direct fermentation and flexible with microbial strains | Pseudomonas putida used to ferment sugars into PHAs for bioplastics. | [51] |
| Combined Enzymatic Hydrolysis and Microbial Fermentation | Enzymes hydrolyze biomass to sugars, followed by microbial fermentation of these sugars into bioplastic precursors like lactic acid or PHAs. | Biomass is hydrolyzed by enzymes and then microbes ferment the resulting sugars into valuable polymers. | High | Higher yield, more efficient conversion, and reduced waste | Clariant's Sunliquid Process integrates enzymatic hydrolysis with microbial fermentation to produce lactic acid for bioplastics from agricultural waste. | [64] |

### C. *Recent advancements in polymerization techniques*

Converting monomers, such as lactic acid or sugar-derived molecules, into polymers is a critical step in bioplastics production [53]. Recent advancements focus on improving polymer quality, material properties, and energy efficiency (Table 7).

Table VII Recent advancements in polymerization techniques for converting monomers into polymers for bioplastics production

| Polymerization Technology | Description | Recent Advancements | Advantages | Example Application | References |
|---|---|---|---|---|---|
| PLA (Polylactic Acid) | Bio-based polyester is produced from lactic acid, derived from renewable resources like corn starch or sugarcane. | Ring-Opening Polymerization (ROP): Improves molecular weight and thermal properties, making PLA suitable for high-performance applications like packaging and 3D printing. | Improved mechanical strength, better heat resistance, and suitable for diverse applications | NatureWorks developed low-energy polymerization methods for producing high-purity PLA, enhancing clarity and strength for food packaging. | [65] |
| PHA (Polyhydroxyalkanoates) | Biodegradable polyester is produced inside microbial cells using engineered microbes to convert sugars into PHA granules. | Engineered microbes produce PHA directly within cells. Properties similar to polypropylene (PP). | Biodegradable, similar properties to petroleum-based plastics (e.g., PP), and suitable for single-use packaging. | Danimer Scientific uses microbial fermentation to produce PHA for bioplastics, offering an eco-friendly alternative to traditional plastics. | [66] |
| Biocatalysts | Bio-based catalysts | Reduced | Greener | MetGen | [67] |

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| | are used in polymerization, offering high selectivity and operating under mild conditions. | environmental footprint. Lower energy requirements. Increased efficiency in polymerization reactions | production processes and reduced toxic by-products | develops biocatalysts to improve the polymerization of bioplastics like PLA and PHA, enhancing their sustainability. | |
| Metal-Free Catalysts | Organic, metal-free catalysts that polymerize bioplastics without the risk of contamination from heavy metals. | Focused on greener, non-metal catalysts. Improved purity of bioplastics | Reduced contamination risks and environmentally friendly | Research in Metal-Free Catalysis has improved the safety and sustainability of bioplastics production, particularly in medical and food applications. | [68] |

### *D. Recent material enhancement and additive technologies*

Bioplastics have traditionally struggled with performance issues, such as mechanical strength, barrier properties, and thermal stability. New technologies are addressing these challenges by developing bio-based additives, composites, and biocomposites [69]. Recent material enhancement and additive technologies are delineated in Table 8.

Table VIII Recent material enhancement and additive technologies for bioplastics production

| Technology | Description | Recent Advancements | Advantages | Example Application | References |
|---|---|---|---|---|---|
| Nanocellulose Additives | Nanocellulose derived from waste biomass is used as a reinforcing agent to improve mechanical properties. | Improves mechanical strength and barrier properties of bioplastics. Derived from renewable sources | Increased strength, better barrier properties, and renewable source | Nanocellulose-reinforced PLA improves packaging materials, making them stronger and more durable. | [70] |
| Nanosilver and Nanoclay | Used in bioplastic films to enhance antimicrobial properties and shelf life in packaging applications. | Nanosilver imparts antimicrobial properties. Nanoclay enhances barrier properties. | Improved shelf life, antimicrobial features, and enhanced food safety | Food packaging films reinforced with nanosilver and nano clay to preserve the freshness and safety of food products. | [71] |
| Lignin-based Composites | Lignin from forest biomass is blended with biopolymers like PLA and PHA for stronger, UV-resistant biocomposites. | Lignin enhances the strength and UV resistance of biocomposites | Increased strength, UV resistance, and eco-friendly alternative | Lignin-based PLA composites are developed for durable and UV-resistant packaging and outdoor materials. | [72] |
| Fiber-reinforced Bioplastics | Agricultural waste fibers | Improved heat resistance and | Stronger bioplastics, | Cellulose nanofibers from | [73] |

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| | (e.g., wheat straw, rice husk) are used to reinforce bioplastics like PLA and PHA. | mechanical durability | increased heat tolerance, and sustainable use of waste | wheat straw are used in automotive bioplastic components to enhance strength and stability. | |

## IV. ENVIRONMENTAL IMPACT OF BIOPLASTICS FROM WASTE BIOMASS

The environmental impact of bioplastics from waste biomass offers significant advantages over conventional, petroleum-based plastics, particularly in areas such as carbon footprint reduction, biodegradability, and waste management [74].

### *A. Life Cycle Assessment (LCA) of bioplastics*

Life Cycle Assessment (LCA) is a crucial tool for evaluating the environmental performance of bioplastics produced from waste biomass. By comparing the entire lifecycle from raw material extraction, processing, and use, to disposal bioplastics show significant advantages over conventional petroleum-based plastics [75]. LCA studies generally report lower carbon footprints for bioplastics from waste biomass. Ali et al., (2023), found that PLA (Polylactic Acid) produced from agricultural waste emits up to 70% less CO2 compared to conventional plastics like polyethylene or polypropylene [76]. Since bioplastics capture $CO_2$ during the biomass growth phase, their net greenhouse gas emissions are significantly reduced. Bioplastics from waste biomass tend to require less energy in production. According to Morris and Hicks (2022), comparing PHA (Polyhydroxyalkanoates) from food waste to traditional polypropylene showed a 25% reduction in energy usage during production due to lower process temperatures and renewable feedstock [77]. Since bioplastics are derived from renewable, often waste, feedstocks, their production can help reduce overall waste generation. Furthermore, producing PLA from corn stover or wheat straw repurposes agricultural residues that would otherwise be discarded, significantly cutting down on waste that would otherwise contribute to landfills or be incinerated [78].

### *B. Biodegradability and Compostability of bioplastics*

Bioplastics, especially those derived from waste biomass such as PLA, PHA, and starch-based plastics, exhibit different degrees of biodegradability depending on environmental conditions. Biodegradable plastics like PLA and PHA break down more readily in soil environments compared to conventional plastics. PLA, for example, can degrade in a few months to a year under industrial composting conditions, but it may take longer in natural soil environments due to cooler temperatures [79]. PHA biodegrades faster than PLA in soil and marine environments, often within 3–6 months under optimal conditions. PHA is considered marine biodegradable, breaking down in oceanic conditions within months. In contrast, PLA is not designed for marine degradation and may persist longer in such environments [80]. According to Lackner et al., (2023), noted that PHA bioplastics in seawater showed 90% degradation within six months, whereas PLA showed minimal degradation over the same period [81]. Bioplastics certified as compostable (e.g., PLA, PHA) can degrade in industrial composting facilities within a few weeks to months [82]. However, their compostability in home composting systems is slower, and not all bioplastics are suitable for such conditions [83]. According to Fogašová et al., (2022), compostable packaging made from PLA was found to decompose fully in industrial facilities in under 12 weeks [84].

### *C. Impact on Waste Management Systems and Landfills*

The widespread adoption of bioplastics from waste biomass has the potential to significantly alter existing waste management infrastructures. The shift from traditional plastics to bioplastics introduces new challenges and opportunities. While bioplastics are recyclable, they require dedicated sorting and processing facilities to avoid contamination of traditional plastic recycling streams. PLA, for instance, is recyclable but needs to be separated from conventional plastics like PET to ensure proper recycling [85]. A lack of infrastructure for sorting and recycling bioplastics could result in higher contamination rates, complicating overall waste management. However, the compostability of bioplastics offers a solution for organic waste disposal, cities with industrial composting facilities can divert compostable bioplastics from landfills, reducing methane emissions associated with traditional waste [86]. In regions without industrial composting facilities, bioplastics may end up in landfills, reducing their environmental benefits. Bioplastics in landfills may still release some greenhouse gases if they degrade anaerobically [87]. However, their overall emissions are significantly lower compared to conventional plastics. According to Afshar et al., (2024), bio-based PHA and PLA suggested that their adoption could reduce the volume of waste going to incineration by 15-20%, lowering both air pollution and energy consumption in waste-to-energy plants [88].

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## V. MARKET POTENTIAL AND ECONOMIC VIABILITY OF BIOPLASTICS FROM WASTE BIOMASS

As of 2023, the global bioplastics market is valued at approximately USD 18 billion [89]. The market for bioplastics is expanding due to increased consumer and regulatory demand for sustainable alternatives to conventional plastics. The bioplastics market is projected to grow at a compound annual growth rate (CAGR) of around 15-20% over the next five years [89]. By 2028, the market size is expected to reach approximately USD 40 billion [90]. This growth is driven by rising environmental concerns, regulatory support, and technological advancements in bioplastics production. The push for reducing plastic pollution and the adoption of circular economy principles are driving the demand for bioplastics. Key sectors such as packaging, agriculture, and automotive are increasingly adopting bioplastics to meet sustainability goals.

### *A. Cost competitiveness of bioplastics from waste biomass*

The economic challenges and opportunities associated with bioplastics production from waste biomass, focusing on raw material costs, production costs, and market pricing, are delineated in Table 9.

Table IX Cost analysis of bioplastics production from waste biomass

| Aspect | Description | Current Challenges | Opportunities for Improvement | Recent Examples | References |
|---|---|---|---|---|---|
| Raw Material Costs | Bioplastics are often produced from feedstocks like corn, sugarcane, or waste biomass. | Higher costs for raw materials compared to fossil fuels. Feedstock variability | Utilizing waste biomass can lower raw material costs. Waste biomass is often less expensive or even free. | LanzaTech uses industrial waste gases to produce ethanol, reducing raw material costs compared to traditional feedstocks. | [91], [92] |
| Production Costs | The process of converting biomass into bioplastics involves several steps, including pretreatment and polymerization. | Energy-intensive processes. High capital costs for advanced technologies | Advancements in technology can reduce energy consumption. Streamlined processes can lower costs. | NatureWorks has invested in improving PLA production technology to reduce costs and increase efficiency. | [93], [94] |
| Market Pricing | The price of bioplastics often remains higher than conventional plastics due to production costs. | Higher prices can limit market adoption. Price volatility in raw materials | Economies of scale and technological advancements can reduce prices. Waste biomass can contribute to lower costs. | Danimer Scientific produces PHA at competitive prices, making it an attractive alternative to traditional plastics. | [95], [96] |

### *B. Commercialization and industry adoption of bioplastics*

The commercialization and industry adoption of bioplastics derived from waste biomass has been significantly advanced by several pioneering companies and their innovative approaches. These success stories illustrate how strategic partnerships and technological innovations can scale production and integrate bioplastics into mainstream markets [96]. According to Pinlova et al., (2024), NatureWorks, a leading company in the bioplastics industry produces PLA (Polylactic Acid), a biodegradable plastic made from agricultural feedstocks such as corn stover [27]. Their success stems from their advanced production techniques and strategic partnerships. The company collaborates with industry giants like Cargill and TotalEnergies to scale up production and ensure widespread distribution [97]. NatureWorks has implemented continuous improvements in its manufacturing process, reducing costs and enhancing the material properties of PLA. Their ability to secure large-scale contracts with major consumer goods and packaging companies has established PLA as a viable alternative to conventional plastics, driving its adoption in various applications from food packaging to disposable cutlery [98].

According to Roohi et al., (2023), Danimer Scientific, specializes in PHA (Polyhydroxyalkanoates), a bioplastic produced from food waste and other biomass sources [99].

Danimer's innovation lies in its use of waste biomass as a feedstock, which not only reduces production costs but also addresses the issue of waste management. The company has formed significant partnerships, including one with Mars Inc., to develop compostable packaging solutions [100].

This collaboration highlights how industry partnerships can facilitate the commercialization of bioplastics by integrating them into established supply chains and meeting the growing consumer demand for sustainable packaging options. Danimer's success in scaling its production capabilities and its ability to offer competitive pricing has helped establish PHA as a practical alternative to conventional plastics [101].

Similarly, according to Karishma et al., (2024), LanzaTech represents another innovative approach to bioplastics commercialization and has developed a process to convert industrial waste gases into ethanol, which can then be used as a feedstock for bioplastics production [102]. This method not only creates a valuable product from waste gases but also reduces reliance on traditional feedstocks like petroleum. The company's strategic partnerships with major corporations have facilitated the integration of their technology into industrial processes. By converting waste gases from steel mills and other industrial sources into ethanol, LanzaTech is pioneering a method that enhances the sustainability of bioplastic production while addressing industrial waste management issues [103].

### *C. Government Policies and Incentives regarding bioplastics*

Government regulations, policies, and incentives play a crucial role in promoting the use of bioplastics derived from waste biomass. These measures are instrumental in shaping market dynamics and fostering industry growth by addressing the challenges of production costs, consumer acceptance, and environmental impact.

In the European Union, policies such as the Directive on Single-Use Plastics and the Circular Economy Action Plan have significantly influenced the bioplastics market [104]. The Single-Use Plastics Directive, enacted in 2019, aims to reduce plastic waste by banning certain single-use plastic items and encouraging the use of alternatives, including biodegradable bioplastics [105]. This regulation has driven demand for bioplastics by creating a market for sustainable packaging solutions. The Circular Economy Action Plan complements this by promoting a shift towards a circular economy, which includes funding for research and development in bioplastics technologies. The EU's commitment to sustainability and waste reduction has provided a robust regulatory framework that supports the growth of bioplastics from waste biomass, helping companies align with environmental goals and secure funding for innovation [106].

In the United States, state and federal policies also support the development and adoption of bioplastics. For instance, various states offer tax credits and subsidies to companies engaged in bioplastic production [107]. According to Awewomom et al., (2024), California, which is known for its stringent environmental regulations, provides incentives for the use of compostable materials through its green business programs [108]. These incentives help offset the higher production costs associated with bioplastics, making them more competitive with traditional plastics. Additionally, the Biodegradable Products Recovery Act at the federal level encourages the development and use of biodegradable plastics by offering grants and research funding [109]. This support helps companies lower production costs and improve the economic feasibility of bioplastics from waste biomass.s

China's approach to bioplastics is shaped by its Plastic Pollution Control Policy, which focuses on reducing plastic waste and promoting sustainable alternatives [15]. This policy has been instrumental in accelerating the adoption of bioplastics in various sectors, particularly packaging and agriculture [8]. China's emphasis on reducing plastic pollution has led to significant investments in bioplastics research and infrastructure, enabling the commercialization of bioplastics from waste biomass. The government's support extends to funding for innovative technologies and the development of recycling and composting facilities, which are crucial for the effective disposal and recycling of bioplastics [110].

According to Hereu-Morales et al., (2024), in Europe, the EU Green Deal has allocated significant funding to support sustainable practices, including bioplastics. This funding has facilitated the development of new technologies and the scaling of production capacities for bioplastics [111]. In the United States, California's incentive programs have enabled companies like BioLogiQ to expand their production of compostable bioplastics made from waste materials [112]. In China, the policy shift towards biodegradable plastics has supported companies like Green Dot Bioplastics in integrating bioplastics into the mainstream market [113].

## VI. CHALLENGES IN BIOPLASTICS PRODUCTION FROM WASTE BIOMASS

Producing bioplastics from waste biomass offers numerous environmental benefits but also presents several challenges. These challenges span feedstock variability, scalability, technological barriers, and consumer acceptance [114]. Addressing these challenges is crucial for advancing bioplastics technology and achieving broader adoption.

### *A. Feedstock Variability*

One of the major challenges in bioplastics production from waste biomass is the variability in feedstock composition and availability. Different sources of biomass, such as agricultural residues, food waste, or industrial by-products, have diverse compositions of cellulose, hemicellulose, and lignin, which affects the quality and yield of the resulting bioplastics.

For instance, corn stover, rice husk, and wheat straw each have different lignocellulosic structures, making it difficult to standardize bioplastics production processes [28]. This variability can result in inconsistent product performance, especially when scaling up to industrial levels. According to Synani et al., (2024), research from the University of Illinois has highlighted the need for pre-treatment standardization to manage the diverse composition of waste biomass [20].

Inconsistent feedstock quality can lead to inefficiencies in processing and variation in the material properties of the bioplastics. Furthermore, seasonal availability and logistical issues with sourcing waste biomass can make it difficult to ensure a continuous, reliable supply for large-scale production [28].

### *B. Scalability and Industrial Integration*

Scaling up bioplastics production from lab-scale experiments to industrial processes presents significant technical and logistical challenges. One of the primary hurdles is integrating bioplastics production into existing industrial systems that were designed for conventional petrochemical plastics [115]. The capital expenditure required to retrofit existing plants or build new bioplastics facilities can be prohibitively high, especially for small and medium-sized enterprises [116]. The integration of bioplastics into industries like packaging and automotive requires not only high production volumes but also compatibility with existing machinery. This necessitates modifications in production processes to accommodate the different properties of bioplastics, such as their biodegradability and lower heat resistance compared to traditional plastics [117].

### *C. Technological Barriers*

Several key technological barriers need to be addressed to make bioplastics from waste biomass more competitive with conventional plastics. Improving polymer properties such as mechanical strength, thermal stability, and durability remains a critical area of research [118]. Traditional bioplastic like PLA (polylactic acid) often struggle to match the strength and flexibility of petroleum-based plastics such as polypropylene and polyethylene [119].

Advancements in nanotechnology, such as the incorporation of nanocellulose or nanoclay into bioplastics, are being explored to improve these properties [71]. Additionally, improving production efficiency is essential to lower costs. Enzymatic hydrolysis and microbial fermentation processes, while effective, are still relatively expensive and energy-intensive compared to petrochemical methods. Innovations in catalyst design and bioprocessing could reduce the environmental footprint and cost of production.

### *D. Consumer Awareness and Acceptance*

Despite the growing interest in sustainable products, consumer awareness and acceptance of bioplastics remain a challenge. Many consumers are still unaware of the benefits of bioplastics derived from waste biomass or hold misconceptions about their performance and environmental impact [120]. The term "biodegradable" can be misleading, as some bioplastics only degrade under specific industrial composting conditions, leading to confusion about their environmental benefits.

Educational campaigns are essential for increasing consumer awareness. For instance, Green Dot Bioplastics has launched marketing initiatives aimed at educating consumers about the performance and sustainability of their products [121]. However, more efforts are needed to overcome consumer skepticism, particularly regarding the price premium associated with bioplastics. Many consumers still perceive bioplastics as inferior in terms of durability or too costly compared to conventional plastics, which can slow down their adoption in everyday products. A recent 2024 survey conducted by Fletcher et al., indicated that while consumers are increasingly aware of plastic pollution, only about 30% understood the benefits of bioplastics, showing a significant gap in awareness and acceptance [122].

## VII. FUTURE PROSPECTS FOR BIOPLASTICS FROM WASTE BIOMASS

The future of bioplastics from waste biomass is promising, driven by advancements in technology, evolving market dynamics, and the increasing emphasis on sustainability. Several key areas hold potential for shaping the future of this field, including emerging technologies, circular economy integration, and long-term sustainability.

### *A. Emerging Technologies*

The future of bioplastics production from waste biomass will be shaped by several emerging technologies and innovations. One promising area is synthetic biology, which offers the potential to engineer microbes and enzymes to more efficiently convert waste biomass into monomers for bioplastics [123]. For example, microbes can be genetically modified to produce bioplastic precursors, such as lactic acid or PHA, directly from agricultural residues, food waste, or industrial by-products. These engineered organisms can be tailored to tolerate different feedstocks and optimize production yields [123].

Advanced material design is another critical frontier. According to Uysal-Unalam et al., (2024), scientists are working on designing bioplastics with enhanced properties, such as greater mechanical strength, improved barrier properties, and enhanced biodegradability [124]. Innovations like nanotechnology using nanocellulose, [71], and other nano-sized additives can improve the performance of bioplastics, making them competitive with traditional petroleum-based plastics. This opens up opportunities for applications in sectors like packaging, automotive, and electronics, where durability and performance are crucial.

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Furthermore, AI-driven process optimization is becoming increasingly important. By leveraging machine learning and artificial intelligence, bioplastics producers can optimize the conversion processes of waste biomass, improving energy efficiency, reducing production costs, and minimizing environmental impacts [125]. AI can help predict the best conditions for enzymatic hydrolysis, fermentation, or polymerization, making the production process more efficient and scalable [125].

### *B. Circular Economy Integration*

Bioplastics from waste biomass are inherently aligned with the principles of the circular economy, which seeks to maximize resource efficiency, minimize waste, and reduce environmental impact. By using waste biomass such as agricultural residues, food waste, and industrial by-products as raw materials, bioplastic production contributes to a more sustainable value chain [105]. These materials, which would otherwise be discarded or incinerated, are repurposed to create valuable products, reducing reliance on fossil fuels and lowering greenhouse gas emissions.

In a circular economy, the end-of-life management of bioplastics is also critical. Many bioplastics are biodegradable or compostable, meaning they can break down in natural environments or industrial composting facilities, closing the loop on resource use [93]. This reduces the accumulation of plastic waste in landfills and oceans, addressing the pressing issue of plastic pollution. Additionally, advancements in recycling technologies, such as chemical recycling, offer the potential to recover and reuse bioplastic materials, further enhancing the circularity of the production process [24].

The integration of bioplastics into a circular economy also promotes industrial symbiosis, where different industries collaborate to exchange waste streams and resources. For example, agricultural industries can supply residues to bioplastics producers, while the by-products of bioplastics production can be repurposed in other sectors, such as energy or fertilizers, creating a closed-loop system [125].

### *C. Long-term Sustainability*

The long-term sustainability of bioplastics from waste biomass depends on several factors, including the availability of raw materials, environmental impacts, and alignment with global sustainability goals. Waste biomass offers a renewable and abundant feedstock, particularly in regions with significant agricultural, forestry, and food processing industries [20]. However, the scalability of bioplastics production will depend on maintaining a stable and consistent supply of high-quality biomass while ensuring that its use does not compete with food production or lead to deforestation [1].

In terms of environmental impact, bioplastics from waste biomass have the potential to significantly reduce carbon emissions and environmental degradation compared to conventional plastics. A life cycle assessment (LCA) of bioplastics shows that they generally have a lower carbon footprint and reduced reliance on non-renewable energy sources [75]. However, the overall sustainability of these materials will depend on factors such as energy use in production, land-use impacts, and the biodegradability or recyclability of the final products [75].

Bioplastics also align with global sustainability goals, such as the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) [126]. By promoting the use of renewable materials, reducing plastic waste, and lowering emissions, bioplastics contribute to global efforts to transition toward a more sustainable economy.

## VIII. CONCLUSIONS

Bioplastics derived from waste biomass present a significant opportunity to address the growing environmental concerns related to conventional plastics. By utilizing agricultural residues, food waste, industrial by-products, municipal solid waste, and forest biomass residues, these bioplastics offer a sustainable alternative that can reduce dependency on fossil fuels, lower greenhouse gas emissions, and manage waste more effectively. Advancements in bioconversion technologies, including microbial fermentation and enzymatic hydrolysis, have streamlined the production of bioplastics, making the process more efficient and environmentally friendly. In particular, innovations like steam explosion, ionic liquids, and deep eutectic solvents have revolutionized feedstock pretreatment, while combined bioconversion techniques have maximized yield and minimized waste. The development of new polymerization methods, such as ring-opening polymerization for PLA and microbial PHA production, is improving the quality and material properties of bioplastics, making them competitive with traditional plastics.

However, despite the progress, the production of bioplastics from waste biomass faces several challenges. Feedstock variability, scalability, technological barriers, and consumer awareness remain key obstacles that must be addressed to achieve widespread industrial integration and market acceptance. Moreover, ensuring cost competitiveness against petroleum-based plastics continues to be a challenge, although utilizing waste biomass as feedstock offers a promising path to reducing production costs. The environmental impact of bioplastics, when assessed through Life Cycle Assessment (LCA), shows a marked reduction in carbon footprint and energy consumption compared to conventional plastics. Their biodegradability and compostability offer potential advantages in waste management, though existing infrastructure needs to be adapted for optimal integration. The role of government policies and incentives will be critical in promoting the adoption and growth of bioplastics, especially with regard to developing supportive regulations and fostering industry partnerships.

Looking forward, the prospects for bioplastics from waste biomass are promising. Emerging technologies, such as synthetic biology and AI-driven optimization, will likely accelerate production efficiency and improve material properties. The integration of bioplastics into a circular economy, with a focus on resource efficiency and waste minimization, aligns well with global sustainability goals. In the long term, bioplastics from waste biomass have the potential to transform the plastics industry, offering an environmentally friendly and economically viable alternative that supports a more sustainable future.

By addressing current challenges and leveraging technological innovations, bioplastics from waste biomass can play a pivotal role in reducing the environmental impact of plastics, driving the industry towards a greener and more circular economy.

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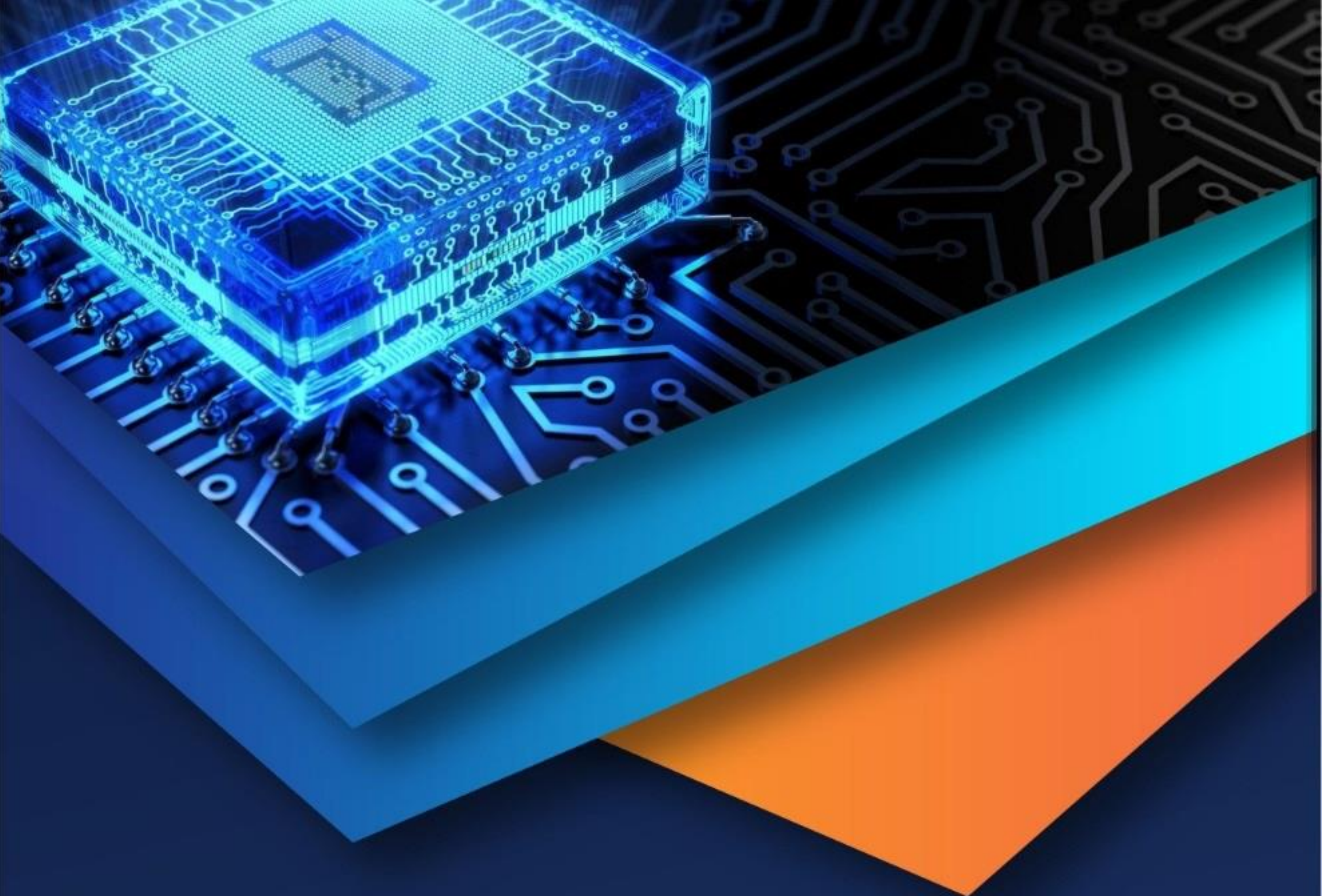

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