
Forest Residue and Side Streams Conversion for Biomass Utilization: A Survey

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Abstract

This survey paper explores the role of biomass utilization within a circular economy framework, emphasizing the transformation of organic waste into bio-based products to promote sustainable development. The paper highlights the importance of understanding biomass's physicochemical properties and optimizing pretreatment strategies to enhance conversion efficiency into biofuels. Despite the economic challenges posed by the competitiveness of fossil fuels, advancements in conversion technologies aim to improve efficiency and reduce costs, bolstering the viability of biomass-derived biofuels. The potential of single cell protein (SCP) to address global protein demands sustainably is underscored, illustrating the innovative solutions necessary for achieving sustainability goals. Additionally, the paper calls for the development of comprehensive guidelines for sustainable forest biomass harvesting to balance environmental conservation with industrial needs. The integration of biomass utilization offers numerous benefits, such as reduced fossil fuel dependency, increased resource efficiency, and significant contributions to environmental conservation and economic resilience. These findings highlight the critical need for advancing biomass conversion technologies and supportive policy frameworks to facilitate a transition towards a more sustainable and resilient economic model.

1 Introduction

1.1 Biomass Utilization in a Circular Economy

Biomass utilization is essential for advancing a circular economy, emphasizing sustainable resource management through waste reduction and material recycling. This is increasingly pertinent given the surge in agricultural and industrial activities driven by population growth, which generates substantial biomass waste. In many developing nations, inefficient management of agricultural residues leads to environmental challenges, including open burning and field decomposition. By converting biomass waste into low-carbon products, we can significantly reduce CO₂ emissions and develop sustainable construction materials, addressing both resource scarcity and environmental sustainability. Implementing comprehensive biomass harvesting guidelines enhances ecological sustainability and social acceptance within the bioeconomy, ensuring effective resource utilization while adhering to environmental and social standards [1, 2]. The conversion of biomass into bio-based products exemplifies this approach, transforming organic waste into valuable resources, thus lessening dependence on fossil fuels and minimizing environmental impacts. As urbanization and population growth escalate global energy demands, the sustainable conversion of biomass into biofuels and other bio-based products becomes a critical strategy for addressing these needs and mitigating greenhouse gas emissions.

Integrating biomass utilization within a circular economy not only supports energy sustainability but also facilitates the recovery of bioactive compounds from food waste and lignocellulosic residues, enhancing resource efficiency [3]. The development of alternative jet fuels (AJF) from biomass

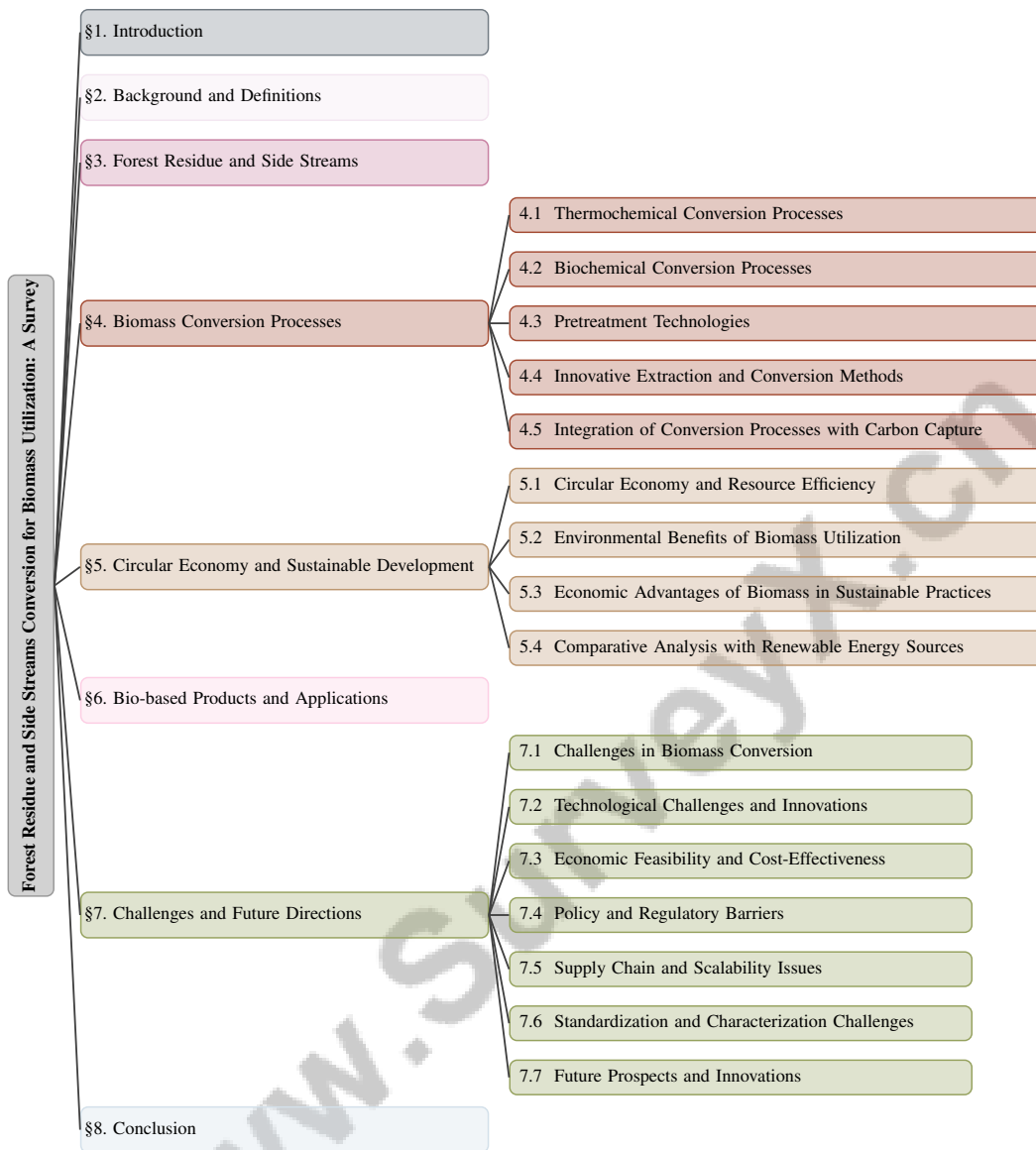


Figure 1: chapter structure

illustrates the potential of these innovations to significantly reduce CO₂ emissions in sectors like aviation, contributing to a more sustainable economic model [4].

The exploration of single cell protein (SCP) as a sustainable alternative to traditional protein sources demonstrates how biomass can effectively meet the rising global protein demand, aligning with circular economy principles by utilizing waste streams [5]. Valorizing biomass residues for low-carbon construction materials further exemplifies the environmental benefits of biomass utilization [1].

This survey underscores the necessity of addressing the recalcitrance of lignocellulosic biomass and enhancing conversion process efficiency. Overcoming technological barriers, such as developing effective pretreatment methods and innovative conversion technologies, can significantly improve biomass hydrolysis and transformation into sustainable biofuels, thereby contributing to renewable energy solutions and reducing greenhouse gas emissions [6, 7, 8]. Through these efforts, biomass utilization not only facilitates the transition to a circular economy but also plays a vital role in achieving sustainable development goals by promoting resource efficiency, minimizing environmental impacts, and fostering economic resilience.

1.2 Importance of Transforming Organic Waste

Transforming organic waste into bio-based products is critical for sustainability and enhancing resource efficiency. Converting organic residues into valuable products such as single cell protein (SCP) addresses the dual challenges of waste management and protein demand, providing a sustainable solution by utilizing waste substrates for protein production [5]. This strategy mitigates the environmental impacts of waste disposal while contributing to food security and resource conservation.

In renewable energy contexts, converting organic waste into biofuels is essential for reducing reliance on fossil fuels and the associated environmental issues. Biofuels derived from organic waste offer a sustainable energy alternative, crucial for addressing the environmental challenges posed by fossil fuel consumption [7]. Additionally, converting food waste and lignocellulosic residues into active pharmaceutical ingredients (APIs) and bioactive compounds exemplifies the potential of organic waste to enhance resource efficiency and sustainability by creating high-value products [3].

The aviation sector, accounting for roughly 2.6% of global CO₂ emissions, presents a significant opportunity for sustainability through the transformation of conventional aviation fuels into alternative jet fuels (AJF). This conversion not only reduces the carbon footprint of commercial aviation but also aligns with broader efforts to achieve resource efficiency within the industry [4].

Moreover, managing organic residues provides benefits beyond energy production, such as soil enhancement, particularly relevant in regions like Brazil facing increasing environmental challenges [9]. By converting organic waste into bio-based products, these practices contribute to a circular economy model that emphasizes waste minimization, resource recovery, and environmental sustainability.

1.3 Structure of the Survey

This survey is systematically organized to comprehensively explore biomass utilization within a circular economy framework, focusing on the transformation of organic waste into bio-based products. The introductory section establishes foundational concepts and underscores the vital role of biomass utilization in promoting sustainability and resource efficiency. Following this, the survey delves into background definitions, elucidating key concepts such as forest residue, side streams, and biomass conversion technologies.

The core of the survey is divided into thematic sections. The third section discusses forest residue and side streams, detailing their sources, types, and potential as raw materials, alongside the environmental implications of their harvesting. The subsequent section examines various biomass conversion processes, including thermochemical and biochemical methods, pretreatment technologies, and innovative extraction techniques, while exploring the integration of these processes with carbon capture technologies to enhance sustainability.

The fifth section situates biomass utilization within the circular economy framework, highlighting its environmental, economic, and resource efficiency benefits. This is followed by an analysis of bio-based products derived from biomass conversion, their industrial applications, and their environmental and economic impacts.

The survey concludes with a discussion of the challenges and future directions in biomass utilization, addressing technological, economic, policy, and supply chain issues, while proposing potential solutions and innovations. This structure promotes a comprehensive understanding of the subject by integrating diverse perspectives and addressing key factors such as ecological sustainability, social license, and regulatory compliance, thereby aligning with the survey's objectives of enhancing knowledge and promoting sustainable development practices in the context of forest biomass utilization and renewable energy systems [2, 9, 1, 7]. The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Lignocellulosic Biomass and Recalcitrance

Lignocellulosic biomass, predominantly composed of cellulose, hemicellulose, and lignin, presents a complex, rigid structure that impedes its degradation and conversion into fermentable sugars, a phenomenon known as recalcitrance [10, 6]. The lignin and hemicellulose matrix encasing cellulose fibers restricts enzymatic access, posing significant challenges in the production of biofuels and

bio-based products. Overcoming this recalcitrance is essential for the economic feasibility and sustainability of biomass conversion technologies. Advanced pretreatment strategies are being developed to enhance enzymatic hydrolysis by altering the physicochemical properties of lignocellulosic biomass [10].

The environmental sustainability of biomass conversion, especially for energy production, necessitates careful management of lignocellulosic resources [7]. An innovative solution involves producing single cell protein (SCP) from lignocellulosic biomass using microorganisms like algae, fungi, and bacteria, contributing to environmental sustainability and food security [5]. In the aviation industry, converting lignocellulosic biomass into alternative jet fuels (AJF) offers a promising avenue for reducing lifecycle emissions and enhancing sustainability [4]. Research continues to optimize emissions reductions from biomass-derived AJF, underscoring the importance of addressing recalcitrance in biomass conversion.

2.2 Biomass Conversion Technologies

Biomass conversion technologies are crucial for transforming organic residues into bio-based products, aligning with circular economy principles by enhancing resource efficiency and minimizing waste. These technologies encompass thermochemical processes—such as gasification, combustion, and pyrolysis—and biochemical processes, including anaerobic digestion and fermentation. Each method has distinct advantages and challenges, with thermochemical processes operating at higher temperatures and biochemical processes relying on biological activity. This diversity enables integration to boost efficiency and sustainability in biofuel production [11, 1, 6, 8].

Thermochemical methods like gasification, pyrolysis, and liquefaction decompose biomass thermally to produce syngas, bio-oil, and char. Gasification is particularly significant for generating renewable aviation fuels via Fischer-Tropsch synthesis, offering a sustainable alternative to traditional jet fuels [12]. Lifecycle assessments of AJF from biomass demonstrate substantial emissions reductions compared to petroleum-based fuels, highlighting the environmental benefits of thermochemical conversion [4].

Biochemical conversion, through processes such as anaerobic digestion, fermentation, and enzymatic hydrolysis, employs microbial and enzymatic actions to break down biomass into simpler compounds like biogas and ethanol. These processes are vital for biofuel and biochemical production, enabling the recycling of organic waste into renewable energy. The incorporation of metal nanoparticles synthesized using supercritical carbon dioxide (scCO₂) shows promise in enhancing conversion efficiency, further promoting biomass as a sustainable resource [13].

Pretreatment technologies play a critical role in improving biomass conversion by modifying the physicochemical properties of lignocellulosic materials, thereby reducing recalcitrance [6]. Techniques such as acid, alkaline, and biological pretreatments increase the accessibility of cellulose and hemicellulose for enzymatic hydrolysis, facilitating the production of fermentable sugars and subsequent biofuel conversion [6].

The successful implementation of biomass conversion technologies faces challenges, including inadequate valorization practices and technological barriers [1]. Addressing these challenges requires consistent definitions and standards across jurisdictions, along with scientifically sound and practically applicable guidelines [2]. Advancing biomass conversion technologies is crucial for integrating biomass into the circular economy, reducing fossil fuel reliance, and contributing to sustainable development goals.

In recent years, there has been increasing interest in the sustainable management of forest resources, particularly in the context of biomass utilization. This paper explores the various dimensions of forest residue and side stream utilization, emphasizing the need for a comprehensive understanding of their ecological implications. Figure 2 illustrates the hierarchical structure of forest residue and side stream utilization, highlighting sources and types of forest residues, potential applications of side streams, and the environmental impact of forest biomass harvesting. The figure categorizes the benefits and challenges associated with forest residues, applications and technological developments in side stream utilization, and ecological considerations and sustainable practices in biomass harvesting. By examining these factors, we can better appreciate the intricate relationship between forest management and environmental sustainability.

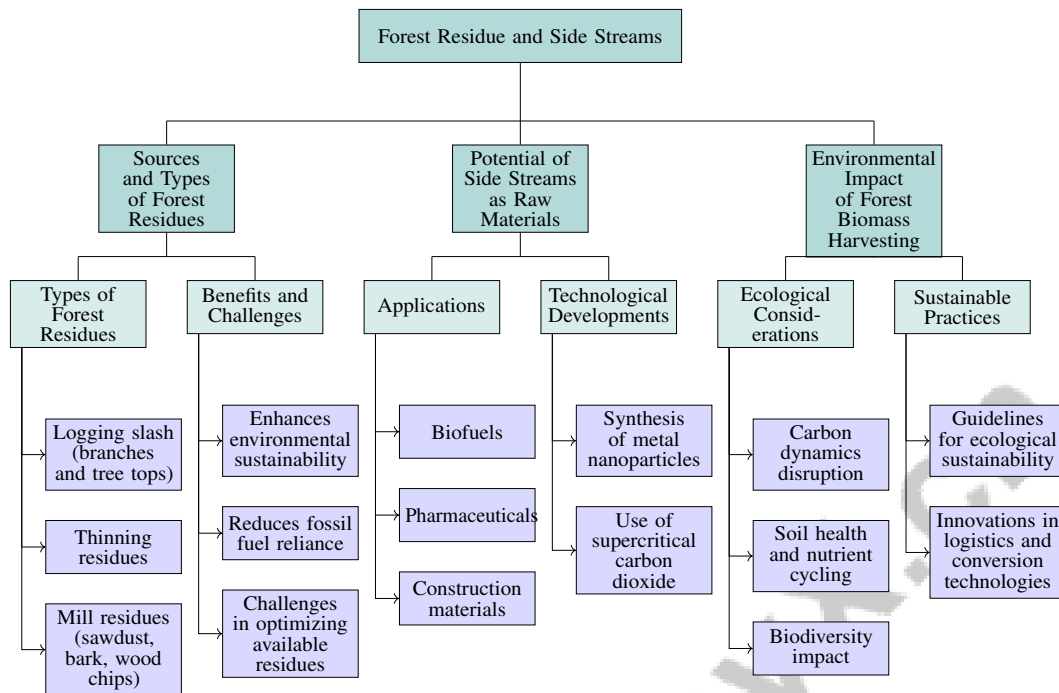


Figure 2: This figure illustrates the hierarchical structure of forest residue and side stream utilization, highlighting sources and types of forest residues, potential applications of side streams, and the environmental impact of forest biomass harvesting. The figure categorizes the benefits and challenges associated with forest residues, applications and technological developments in side stream utilization, and ecological considerations and sustainable practices in biomass harvesting.

3 Forest Residue and Side Streams

3.1 Sources and Types of Forest Residues

Forest residues, comprising materials left after logging and forest management, are crucial feedstocks for biomass conversion. These include logging slash, such as branches and tree tops, and thinning residues that reduce fire risks and enhance forest health [11]. Mill residues, including sawdust, bark, and wood chips from wood processing, also contribute significantly to biomass for biofuel and bio-based product conversion [12]. Utilizing forest residues enhances environmental sustainability and resource efficiency by reducing fossil fuel reliance and mitigating waste disposal impacts [11]. This integration aligns with sustainability guidelines promoting soil conservation, biodiversity protection, and carbon management [2].

The diversity of forest residues presents both opportunities and challenges. While residues like sugarcane bagasse have established conversion technologies, they are not the most abundant, necessitating further research to optimize available residues [9]. The potential use of side streams and waste substrates, such as those from single cell protein (SCP) production, underscores the value of forest residues in biomass conversion [5].

3.2 Potential of Side Streams as Raw Materials

Side streams, secondary products or waste materials from industrial processes, offer significant potential as raw materials for biomass conversion. These materials can be transformed into high-value bio-based products, including biofuels, pharmaceuticals, and construction materials, enhancing resource efficiency and sustainability within a circular economy framework [1, 7, 8]. Integrating side streams into biomass processes reduces waste and recovers valuable compounds for various industrial applications. Developments in utilizing side streams include synthesizing metal nanoparticles that catalyze biomass-derived chemical conversions. The use of supercritical carbon dioxide (scCO₂) in

synthesizing these nanoparticles enhances biomass conversion efficiency while minimizing hazardous solvent use [13].

The valorization of side streams is particularly relevant for SCP production, utilizing waste substrates from diverse industries to create alternative protein sources. This approach addresses the growing global protein demand and exemplifies circular economy principles by effectively utilizing waste streams [5]. Additionally, converting side streams into biofuels and biochemicals provides a sustainable alternative to fossil-based products, reducing greenhouse gas emissions and enhancing energy security [8].

3.3 Environmental Impact of Forest Biomass Harvesting

Harvesting forest biomass for bioenergy and bioproducts has significant environmental implications, necessitating thorough assessment of its effects on ecosystems, carbon emissions, and biodiversity. Established harvesting guidelines are crucial for ensuring ecological sustainability, addressing local contexts, and integrating scientific insights. These guidelines balance the demand for renewable energy with the preservation of soil health, site productivity, and biodiversity integrity, while considering social factors like visual aesthetics and cultural heritage. Effective biomass waste management can mitigate carbon emissions and contribute to low-carbon product development [2, 1, 7]. The use of forest residues and side streams supports a circular economy, providing renewable resources for bio-based products, yet the processes involved in biomass harvesting can yield both positive and negative environmental outcomes.

A critical concern with forest biomass harvesting is its potential to disrupt carbon dynamics, impacting carbon sequestration and greenhouse gas emissions. This issue is particularly pertinent in sustainable forest management (SFM) and bioenergy production, as improper practices may lead to soil degradation, biodiversity loss, and decreased site productivity. Comprehensive biomass harvesting guidelines are vital for mitigating these risks while ensuring ecological sustainability and addressing local environmental considerations [2, 9, 1, 7]. Although forest biomass removal can alter carbon sequestration processes, sustainable management can contribute to carbon neutrality by offsetting fossil fuel emissions through renewable energy production.

Soil health and nutrient cycling are also critical considerations in biomass extraction. Residue removal can lead to soil erosion, nutrient depletion, and diminished fertility, affecting forest regeneration and long-term productivity. Sustainable harvesting practices, such as retaining a portion of residues on-site, can help maintain soil structure and nutrient balance [2].

Biodiversity is profoundly influenced by forest biomass harvesting. Forest ecosystems host diverse species, and disturbances from biomass extraction can affect habitat availability and species composition. Implementing guidelines that prioritize biodiversity conservation—such as maintaining buffer zones and protecting critical habitats—is essential for minimizing the ecological footprint of biomass harvesting [2].

Transportation and processing of forest biomass contribute to greenhouse gas emissions and air pollution. Advancements in logistics and innovative conversion technologies are crucial for minimizing the environmental impact of energy production and waste management, especially in the context of urbanization and population growth, which increase the demand for sustainable solutions to mitigate emissions and promote resource conservation [1, 2, 7, 8]. Innovations in biomass conversion, including advanced pretreatment and processing methods, can enhance resource efficiency and reduce emissions.

The environmental impact of forest biomass harvesting is complex, necessitating a balanced approach that integrates ecological sustainability with economic and energy objectives. This involves adhering to established guidelines that promote sustainable forest management, addressing local contexts, and considering social concerns such as biodiversity, soil health, and cultural preservation. As global energy demands rise and the need to mitigate greenhouse gas emissions intensifies, developing and refining biomass harvesting practices that align with environmental goals and the growing bioeconomy is crucial, ensuring resource exploitation does not outpace natural regeneration [2, 9, 1, 7]. By adopting sustainable management practices and leveraging technological advancements, forest biomass conversion can align with environmental conservation objectives and support the transition toward a more sustainable and circular economy.

4 Biomass Conversion Processes

Biomass conversion processes involve diverse methodologies for transforming biomass into valuable energy sources and products. Table 1 presents a comparative overview of various biomass conversion processes, elucidating their conversion methods, environmental impacts, and efficiencies, which are critical for understanding their contributions to sustainable energy solutions. This section explores fundamental approaches, starting with thermochemical conversion processes, which utilize thermal energy to decompose biomass into energy-generating and material-producing products. The following subsection delves into thermochemical conversion processes, highlighting key technologies like pyrolysis and gasification, essential for improving biomass utilization efficiency and sustainability.

4.1 Thermochemical Conversion Processes

Thermochemical conversion processes, particularly pyrolysis and gasification, are pivotal for converting biomass into energy and bio-based products, fostering resource efficiency and waste reduction within a circular economy framework. Pyrolysis involves the thermal decomposition of biomass in an oxygen-free environment, producing bio-oil, syngas, and char, and is notable for its flexibility in processing diverse biomass feedstocks [11]. Gasification, which partially oxidizes biomass at high temperatures to produce syngas, includes technologies such as fixed bed, fluidized bed, and plasma gasification, each with unique operational characteristics influenced by feedstock type and economic factors [12].

Recent advancements focus on enhancing the efficiency and sustainability of thermochemical conversion. Environmentally friendly synthesis methods using supercritical carbon dioxide (scCO₂) have improved catalyst dispersion and catalytic efficiency, boosting biomass conversion performance [13]. Furthermore, innovative extraction methods, like microwave-assisted and enzyme-assisted extraction, have shown higher efficiency and lower environmental impact than traditional techniques.

Integrating thermochemical and biochemical processes is emphasized to optimize resource utilization and maximize bio-based product yields [11]. Moreover, innovative microbial protein production methods can synergize with thermochemical processes, providing new pathways for generating high-value products from biomass [5]. Despite these advancements, challenges such as high energy demands and feedstock management complexity hinder the efficiency and economic viability of biomass conversion, necessitating ongoing research to overcome these barriers and meet sustainability targets [12, 8, 1, 7, 11].

4.2 Biochemical Conversion Processes

Biochemical conversion processes, including fermentation and anaerobic digestion, are essential for transforming biomass into biofuels and value-added products through microbial metabolism. Fermentation, widely used for bioethanol production, converts sugars into ethanol and biochemicals, reducing greenhouse gas emissions and fossil fuel reliance [11]. Anaerobic digestion decomposes organic matter without oxygen, producing biogas and digestate, a nutrient-rich residue suitable for fertilization, effectively managing organic waste while generating renewable energy [11].

Challenges in biochemical conversion include the recalcitrance of lignocellulosic biomass, requiring pretreatment technologies to enhance enzymatic hydrolysis [11]. Scalability is also hindered by high capital costs and specialized infrastructure needs. While biochemical methods offer environmental benefits, they generally exhibit lower efficiency and versatility compared to thermochemical methods like gasification and pyrolysis [11]. Research aims to enhance the efficiency and economic viability of biochemical technologies through microbial engineering innovations, process optimization, and integration with other conversion processes [12].

4.3 Pretreatment Technologies

Pretreatment technologies are vital for enhancing biomass conversion efficiency by altering the structural and chemical properties of lignocellulosic biomass, improving digestibility and enzymatic hydrolysis accessibility. These technologies include acid, alkaline, steam explosion, and biological treatments, each with specific mechanisms and impacts on biomass structure [6].

Acid pretreatment uses dilute acids to hydrolyze hemicellulose, disrupting the lignin-carbohydrate complex and enhancing cellulose accessibility, though careful management is needed to minimize inhibitory compound formation. Alkaline pretreatment employs alkaline solutions to saponify lignin and hemicellulose, increasing biomass porosity for better enzyme penetration [6]. Steam explosion subjects biomass to high-pressure steam followed by rapid decompression, enhancing surface area and reducing cellulose crystallinity. Biological pretreatment involves lignin-degrading microorganisms, like fungi, improving cellulose and hemicellulose digestibility, albeit with longer processing times [6].

Advancements in understanding lignocellulosic biomass properties have led to more efficient pretreatment technologies, optimizing conditions to reduce energy consumption and enhance economic viability [10]. By improving conversion efficiency, pretreatment technologies significantly contribute to sustainable biofuel and bio-based product production, supporting circular economy and sustainable development goals.

4.4 Innovative Extraction and Conversion Methods

Innovative extraction and conversion methods are crucial for enhancing biomass utilization efficiency and sustainability, aligning with circular economy principles by maximizing resource recovery and minimizing waste. Recent advancements in extraction technologies emphasize environmentally friendly processes that reduce hazardous solvent use and energy consumption. Supercritical carbon dioxide (scCO₂) extraction has emerged as a promising technique, offering a green alternative for extracting bioactive compounds and essential oils from biomass with high efficiency and minimal environmental impact [13].

Innovative conversion methods have been developed to enhance biomass valorization into high-value products. Microwave-assisted and enzyme-assisted extraction techniques increase yield and purity while reducing processing time and energy requirements, suitable for large-scale applications. Advanced catalytic processes in biomass conversion, such as metal nanoparticles synthesized via scCO₂, have shown enhanced catalytic activity and selectivity, optimizing conversion processes and supporting sustainable, economically viable technologies [13].

Exploring microbial protein production as a novel conversion pathway exemplifies innovative methods for transforming biomass into valuable products. Utilizing waste substrates and side streams, microbial protein production offers a sustainable alternative to traditional protein sources, addressing environmental and food security challenges [5]. The adoption of innovative extraction and conversion methods is essential for advancing sustainable biomass utilization, achieving significant improvements in resource efficiency, mitigating greenhouse gas emissions, and fostering a transition toward a circular economy that prioritizes environmental sustainability and economic resilience [1, 3, 7, 8].

4.5 Integration of Conversion Processes with Carbon Capture

Integrating biomass conversion processes with carbon capture technologies enhances biomass utilization sustainability by improving energy efficiency and reducing greenhouse gas emissions while transforming waste into valuable resources. This strategy supports global climate change mitigation efforts by capturing and storing CO₂ produced during biomass conversion [11, 1, 7, 8].

A promising approach is bioenergy with carbon capture and storage (BECCS) systems, which capture CO₂ emissions during thermochemical conversion processes like gasification and pyrolysis, storing it in geological formations or utilizing it in industrial applications. By integrating advanced technologies, including life cycle assessments, BECCS systems aim to improve efficiency and minimize environmental impacts, supporting circular economy and sustainable energy practices. BECCS could achieve negative emissions by permanently sequestering CO₂ captured from biomass conversion, offsetting emissions from other sectors [12, 8, 1, 7, 11].

Innovative carbon capture technologies, such as advanced materials and solvents for CO₂ absorption, enhance the feasibility of integrating carbon capture with biomass conversion. Metal-organic frameworks (MOFs) and amine-based solvents improve selectivity and capacity in CO₂ capture processes, reducing energy consumption and operational costs [13]. These advancements contribute to the economic viability of carbon capture technologies, facilitating their adoption in biomass conversion systems.

Integrating carbon capture with biochemical conversion processes, like anaerobic digestion and fermentation, offers additional emission reduction pathways. Capturing CO₂ during these processes enhances biofuel production sustainability and contributes to developing carbon-neutral energy systems [11]. The captured CO₂ can also be utilized in producing value-added products, such as chemicals and materials, further aligning with circular economy principles.

Feature	Thermochemical Conversion Processes	Biochemical Conversion Processes	Pretreatment Technologies
Conversion Method	Pyrolysis, Gasification	Fermentation, Anaerobic Digestion	Acid, Alkaline, Steam
Environmental Impact	Resource Efficiency Focus	Lower Emissions	Enhances Digestibility
Efficiency	High With SccO ₂	Lower Than Thermochemical	Improves Conversion

Table 1: This table provides a comparative analysis of biomass conversion processes, including thermochemical, biochemical, and pretreatment technologies. It highlights the conversion methods, environmental impact, and efficiency associated with each process, offering insights into their respective roles in enhancing biomass utilization and sustainability.

5 Circular Economy and Sustainable Development

5.1 Circular Economy and Resource Efficiency

Circular economy principles emphasize sustainable resource management by minimizing waste, recycling materials, and extending product lifecycles. Biomass utilization is pivotal in this framework, transforming organic waste into renewable energy and bio-based products, thus reducing reliance on finite resources and mitigating environmental impacts. The production of single-cell protein (SCP) from biomass is a resource-efficient alternative to conventional animal farming [5].

Biomass serves as both a renewable energy source and a soil amendment, promoting sustainability across various sectors. Biomass-derived biofuels offer a renewable alternative to fossil fuels, enhancing energy security and reducing greenhouse gas emissions. Concurrently, using biomass to enhance soil fertility supports agricultural productivity and environmental sustainability [9]. This versatility underscores biomass's role in advancing resource efficiency and aligns with circular economy objectives.

Integrating biomass into circular economy frameworks facilitates closed-loop systems that optimize resource utilization and minimize waste. Valorizing biomass residues and side streams is crucial for energy sustainability, enabling the extraction of valuable bioactive compounds for diverse industrial applications, including pharmaceuticals and nutraceuticals. This process not only reduces waste but also promotes eco-friendly extraction methods and innovative green synthesis routes, contributing to a circular economy where biomass waste is converted into high-value products before being utilized as lower-value energy sources [1]. Such practices highlight biomass's potential to enhance resource efficiency and support a transition to a sustainable, resilient economic model.

5.2 Environmental Benefits of Biomass Utilization

Biomass utilization provides substantial environmental benefits, notably reducing carbon footprints and minimizing waste. Biomass-derived alternative jet fuels (AJF) could lower lifecycle greenhouse gas emissions by up to 68.1

In construction, replacing traditional materials with biomass waste reduces carbon emissions, emphasizing the need for innovative approaches to maximize environmental benefits and ensure efficient resource use [1]. Converting organic residues into biofuels, biochemicals, and bioproducts minimizes waste and diverts materials from landfills, reducing environmental pollution. This conversion generates renewable energy and raw materials for various industries, fostering economic growth and mitigating greenhouse gas emissions [7, 8].

The environmental advantages of biomass utilization extend beyond carbon reduction, encompassing waste minimization, resource conservation, and promoting sustainable forestry and agricultural practices, thus supporting a resilient bioeconomy. Transforming biomass waste into low-carbon products can mitigate CO₂ emissions and lessen the environmental burdens associated with traditional waste disposal. Implementing comprehensive biomass harvesting guidelines safeguards ecological sustainability by addressing soil health, biodiversity, and water quality, while ensuring regulatory

compliance and enhancing public acceptance of biomass initiatives [2, 8, 1, 7, 11]. By harnessing biomass's potential to replace fossil-based products and curtail waste, a more sustainable economic model can be achieved.

5.3 Economic Advantages of Biomass in Sustainable Practices

Incorporating biomass into sustainable practices addresses environmental concerns and offers significant economic benefits. These include cost savings from reduced waste disposal and energy expenses, job creation in the biomass sector, and emerging markets for biofuels and low-carbon construction materials. Utilizing biomass waste, particularly from agricultural and industrial sources, enhances resource efficiency while contributing to climate change mitigation and promoting a circular economy [11, 1, 2, 7]. Converting organic waste into bio-based products reduces waste disposal costs and generates revenue streams through value-added products, enhancing the economic viability of biomass conversion technologies.

A key economic advantage of biomass utilization is cost savings in energy production. Biomass-derived biofuels, such as ethanol and biodiesel, offer renewable alternatives to fossil fuels, addressing greenhouse gas emissions and air quality issues. Advanced conversion technologies—thermochemical and biochemical processes—can stabilize energy costs and mitigate fossil fuel market volatility. Ongoing research aims to improve the efficiency and cost-effectiveness of biofuel production, positioning it competitively within the global energy landscape as demand for sustainable energy sources rises [11, 12, 7, 8]. Utilizing biomass for energy also reduces reliance on imported fuels, enhancing energy security and economic resilience.

The biomass industry is a significant job creator, especially in rural and underdeveloped regions where biomass resources are abundant. Developing biomass conversion facilities and associated supply chains fosters employment in agriculture, manufacturing, and logistics, stimulating regional economic growth. For instance, producing single-cell protein (SCP) from biomass addresses food security challenges while generating jobs in the biotechnology sector [5].

The economic benefits of biomass utilization extend to the establishment of new markets for bio-based products. As demand for sustainable and eco-friendly products rises, innovation and investment in the biomass sector are driven forward. The production of alternative jet fuels (AJF) from biomass represents a burgeoning market opportunity with the potential for significant greenhouse gas emissions reductions and enhanced aviation industry sustainability [4].

Integrating biomass into sustainable practices yields substantial economic advantages, including notable cost savings from reduced waste disposal and energy production expenses, job creation in biomass management and bioenergy sectors, and the development of emerging markets for biofuels and low-carbon products. These factors collectively contribute to a more resilient and sustainable economy [2, 8, 1, 7, 11]. By capitalizing on these advantages, biomass utilization can significantly advance a sustainable and resilient economic model that aligns with circular economy and sustainable development goals.

5.4 Comparative Analysis with Renewable Energy Sources

Biomass utilization, as a renewable energy source, presents distinct advantages and challenges compared to solar, wind, and hydropower. Biomass's primary benefit lies in its versatility, converting organic waste into biofuels, biochemicals, and bioenergy, thereby promoting resource efficiency and waste minimization. Unlike solar and wind energy, which are intermittent and weather-dependent, biomass provides a stable and reliable energy supply, as it can be stored and utilized on demand [12].

Biomass utilization significantly reduces greenhouse gas emissions. For instance, producing alternative jet fuels (AJF) from biomass can achieve substantial emissions reductions compared to conventional fossil fuels, aiding the aviation industry's decarbonization [4]. Additionally, utilizing biomass in low-carbon construction materials and soil amendments further enhances environmental sustainability across various sectors.

However, biomass conversion processes face challenges related to efficiency and scalability. The recalcitrance of lignocellulosic biomass hinders efficient conversion, necessitating advanced pretreatment technologies to enhance enzymatic hydrolysis and fermentation processes [6]. Furthermore,

the economic feasibility of biomass utilization is influenced by feedstock availability, conversion technology costs, and market demand for bio-based products [8].

Compared to other renewable energy sources, biomass uniquely produces both energy and valuable co-products, such as single-cell protein (SCP) and biochemicals, contributing to food security and resource conservation [5]. This multifunctionality positions biomass as an integral component of a sustainable energy portfolio, complementing other renewable sources and facilitating the transition to a low-carbon economy.

6 Bio-based Products and Applications

6.1 Types of Bio-based Products

Biomass conversion into bio-based products encompasses diverse materials with industrial and commercial applications, including biofuels, biochemicals, and bioproducts. These products are central to fostering a circular economy by enhancing sustainability and resource efficiency. Derived from biomass waste and residues, such as food waste and lignocellulosic materials, they are transformed into valuable bioactive compounds, pharmaceuticals, and energy sources. Advanced extraction and conversion technologies are being developed to maximize material recovery, reduce environmental impacts, and promote sustainable resource management. Prioritizing high-value applications for biomass waste before converting it into lower-value products effectively mitigates waste and supports a sustainable economy [2, 8, 1, 11].

Biofuels, including bioethanol, biodiesel, and biogas, are prominent bio-based products offering renewable alternatives to fossil fuels, contributing to greenhouse gas emissions reduction and enhancing energy security. Producing alternative jet fuels (AJF) from biomass represents a significant advancement in aviation, achieving substantial emissions reductions compared to conventional jet fuels [4].

Biochemicals, such as organic acids, alcohols, and biopolymers, provide sustainable alternatives to petrochemical-derived products. For instance, lignocellulosic biomass is enzymatically broken down into fermentable sugars, which are further converted into high-value chemicals through fermentation and other biochemical processes [6].

Valorization of biomass into bioproducts, like single cell protein (SCP), addresses food security by providing alternative protein sources. SCP production uses microorganisms such as algae, fungi, and bacteria to convert waste substrates into protein-rich products, contributing to environmental sustainability and nutritional needs [5].

Additionally, developing low-carbon construction materials from biomass residues highlights the versatility of bio-based products. Utilizing agricultural and forest residues offers a sustainable alternative to traditional materials, reducing carbon emissions and promoting resource efficiency in construction [1].

The diverse range of bio-based products derived from biomass underscores biomass's potential to contribute to a sustainable and circular economy. Employing advanced conversion technologies, such as thermochemical and biochemical processes, alongside innovative applications, enhances the economic value of biomass resources. This approach facilitates biofuels and bioelectricity production while mitigating greenhouse gas emissions and supporting a sustainable economic model prioritizing environmental health and resource efficiency [8, 1, 7, 11, 6].

6.2 Industrial Applications

Bio-based products from biomass conversion are increasingly applied across various industrial sectors, offering sustainable alternatives to fossil-based products and contributing to a circular economy. The energy sector leads in adopting biofuels like bioethanol, biodiesel, and biogas, serving as renewable energy sources derived from agricultural residues and waste. Advanced conversion technologies, including thermochemical processes (gasification, pyrolysis) and biochemical methods (anaerobic digestion, fermentation), produce these biofuels. Despite challenges in cost competitiveness with fossil fuels, extensive research aims to enhance these technologies, making biofuels viable alternatives that reduce greenhouse gas emissions and promote sustainable energy solutions [8, 1, 7, 11]. These biofuels significantly reduce reliance on fossil fuels, enhancing energy security.

In the chemical industry, biochemicals such as organic acids, alcohols, and biopolymers are gaining traction as sustainable substitutes for petrochemical-derived products. Producing these biochemicals from lignocellulosic biomass involves enzymatic conversion of cellulose and hemicellulose into fermentable sugars, subsequently transformed into high-value chemicals through fermentation processes [6]. This shift reduces the environmental footprint of chemical manufacturing while aligning with resource efficiency and waste minimization principles.

The food industry explores bio-based products, particularly through producing single cell protein (SCP) as an alternative protein source. SCP production utilizes microorganisms like algae, fungi, and bacteria to convert waste substrates into protein-rich products, addressing global food security challenges and promoting environmental sustainability [5]. This innovative approach meets the growing demand for protein without the environmental impact associated with traditional animal farming.

The construction industry benefits from developing low-carbon construction materials derived from biomass residues. By utilizing agricultural and forest residues, these materials provide a sustainable alternative to conventional materials, reducing carbon emissions and promoting resource efficiency [1]. This application supports the transition to a low-carbon economy and enhances the sustainability of the construction sector.

Integrating bio-based products into various industrial applications highlights their potential to replace fossil-based products and contribute to a more sustainable economic model. By leveraging biomass's adaptability and renewability, industries can significantly improve their environmental performance by transforming agricultural and industrial waste into low-carbon products. This approach mitigates adverse waste disposal effects, such as open burning and inefficient management practices, while aligning with circular economy principles. Utilizing biomass residues as feedstock for producing sustainable energy and construction materials reduces carbon emissions, enhances resource efficiency, and contributes to developing a more sustainable bioeconomy [11, 1, 2, 8].

6.3 Environmental and Economic Impact

The environmental and economic impacts of bio-based products are significant compared to conventional fossil-based products, offering pathways toward sustainability and economic resilience. Environmentally, utilizing biomass for producing bio-based products contributes to reducing greenhouse gas emissions, a critical factor in mitigating climate change. For instance, producing alternative jet fuels (AJF) from biomass can result in substantial emissions reductions, highlighting the environmental benefits of transitioning from conventional aviation fuels [4]. This shift addresses the aviation industry's carbon footprint and aligns with global efforts to achieve carbon neutrality.

In addition to emissions reduction, bio-based products contribute to waste minimization and resource conservation. Converting organic waste into biofuels, biochemicals, and bioproducts diverts significant amounts of waste from landfills, mitigating environmental challenges associated with waste disposal. Advanced conversion technologies, including gasification, pyrolysis, and anaerobic digestion, offer sustainable alternatives to fossil fuels while reducing greenhouse gas emissions and promoting a circular economy by transforming waste into valuable energy and materials [8, 1, 11, 9]. This process exemplifies circular economy principles, where waste is transformed into valuable resources, promoting sustainability and resource efficiency.

Economically, integrating bio-based products into various industries presents opportunities for cost savings and revenue generation. By decreasing dependence on fossil fuels, biofuels enhance energy security and stabilize energy costs, fostering economic resilience against fossil fuel market volatility. This shift addresses rising global energy demands driven by urbanization and population growth while contributing to mitigating greenhouse gas emissions, supporting environmental sustainability, and combating climate change. As biofuel development advances through innovative conversion technologies and sustainable sourcing, it offers a promising alternative to traditional energy systems, aligning economic growth with ecological preservation [4, 2, 7, 8]. Furthermore, producing bio-based products creates new markets and drives innovation, particularly in biotechnology and green chemistry.

The economic advantages of bio-based products extend to job creation, especially in rural and underdeveloped regions with abundant biomass resources. Establishing biomass conversion facilities and associated supply chains generates employment opportunities in agriculture, manufacturing, and

logistics, contributing to regional economic development [5]. This socio-economic impact is further enhanced by bio-based products addressing food security challenges, as seen in SCP production, which provides an alternative protein source while promoting environmental sustainability [5].

7 Challenges and Future Directions

7.1 Challenges in Biomass Conversion

Biomass conversion to bio-based products faces technological, economic, and policy challenges. Technologically, the recalcitrance of lignocellulosic biomass requires advanced pretreatment and conversion methods to improve enzymatic hydrolysis [11]. Integrating thermochemical and biochemical routes demands sophisticated evaluation tools like life cycle assessment (LCA) to ensure environmental and economic feasibility [11]. Economically, high production costs relative to fossil fuels challenge biomass conversion's cost-effectiveness. Variability in biomass feedstock composition complicates economic viability, necessitating scalable solutions for competitiveness with conventional energy sources [11]. Significant capital investment is required for gasification technologies essential for efficient conversion, which currently exhibit low carbon efficiency [11]. Policy-wise, the dominance of fossil fuels underscores the need for supportive frameworks that incentivize biomass conversion technologies. These frameworks should address regulatory barriers, especially for integrating novel bio-based products like single cell protein (SCP) into mainstream markets, where public perception and dietary acceptance pose challenges [11].

The production of alternative jet fuels (AJF) from biomass also faces challenges, with current benchmarks inadequately addressing industrial-scale implications and resource requirements. The synthesis of metal nanoparticles, crucial for catalytic processes, is hindered by difficulties in achieving uniform size and distribution, as well as controlling catalytic properties [11]. Future research should focus on economically viable technologies for biomass waste valorization, innovative bio-based materials, and comprehensive life cycle assessments to evaluate environmental impacts. Addressing waste management practices and socio-economic impacts of agricultural activities contributing to biomass generation can enhance conversion sustainability and economic viability, supporting a circular economy and sustainable development [2, 8, 1, 11, 9].

7.2 Technological Challenges and Innovations

Technological challenges in biomass conversion include the recalcitrance of lignocellulosic biomass, requiring advanced pretreatment to improve enzymatic hydrolysis and fermentable sugar accessibility [10]. Innovations in pretreatment, such as steam explosion and acid/alkaline methods, promise to reduce recalcitrance by altering structural and chemical properties, enhancing biofuels and biochemicals yield [10]. Integration of thermochemical and biochemical processes necessitates sophisticated evaluation tools for environmental and economic sustainability. Life cycle assessment (LCA) models are increasingly used for environmental impact evaluation, though standardization limitations can cause inconsistencies [10]. Recent innovations in catalytic processes, particularly using metal nanoparticles synthesized through eco-friendly methods like supercritical carbon dioxide (scCO₂) extraction, enhance catalytic activity and selectivity, aligning with sustainability goals by minimizing hazardous solvent use [10].

Exploration of microbial consortia and advanced genetic engineering techniques holds promise for addressing biomass conversion challenges, particularly in enhancing biofuel production efficiency and sustainability from diverse residues and waste. Leveraging biotechnological advances can improve microorganisms' metabolic capabilities in biochemical conversion, increasing yield and efficiency of bio-based products [11, 1, 7, 8].

7.3 Economic Feasibility and Cost-Effectiveness

Economic feasibility and cost-effectiveness are critical for biomass conversion technology viability in transitioning to a sustainable economy. Biomass conversion offers economic opportunities, such as sustainable energy production and reduced greenhouse gas emissions, but challenges remain in lowering production costs and ensuring sustainable practices [11, 8]. A primary economic advantage is potential cost savings, as biomass-derived biofuels like ethanol and biodiesel provide renewable alternatives to fossil fuels, reducing market volatility and stabilizing energy costs.

Factors influencing economic feasibility include feedstock availability, conversion technology costs, and market demand for bio-based products. Variability in biomass feedstock composition affects conversion efficiency and scalability, necessitating scalable solutions for competitiveness [11]. Substantial capital investment is needed for gasification technologies critical for efficient conversion, currently limited by low carbon efficiency [11]. Advanced technologies like metal nanoparticles synthesized via supercritical carbon dioxide (scCO₂) show promise in enhancing conversion efficiency and cost-effectiveness [13]. Exploring microbial consortia and genetic engineering techniques offers additional pathways to increase yield and efficiency of bio-based products, improving economic viability.

Policy frameworks and regulatory support are crucial for enhancing economic viability, establishing guidelines for ecological sustainability, promoting social acceptance, and aligning with regulations. Incentives and subsidies for renewable energy production, alongside carbon pricing mechanisms, can drive investment in biomass conversion and promote bio-based product adoption [2, 8, 1, 7, 11]. Addressing economic challenges and leveraging technological advancements can enhance biomass conversion's cost-effectiveness, supporting a sustainable economic model.

7.4 Policy and Regulatory Barriers

Policy and regulatory frameworks significantly influence biomass utilization technology adoption and expansion, presenting opportunities and challenges. A primary challenge is misalignment between existing policies and the evolving needs of biomass technologies. Insufficient government policies and outdated regulations hinder effective biomass management and utilization, limiting the sector's sustainable development potential [9]. This misalignment is exacerbated by a lack of public awareness and understanding of sustainable biomass management practices, impeding technology adoption.

In renewable energy contexts, unanswered questions regarding energy policy impacts on renewable source adoption highlight significant barriers [7]. These barriers are evident in the aviation sector, where alternative jet fuel (AJF) adoption is constrained by regulatory frameworks inadequately addressing industrial-scale implications and resource requirements [4]. Regulatory challenges also affect microbial protein adoption, aligning with broader sectoral challenges [5]. Integration into mainstream markets is hindered by regulatory barriers related to public perception and dietary acceptance, necessitating reforms for market entry and consumer acceptance.

Current studies on biomass conversion technologies often lack a holistic approach, focusing on specific processes rather than the entire biofuel production chain. This limitation restricts understanding of cumulative impacts and hinders comprehensive policy framework development supporting the entire conversion ecosystem [11]. Scalability and reproducibility of advanced technologies like metal nanoparticles synthesis face regulatory challenges due to a lack of comprehensive understanding and standardized guidelines [13]. Future research should prioritize cost-effective pretreatment technologies and explore biomass genetic modifications for improved properties, informing policy decisions and regulatory frameworks [6]. Addressing policy and regulatory barriers can enhance biomass utilization technology adoption, supporting a sustainable and circular economy.

7.5 Supply Chain and Scalability Issues

The biomass conversion industry faces supply chain management and scalability challenges, particularly in collecting, transporting, and processing raw materials like food waste and lignocellulosic residues. The lack of established supply chains poses a barrier to efficient and cost-effective scaling of conversion technologies [3]. Biomass feedstock availability and composition variability complicate supply chain logistics, impacting conversion process consistency and reliability.

Establishing robust supply chains is crucial for scalability, ensuring steady raw material supply for large-scale operations. This involves creating efficient logistics and transportation networks to minimize costs and environmental impacts. Adhering to ecological sustainability guidelines in biomass harvesting and addressing local and regional regulatory contexts is essential. Optimizing these networks can enhance biomass waste utilization, supporting greenhouse gas reduction and resource management goals amid rising global energy demands [2, 8, 1, 4, 7]. Integrating advanced technologies for preprocessing and storage can enhance scalability by ensuring feedstock quality and consistency.

Scalability is also influenced by economic and regulatory landscapes, which can facilitate or hinder large-scale operation development. Supportive policies and incentives can encourage investment in supply chain infrastructure and promote innovative technology adoption enhancing scalability. Engaging public perceptions and enhancing market acceptance of bio-based products is essential for expanding market demand and fostering industry growth. Addressing environmental benefits of biomass waste utilization, promoting sustainable practices, and showcasing bio-based products' potential in reducing emissions and supporting a circular economy can create a favorable adoption environment, driving demand and supporting growth [3, 8, 1, 5, 9].

7.6 Standardization and Characterization Challenges

Commercialization and market acceptance of bio-based products from biomass conversion rely on robust standardization and characterization protocols. These protocols ensure product quality, safety, and performance, fostering consumer trust and facilitating regulatory approval. The diversity of bio-based products necessitates comprehensive standards addressing specific attributes and applications of each product category [8].

Standardizing bio-based products is challenged by biomass feedstock and conversion process variability, leading to product quality and performance inconsistencies. Advanced characterization techniques are needed to accurately assess physicochemical properties, ensuring compliance with industry standards and regulatory requirements [8]. Developing cost-effective technologies to enhance conversion process efficiency is critical for achieving consistent product quality and facilitating standardization efforts.

Lack of standardized guidelines for synthesizing and characterizing emerging bio-based products involving novel microbial or catalytic processes poses market entry and acceptance barriers. Addressing sustainable biomass waste utilization gaps requires collaborative partnerships among industry stakeholders, regulatory bodies, and research institutions. These collaborations should focus on developing comprehensive standards covering the entire bio-based product lifecycle, including sustainable raw material sourcing, innovative processing techniques, and final product applications. This approach will enhance biomass waste valorization into low-carbon products, contribute to significant carbon emission reductions, and promote environmentally friendly practices throughout the supply chain [1, 3].

7.7 Future Prospects and Innovations

The future of biomass utilization depends on advancing research and technologies that enhance conversion efficiency and sustainability. A critical focus area is optimizing extraction and conversion processes, involving novel synthesis techniques and enhancing catalytic mechanism understanding, particularly with metal nanoparticles, which show significant potential in improving conversion efficiency [13]. Developing standardized methods for characterizing lignocellulosic biomass properties is essential. Understanding interactions between these properties is crucial for advancing conversion technologies and designing more efficient processes [10]. Exploring innovative biomass management techniques and developing supportive policies for sustainable practices are also essential for fostering growth [9].

Improving reactor designs and catalyst stability is key for future research, particularly in integrating renewable energy sources into fuel production. These advancements will improve conversion efficiency and contribute to broader renewable energy integration within the circular economy framework [12]. Optimizing conversion methods integration and improving life cycle assessment (LCA) methodologies will be critical for advancing biofuel production technologies and ensuring environmental and economic viability [11]. Developing robust supply chains for biomass-derived feedstocks ensures consistent raw material availability for large-scale operations [3]. Addressing these research priorities and exploring emerging trends in biomass energy can enhance sustainability and scalability, supporting a more sustainable and resilient economic model.

8 Conclusion

Biomass utilization emerges as a pivotal component in advancing sustainable development, particularly through the transformation of organic waste into bio-based products within a circular economy

framework. Understanding the physicochemical properties of biomass and optimizing pretreatment strategies are crucial for enhancing the efficiency of biomass conversion into biofuels. Although economic challenges persist in comparison to fossil fuels, research efforts are concentrated on improving conversion efficiencies and reducing associated costs to bolster the competitiveness of biofuels derived from biomass waste.

The exploration of single cell protein (SCP) offers a promising avenue for addressing global protein demands sustainably, highlighting the necessity for innovative approaches in this area. Moreover, the establishment of comprehensive and scientifically grounded guidelines for the sustainable management of forest biomass harvesting is imperative, balancing environmental conservation with the needs of the biomass industry.

The integration of biomass utilization into sustainable practices yields numerous advantages, including reduced dependency on fossil fuels, enhanced resource efficiency, and substantial contributions to environmental conservation and economic resilience. These insights emphasize the importance of advancing biomass conversion technologies and developing robust policy frameworks to support the transition towards a more sustainable and resilient economic model.

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