processes

MDPI

Review

Innovative Applications of Sugarcane Bagasse in the Global Sugarcane Industry

Sylvere Ndikumana [1,*], Omar Tanane [1], Youness Aichi [1,2], El Farissi Latifa [2] and Lina Goudali [2,3]

[1] Laboratory of Physical Chemistry of Applied Materials (LCPMA), Faculty of Sciences Ben M'Sick, Hassan II University of Casablanca, B.P 7955 Casablanca, Morocco; omar.tanane@univh2c.ma (O.T.); aichi@ctpc.ma (Y.A.)
[2] Centre Technique de Plasturgie et de Caoutchouc (CTPC), Sidi Maarouf, 20280 Casablanca, Morocco; elfarissi@ctpc.ma (E.F.L.); goudali@ctpc.ma (L.G.)
[3] Modeling and Simulation of Intelligent Industrial Systems Laboratory (M2S2I), ENSET Mohammedia, Hassan II University of Casablanca, B.P 159 Mohammedia, Morocco
* Correspondence: sylvere.ndikumana-etu@etu.univh2c.ma; Tel.: +212-715209069

Abstract

Sugarcane bagasse (SCB), a major byproduct of the sugar industry produced in millions of tons annually, is traditionally burned for energy but holds untapped potential for sustainable valorization amid global shifts toward renewable resources and reduced fossil fuel reliance. This review synthesizes recent advancements in SCB applications beyond energy, emphasizing bioenergy, bioplastics, construction materials, and agriculture to advance circular economy principles—addressing a gap in the existing literature by providing a holistic, comparative analysis of processing technologies, including their efficiency, costs, and scalability, which prior reviews have overlooked. Drawing from scientific literature, industry reports, case studies, and datasets, we evaluate SCB's composition (40–50% cellulose, 25–30% hemicellulose, 20–25% lignin) and processing methods (e.g., pretreatment, hydrolysis, gasification, pyrolysis). Key findings highlight versatile applications: bioethanol production yielding 40–70% GHG reductions per life cycle assessments; pulp/paper substitution reducing water and chemical use; nanocellulose composites for automotive and medical sectors; particleboard and ash-cement in construction cutting deforestation and carbon footprints by ~20%; and biochar/processed feed enhancing crop yields by 25% while amending soil. Unlike previous reviews focused on isolated applications, this work integrates environmental, economic, and regulatory insights, identifying challenges like standardization gaps and proposing pathways for commercialization to drive scalable, green industry transitions. Continued research and policy support are essential for realizing SCB's role in sustainable development.

Keywords: bagasse; bioenergy; bioplastics; pulp and paper; construction materials; sustainable development

check for updates

Academic Editors: Marcos Alberto Coronado Ortega and José Ramón Ayala Bautista

Received: 10 September 2025
Revised: 22 October 2025
Accepted: 24 October 2025
Published: 24 November 2025

Citation: Ndikumana, S.; Tanane, O.; Aichi, Y.; Latifa, E.F.; Goudali, L. Innovative Applications of Sugarcane Bagasse in the Global Sugarcane Industry. *Processes* **2025**, *13*, 3796. https://doi.org/10.3390/pr13123796

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

1.1. Context and Significance of the Topic

The ongoing global effort to find sustainable, clean, and renewable alternatives to meet the rising demand for materials and energy, while simultaneously reducing dependence on fossil fuels, has highlighted sugarcane as a strategic raw material. Cultivated in over 100 countries, the sugarcane has significant potential to mitigate greenhouse gas (GHG) emissions. In this context, the production of bio-based materials and biofuels, along with

their efficient utilization, represents key avenues toward achieving sustainable development goals. As noted by Sheikhdavoodi et al. (2015), energy security and environmental protection remain among the most critical long-term challenges facing humanity [1].

Lignocellulosic biomass such as sugarcane bagasse (SCB), corn stover, cereal straw, and forest residues (birch, eucalyptus) is notable for its high energy density, making it an essential resource in addressing the imminent energy crisis [2,3]. These plant-based residues are the most abundant renewable resources globally, with an estimated annual production of approximately 1010 million tons [4].

Global sugarcane production reached approximately 1.95 billion metric tons in 2023, generating an estimated 540–585 million tons of bagasse annually (primarily in Brazil, India, and China, which together account for ~80% of output) [5,6]. This update from FAO's 2023 Statistical Yearbook reflects a 22% increase since 2020, driven by yield improvements in tropical regions, though climate variability and land constraints may temper future growth [7,8]. The proper management of this volume is critical to avoid environmental burdens, with valorization pathways offering opportunities for waste minimization.

1.2. Problem Statement and Challenges

SCB is characterized by a substantial chemical composition containing 40–50% cellulose, 25–30% hemicellulose, and 20–25% lignin, with negligible ash and extractives [9].The complex bonds between lignin and polysaccharides hinder direct breakdown into simple sugars, requiring efficient, non-destructive pretreatment methods to isolate lignin and facilitate its conversion into valuable products [10]. These processes aim to disrupt the cell–matrix, producing high-quality fermentable sugars suitable for bioenergy applications such as bioethanol, biogas, or biohydrogen [11].

Furthermore, SCB valorization extends to manufacturing bricks, ceramics, cement additives, reinforced composites, and bioplastics, as well as energy generation via pyrolysis or gasification. These diverse applications underscore SCB's significant potential as a sustainable resource. However, optimizing pretreatment techniques remains crucial to maximize its use for bioenergy and value-added products, necessitating ongoing research over the past two decades to evaluate the influence of various processing methodologies.

In the sugar industry, modifying the physical and chemical properties of SCB is vital for its industrial applications. Delignification—the removal of lignin—enhances biomass enzymatic digestibility for biofuel production. This can be achieved via chemical methods, notably alkaline treatments like soda (NaOH) or hybrid acid/alkali processes, which efficiently release reducing sugars necessary for fermentation [12,13]. Process parameters such as temperature and alkali concentration (e.g., 0.5 M Na_2CO_3 at 140 °C) are optimized to improve yield, reduce costs, and minimize environmental impact [14].

The hydrolysis stage, which precedes biofuel or bioproduct production, involves breaking down polysaccharides into simple sugars. Enzymatic hydrolysis using cellulases from microorganisms like Trichoderma reesei can produce substantial glucose yields under moderate conditions (40–50 °C, pH 4.8–6.0, over 72 h). Alternatively, dilute acid hydrolysis with weak acids such as sulfuric acid (H_2SO_4) allows faster processing, often without prior pretreatment, and maximizes fermentable sugar recovery [15,16].

The resulting sugars can then undergo fermentation to produce various biofuels, including bioethanol and biogas (methanization), as well as biochemicals like xylitol and biobutanol. Microorganisms such as Saccharomyces cerevisiae or Clostridium spp. have demonstrated promising results in renewable energy sectors [12,17]. Additionally, SCB enables the synthesis of biomolecules like biohydrogen—a clean energy carrier—and biobutanol, which is considered a more effective fuel than ethanol and offers significant GHG reduction potential [18,19].

In the broader context, lignocellulosic biomass facilitates the production of diverse bioproducts, such as organic acids (lactic, succinic, citric), derived from enzymatic hydrolysis or fermentation. These resources support a circular economy model by utilizing agricultural residues like molasses, straw, and corn husks as cost-effective carbon sources, thereby avoiding competition with food production [2,20,21]. Such strategies are vital for advancing the bioeconomy and transitioning toward more sustainable, less fossil fuel-dependent industries.

1.3. Objectives of the Review

This review aims to synthesize recent research advancements related to the innovative applications of sugarcane bagasse beyond energy generation. It focuses on processing techniques, product development, and environmental and economic impacts. By analyzing scientific publications, industry reports, and case studies, the study seeks to identify pathways for sustainable and innovative utilization of this renewable resource.

1.4. Scope of the Study

The scope incorporates a comprehensive investigation of applications such as bioenergy (bioethanol, biogas, biohydrogen), bioplastics, construction materials, and agricultural uses. It evaluates processing methods, compositional factors, environmental benefits, and economic viability. Finally, it underscores the importance of continuous research and technological advancement to fully harness the potential of sugarcane bagasse within a sustainable development framework.

Justification and need for this review

In spite of the broad body of research on sugarcane bagasse valorization, several limitations persist in the current literature. Many studies focus narrowly on specific processes or applications without providing an integrated, comprehensive overview of the diverse valorization pathways. Additionally, technological advancements such as improvements in bioprocessing, composite materials, and bioplastics are progressing rapidly, requiring regular updates to assess their maturity, scalability, and environmental impacts. Furthermore, few reviews offer a systematic comparison of processing methods, considering factors like efficiency, cost, environmental sustainability, and potential for industrial implementation on a global scale. This highlights the need for a new, comprehensive review that consolidates recent developments, compares different technologies, and identifies gaps and challenges in the field. The added value of this article lies in providing a holistic analysis of the latest developments, including novel processes, technological breakthroughs, and sustainable approaches, while offering a clear comparative perspective. It aims to serve as a key guide for researchers, industry stakeholders, and policymakers by delivering an up-to-date, critical synthesis of the state-of-the-art in sugarcane bagasse valorization, ultimately supporting the transition towards more sustainable and integrated bio-based industries.

2. Products from Different Thermochemical Processes

2.1. Gasification (Air Gasification)

Biomass gasification is a promising method for converting SCB into syngas, primarily composed of carbon monoxide and hydrogen, which is suitable for electricity generation, biofuel production, or chemical synthesis [22,23]. Different reactor configurations offer unique advantages and face specific challenges. The downdraft fixed-bed gasification produces high-quality syngas but struggles with efficiency under certain conditions and requires effective tar management [22,23]. Fluidized bed gasification enhances heat transfer, thereby improving efficiency, though it faces issues such as fouling and biomass

bridging [23,24]. Cyclone gasifiers improve combustion stability but involve higher construction complexity [25]. Modeling approaches, such as thermodynamic simulations and exergy analyses, provide critical insights for optimizing processes by identifying key constraints and guiding improvements [24–26]. Lab-scale steam reforming of bagasse demonstrates potential for high hydrogen yields, but industrial applications face challenges related to tar management and energy integration [27,28].

2.1.1. Process Optimization and Innovations for Efficient and Sustainable Gasification

Ongoing innovations aim to enhance gasification efficiency and promote sustainability. Advanced pretreatment techniques, such as pre-drying and decontamination, aim to reduce tar formation [29]. Integration with combined cycle configurations enhances energy efficiency by utilizing waste heat [30]. Multiphysical models improve predictions of tar formation and optimize operating conditions. Research into reactor materials that withstand high temperatures and resist corrosion is also advancing, with the goal of improving infrastructure longevity and reliability [31,32].

2.1.2. Technical Challenges and Prospects for Industrial Development of SCB Gasification

SCB gasification shows promise but remains primarily at the research stage due to technical challenges. Tar production affects process stability, requiring costly cleaning systems [2]. High moisture content in biomass reduces efficiency, necessitating energy-intensive pre-drying [2]. The lack of standardized regulations hinders large-scale deployment and commercial viability by creating uncertainty for investors, complicating compliance across regions, and delaying market entry—potentially increasing project costs by 20–30% due to custom adaptations [33]. For instance, inconsistent syngas quality standards can lead to rejected products in energy markets, limiting integration into existing grids. Most research is limited to prototypes, with few industrial-scale projects, posing challenges for scaling up [34]. Future progress depends on a better understanding of non-equilibrium reactions to optimize syngas yields, on reducing costs, and on integrating gasification into sustainable industrial chains to support a circular economy [35,36]. To address standardization gaps, pathways for harmonization could include collaboration with bodies like ISO or ASTM to develop global syngas quality benchmarks (e.g., minimum H_2/CO ratios and impurity thresholds), pilot certification programs in major SCB-producing countries (Brazil, India), and incentives like subsidies for compliant technologies to accelerate commercialization.

2.2. Steam Reforming (Steam Gasification)

Steam reforming offers a pathway to produce hydrogen from lignocellulosic biomass like SCB, supporting carbon-free energy carriers that are critical for the energy transition [36]. SCB is less reactive than other biomass types due to its composition, with efficiency depending on lignin and cellulose content [36]. Catalysis plays a crucial role, with certain catalysts significantly enhancing hydrogen yields compared to non-catalytic methods [37,38]. Supercritical water reforming reduces tar formation, though it is less efficient than traditional catalysts [1,39]. Solar reactors lower energy consumption, producing higher-quality syngas sustainably [1]. Optimal operating conditions are critical to maximize hydrogen production while minimizing tar deposits [1,39]. Pilot studies highlight potential, but commercial applications often prioritize electricity over pure hydrogen extraction, with hybrid systems showing greater viability [29]. Industrial challenges include tar formation, catalyst deactivation, and scale-up inefficiencies [40,41].

2.2.1. Current Challenges and Prospects for Improvement in Biomass Gasification

The key challenges in biomass gasification include modest yields due to tar formation, which affects process stability and profitability, particularly in high-humidity conditions [42]. Catalyst durability, especially for materials like ruthenium or nickel, is a concern due to rapid deterioration at high temperatures, leading to high maintenance costs [43]. High temperatures and advanced systems increase initial costs, while the lack of standardized syngas quality criteria limits industrial integration [44].

2.2.2. Innovative Approaches to Overcoming the Challenges of Biomass Gasification

Research is exploring more efficient and cost-effective catalysts, including nanostructured materials and industrial waste-derived options, to improve process stability and profitability [45]. Solar and hybrid systems aim to reduce energy consumption, enhancing sustainability [46]. Low-moisture processes compatible with diverse biomass types could improve efficiency [47]. Systematic descaling and de-tarring procedures are essential to ensure operational stability and reduce maintenance costs. Large-scale experimental studies are needed to validate industrial feasibility and long-term profitability.

2.2.3. Prospects and Challenges for Biomass Steam Reforming in the Field of Catalysis

Biomass steam reforming shows significant promise in catalysis, but most studies remain at the experimental or modeling stage, with limited industrial demonstrations [48]. The challenges include catalyst stability under continuous operation, cost control for high-temperature processes, and tar management. Biomass sensitivity to initial composition restricts result reproducibility [49]. Advancing this technology for sustainable industrial applications requires significant progress in catalysis and thermal management [50].

2.3. Pyrolysis

Pyrolysis efficiently converts SCB into biochar, biogas, and bio-oils, with applications in agriculture, energy, and green chemistry [51]. The process's effectiveness depends on operating conditions, particle size, and pyrolysis type (slow, flash, or vacuum) [52]. Two-phase processes are ideal for sustainable agricultural biochar, while specific conditions favor gas production for fuel cells [53]. Temperature significantly influences product distribution, with different temperatures optimizing biochar, bio-oil, or biogas yields [52]. Vacuum pyrolysis increases biochar yield but requires more energy, and combining SCB with certain residues can limit adsorption applications [54]. Smaller, compacted pellets enhance biochar production with less shrinkage [55]. SCB generally outperforms other biomass types in oil yield, though industrial-scale applications face thermal constraints [56].

2.3.1. Technical and Regulatory Challenges Related to the Production and Use of Biochar Through Pyrolysis

Biochar quality for agricultural or environmental applications depends on controlling specific surface area and porosity [56]. Smaller pellets increase biochar production but raise energy consumption, and tar production at high yields can impair equipment functionality, necessitating precise thermal regulation [57]. High-temperature pyrolysis, especially in vacuum or controlled atmospheres, is costly and challenging to scale up [58]. The lack of international standards for biochar and bio-oil quality hinders market entry and large-scale deployment by increasing regulatory risks, deterring investments, and fragmenting global trade—potentially stalling commercialization in regions like the EU, where certification is mandatory for soil amendments [59]. This results in higher compliance costs and limited consumer trust. Harmonization pathways include adopting frameworks from the International Biochar Initiative (IBI) for standardized testing (e.g., carbon stability metrics),

regional policy alignments via UN FAO guidelines, and R&D consortia to validate biochar across applications, facilitating broader adoption.

2.3.2. Research Prospects for Optimizing Biomass Pyrolysis and Integrated Recovery

Research is focused on optimizing pyrolysis through precise thermochemical models to improve oil efficiency and reduce tar production [39]. Developing catalysts to enhance selectivity for aromatic compounds or hydrocarbons supports specific chemical applications [60]. Pyrolysis in mixed atmospheres with inert gases and water vapor can improve product quality. Integrating pyrolysis with gasification or fermentation could enhance resource efficiency [30]. Small- and large-scale studies are essential to confirm process viability, stability, and efficiency.

2.3.3. Challenges and Prospects for Sustainable Industrial Development

Preliminary findings suggest that pyrolysis can be tailored to produce diverse end products, but challenges include yield fluctuations and tar production [61]. Most results come from lab or small-scale facilities, limiting scalability. Optimizing thermal parameters, equipment design, and waste management is critical for stability and profitability in sustainable industrial processes [62].

2.4. Combustion

SCB is primarily used for combustion to generate heat, steam, or electricity, traditionally through inefficient open fires in rural settings, which pose environmental and safety concerns [63]. Modern high-pressure industrial boilers improve efficiency and emission control, particularly in sugar or biomass power plants [18,64]. Briquetting enhances density, handling, and storage, reducing pollution through uniform combustion [65]. Advanced techniques like thermo-catalytic reforming produce high-quality syngas and biochar for industrial applications [66]. Hydrothermal torrefaction enhances SCB's thermal stability and energy density, improving fuel storage and utilization [67]. Combustion conditions significantly affect stability and emissions, requiring comparative analysis to optimize cost-effectiveness and efficiency [68,69].

2.4.1. Environmental and Economic Challenges of Combustion: Pollution, Efficiency, and Regulatory Framework

Open-fire combustion emits high levels of pollutants, contributing to environmental and health issues, while low efficiency wastes energy [70,71]. Modern high-pressure boilers and briquetting reduce emissions and improve efficiency [72]. However, managing ash and residues like tar poses maintenance and environmental challenges. Modernizing equipment, such as high-pressure boilers and pollution control devices, requires significant investment, increasing costs [18]. The lack of clear standards for agricultural biomass combustion limits large-scale adoption [73].

2.4.2. Prospects for Optimizing Biomass Combustion Systems for Sustainable and Clean Use

Optimizing combustion involves designing efficient, low-polluting boilers with ash recycling systems to minimize environmental impact and maximize energy recovery [74]. Integrating combustion with gas treatment or purification processes can produce high-purity biogas or biohydrogen [75]. Optimizing briquettes with eco-friendly binders and standardized quality ensures efficient, safe combustion [76]. Pollution control technologies, such as particulate filters and selective catalytic reduction systems, are essential for reducing emissions and meeting standards [77]. Pilot and industrial-scale validation is needed to confirm performance, stability, and profitability [78].

2.4.3. Challenges and Prospects for the Large-Scale Deployment of LPG Combustion: Pollution, Reliability, and Technological Innovations

SCB combustion is widely used domestically and industrially, but large-scale deployment faces challenges related to pollution, equipment reliability, and costs. Conventional open-fire methods are inefficient and environmentally harmful, necessitating a shift to greener systems [79]. Briquetting offers an economically viable option but requires rigorous quality control and regulatory frameworks. Advanced methods like pyrolysis or reformulation show promise but face technical and financial hurdles for sustainable industrial implementation [80]. Table 1 compares biomass conversion technologies for sugarcane bagasse, detailing their advantages, disadvantages, Technology Readiness Levels (TRL), and estimated costs, highlighting trade-offs in efficiency, scalability, and economic viability across gasification, steam reforming, pyrolysis, and combustion methods. Figure 1 compares the cost ranges of biomass conversion technologies, highlighting initial investment and operational costs for sugarcane bagasse (SCB) valorization. Figure 2 illustrates the estimated sugarcane production for the top 10 countries in 2024, highlighting the global leaders in this biomass cultivation.

Table 1. Comparative analysis of biomass conversion technologies.

Technique	Advantages	Disadvantages	TRL	Estimated Cost	References
Gasification (Downdraft Fixed-Bed)	High CO/H_2 syngas yield, energy valorization	Tar formation, low efficiency with high moisture	3–4	600–900 $/kW	[23,24,81,82]
Gasification (Fluidized Bed)	Better heat transfer, high efficiency (70%)	Fouling, biomass bridging, thermal losses	4–5	500–800 $/kW	[24,81,82]
Gasification (Cyclone)	Improved combustion stability	High construction costs, complexity	3–4	700–1000 $/kW	[24,82]
Gasification (Modeling/Exergy)	Optimizes parameters, identifies constraints	Tar modeling difficulty, preprocessing costs	3–4	15–30 $/tonne	[83,84]
Steam Reforming (Catalytic, Ni/Ru)	High H_2 yield (25–75 mmol/g), tar reduction	Catalyst degradation, high costs	3–4	800–1200 $/kW	[1,25,41,66]
Steam Reforming (Supercritical Water)	Tar mitigation, residue handling	Technical complexity, high equipment costs	3–4	1000–1500 $/kW	[1,42,85]
Steam Reforming (Solar)	Low energy use, eco-friendly	Solar dependence, integration challenges	3	900–1300 $/kW	[86,87]
Pyrolysis (Biochar for Agriculture)	Soil improvement, carbon storage	Limited yield, thermal degradation	4–5	200–500 $/tonne	[88,89]
Pyrolysis (Bio-oil for Chemicals)	High-value fuel, 63% yield at 500 °C	Purification needs, variable yield	3–4	300–600 $/tonne	[40,90,91]
Pyrolysis (Biogas/Syngas)	Renewable energy for fuel cells	Requires refining, process-dependent costs	3–4	12–20 $/tonne	[61,70,71]
Combustion (Domestic Open Fire)	Low cost, easy access	High pollution, low efficiency	2–3	<100 $/kW	[70,92]
Combustion (Industrial Boilers)	High efficiency (85–90%), electricity generation	High investment, maintenance	4–5	1000–2000 $/kW	[18,93]
Combustion (Briquetting)	Uniform combustion, reduced pollution	Manufacturing costs, variable quality	3–4	200–500 $/tonne	[94,95]
Combustion (Thermo-catalytic)	High-quality syngas, biochar production	Energy costs, complexity	3	0.5–1.5 $/L	[73,96]
Combustion (Wet Torrefaction)	Improved stability, energy density	Processing costs, specialized equipment	3–4	10–20 $/tonne	[74,97]

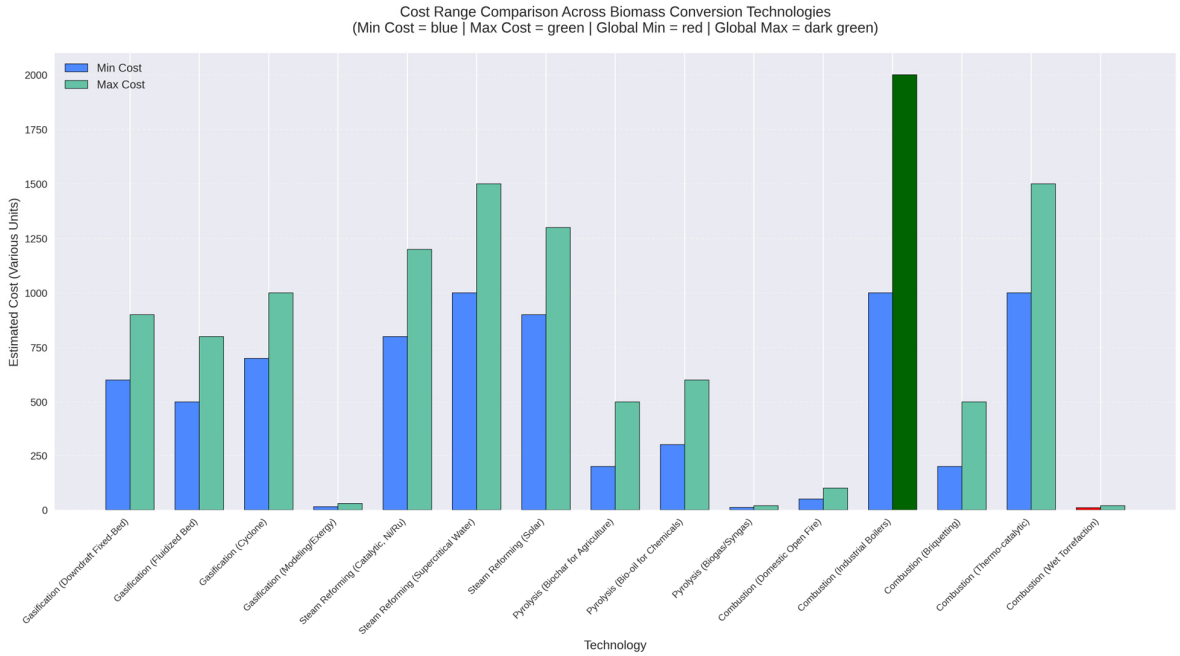


Figure 1. Cost range comparison across biomass conversion technologies.

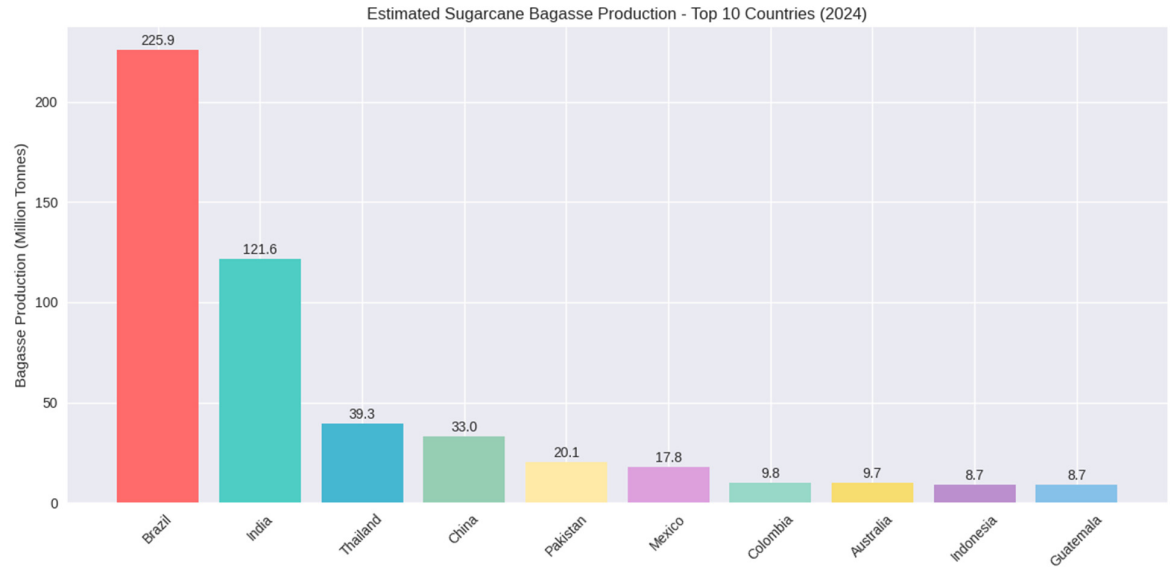


Figure 2. Estimated sugarcane production—Top 10 countries (2024).

3. Adsorbents

SCB is a cost-effective, abundant resource for producing adsorbents used in water and gas purification, owing to its cellulose, lignin, and hemicellulose composition, which interacts effectively with pollutants like heavy metals, dyes, hydrocarbons, and volatile organic compounds [92]. SCB's low cost and ease of processing make it ideal for environmental applications. Biosorbents are created through chemical or physical modifications to enhance surface area and pollutant binding [98]. Chemical agents like $FeCl_2$, NaOH, or H_3PO_4 improve adsorption, particularly for heavy metals and phosphates, with a 42% increase in phosphate adsorption capacity [93]. Activated carbon (AC) from SCB, produced via chemical activation (H_3PO_4, KOH) and high-temperature carbonization (700–900 °C), offers a specific surface area of 536.5 m^2/g and a lead adsorption capacity of 140.85 mg/g, surpassing commercial carbon. For nickel, raw SCB adsorbs 73.56 mg/g, while AC achieves 111 mg/g [94]. Biosorption, an exothermic and spontaneous process, effectively removes

methylene red (2 mg/g at pH 9, 25 °C) and hydrocarbons like gasoline (99%) and n-heptane (90%) [99,100]. SCB-based zeolites and nanocatalysts serve as ion exchangers and catalysts, while biological filters remove 99% of air pollutants like benzene and toluene [101,102]. In contrast, rice straw and rice husks have significantly higher ash contents (15–20%), primarily due to silica, which can pose challenges in thermal processing by causing equipment wear but offers opportunities for applications like biochar production or silica-based adsorbents [103].

3.1. Challenges and Prospects in the Sustainability and Commercialization of SCB-Based Bioadsorbents

The durability and regeneration of adsorbents remain a crucial issue, given that the sustainability of these substances after several regeneration cycles is still limited, which poses an obstacle to their economic recycling [104]. Furthermore, enhancing preparation methodologies, whether chemical or physical, necessitates meticulously controlled conditions, thereby escalating the expense and intricacy of their large-scale implementation. The porosity of the material is also a critical factor in determining its capacity for adsorption; it is therefore essential to regulate both porosity and the specific surface area in order to optimize the material's ability to adsorb high concentrations of heavy metals [105]. In terms of scalability, the industrial production of bioadsorbents or activated carbon derived from SCB must overcome technical and energy barriers to remain competitive. Regulatory approval for the utilization of modified bioadsorbents or nanomaterials is still in development, which is currently impeding their market entry [106].

3.2. Research Prospects for Improving the Performance and Sustainability of SCB-Based Adsorbents

A range of research directions is currently being investigated with the objective of enhancing the efficiency and sustainability of adsorbents derived from SCB. The objective of enhancing modeling and synthesis methodologies is to devise techniques that augment the specific surface area and porosity of materials while diminishing manufacturing expenses [107]. The combination of SCB with materials such as clay, silica, or other biomasses in the manufacture of composites has the potential to enhance their mechanical stability and pollution control performance [108]. It is imperative to enhance the regeneration and recycling processes for adsorbents. The development of more efficient and environmentally friendly methods for their regeneration would contribute to prolonging their lifespan [109]. The recovery of by-products generated during the production of adsorbents is a strategy aimed at minimizing their environmental impact by converting these residues into new raw materials [110]. The development of innovative applications, such as incorporating these materials into air filters, membranes, or industrial and domestic equipment, could broaden their scope of application and optimize their environmental impact [111].

3.3. Development Prospects for the Large-Scale Commercialization of SCB-Based Adsorbents: Technical, Environmental, and Economic Challenges

Recent studies have demonstrated the potential of SCB to function as highly effective adsorbents, exhibiting a broad spectrum of efficacy against various pollutants [112]. However, the majority of research is conducted at the laboratory or pilot scale, with an urgent need for validation at the industrial scale [112]. The primary challenges pertain to the long-term durability, regeneration, and manufacturing costs of the adsorbents. The process of chemical modification has been demonstrated to enhance the capacity for adsorption; however, this method is accompanied by significant environmental concerns, primarily due to the substances utilized in the process [113]. Consequently, the research endeavors should

prioritize the reduction of costs, the optimization of service life, and the standardization of processes to facilitate large-scale adoption [114].

4. Commercial Products Made from Bagasse

Bagasse is the fibrous residue remaining after the extraction of sugarcane juice, accounting for approximately 30 to 40% of the initial weight of the sugarcane [115]. It has been determined that approximately 280 kg of bagasse are produced from one ton of sugarcane. According to Bantacut et al. and Guerra et al., the amount of bagasse produced is influenced by several factors, including (i) the harvest season, (ii) agro-environmental methods, (iii) soil condition, and (iv) the intensity of the crushing and grinding processes carried out in the sugar mill. Bagasse is composed of approximately 48% cellulose, 29% hemicellulose, and 24% lignin, with a negligible amount of ash (less than 2%) and variable moisture content [116,117]. Bagasse can be converted into various beneficial products. This section elucidates the methodologies employed for the conversion of bagasse into various products, along with recent advancements in these techniques aimed at enhancing productivity [118].

4.1. Bagasse and Pectin-Based Composites for Food Packaging Applications

Composite materials made from bagasse are biodegradable, renewable, and suitable for a circular economy, providing an environmentally friendly solution for non-structural uses in the packaging and automotive sectors [119]. Bagasse fibers combined with pectin create eco-friendly, biodegradable films for food packaging, offering a sustainable alternative to conventional plastics with adjustable mechanical and barrier properties based on particle size and formulation. These composites, designed for flexible packaging, reduce the agri-food industry's environmental impact [119,120]. Versino and García [121] note that bagasse particle size in cassava starch films affects mechanical strength, clarity, and water vapor transmission. Enhanced particle size improves UV barrier properties, extending preservation for packaging [122]. Huerta-Cardoso et al. [123] report that bagasse in a polylactic acid (PLA) matrix achieves peak tensile strength and impact resistance at 20% load, with optimal water absorption at 40% [124], suiting humid, demanding environments like automotive and food packaging [116]. Guimarães et al. [117] describe bagasse's thermal degradation in three stages: moisture (100 °C), cellulose/hemicellulose (340 °C), and lignin (472 °C). Thermal stability varies with matrices like PLA or polypropylene, but nanoclay or nanographene (0.5–3%) enhances it [125,126]. These renewable composites support a circular economy for non-structural applications [126].

4.2. Technical and Regulatory Challenges in Integrating Bagasse Fiber into Polymer Matrices for Biodegradable Packaging

The integration of bagasse fiber into polymer matrices poses a series of technical and regulatory challenges [32]. Compatibility between the fiber and the matrix frequently necessitates surface treatments or the incorporation of compatibility agents such as maleic anhydride, silanes (e.g., alkylsilanes, amino-silanes), or other coupling agents, which complicates the manufacturing process. Furthermore, thermal stability represents a significant constraint, as the reduction in decomposition temperature in specific thermoplastic matrices imposes limitations on their utilization for packaging intended for severe conditions, such as elevated temperatures or high humidity [127]. Although the incorporation of nanocomposites has the potential to enhance the quality of the product, this process is accompanied by an increase in production costs [128]. It is imperative to exercise stringent control over the size and distribution of bagasse particles, as uneven dispersion or inadequate size can have a deleterious effect on mechanical and barrier properties, necessitating highly precise molding and screening techniques [116]. With regard to scaling up bagasse-based com-

posites, especially those incorporating nanometric additives, the cost remains a significant challenge [129]. To achieve competitiveness, process optimization is imperative. From a regulatory perspective, the framework for biodegradable packaging materials is still evolving. Standards such as EN 13432, which certifies compostability and biodegradability under industrial conditions, provide important benchmarks, but the lack of comprehensive and harmonized regulations globally can hinder widespread commercialization [130].

4.3. Research Prospects for Optimizing Bagasse Fiber-Based Composites in Biodegradable Packaging

To advance bagasse fiber-based composites, a few key focuses should be addressed. First, particle size and distribution have to be carefully controlled through advanced techniques to ensure uniform dispersion within the matrix, which directly improves the mechanical and barrier properties of the final material [131]. Enhancing fiber-matrix adhesion is also vital; this can be accomplished by applying chemical or enzymatic surface treatments that improve compatibility without significantly increasing manufacturing costs [132]. Incorporating nanotechnologies, such as nanoclay or nanographene, offers the potential to significantly improve thermal stability and resistance to moisture and light, provided that nanomaterials are dispersed homogeneously and costs are kept under control. Moreover, developing hybrid biodegradable formulations by combining biopolymers like chitosan, polylactic acid (PLA), or pectin can lead to more effective and environmentally friendly packaging solutions [133]. Equally important is conducting comprehensive biodegradability and environmental testing, including studies of degradation under natural conditions such as soil, compost, or water, to ensure compliance with environmental and regulatory standards [134].

Future Trends

Looking ahead, future trends include leveraging nanotechnologies to further improve thermal and moisture resistance, designing hybrid biopolymer systems for more effective biodegradability, and optimizing manufacturing processes to reduce costs and improve scalability [135,136]. These advancements will be critical for transforming bagasse fibers into sustainable, high-performance materials suitable for a wide range of industrial applications [137].

4.4. Bagasse–Pectin Composites for Sustainable Packaging: Challenges and Prospects

Composite materials derived from bagasse and pectin exhibit considerable promise for sustainable food packaging, primarily due to their capacity for biodegradation, their cost-effectiveness, and their versatility in application [138]. The worldwide market for biodegradable packaging is expected to reach around $15 billion by 2027, driven by rising environmental consciousness and stricter regulations aimed at decreasing plastic waste. Despite this growth, the large-scale adoption of bagasse–pectin composites remains limited due to obstacles related to processing techniques, mechanical and thermal stability, and regulatory hurdles [139]. To enable broader industrial implementation, further research is essential to enhance fiber-matrix compatibility, ensure uniform nanometric dispersion, and reduce manufacturing costs [140].

From an environmental standpoint, these biocomposites offer substantial advantages, including a potential reduction in CO_2 emissions of up to 50–70% compared to traditional plastics, by replacing fossil-based materials with renewable biomass [141]. They also help decrease embodied energy—the total energy consumed over the product's lifecycle—referred to as the "energy footprint or energy guise," thereby significantly lowering the overall environmental impact associated with packaging waste [142]. However, their large-scale deployment remains limited due to dependence on processing methods, mechanical and

thermal stability, and regulatory constraints [143]. Consequently, further research is necessary to enhance fiber-matrix compatibility, regulate nanometric dispersion, and reduce production costs, thereby facilitating industrial adoption [140].

5. Bagasse Ash as a Substitute for Cement

The utilization of ash has been demonstrated to curtail the accumulation of agricultural waste, temper the extraction of primary resources, and curtail energy consumption during cement production [144]. According to Agrawal et al. (2013), the incorporation of ash into concrete has been shown to reduce the proportion of clinker, a major contributor to CO_2 emissions, while maintaining satisfactory mechanical characteristics [145]. The financial implications of this process are contingent upon the selected treatment method, the particle size of the ash, and its compatibility with the cement matrix or other materials. The incorporation of ash as an additive or filler has been demonstrated to reduce the overall manufacturing cost of composite materials [144]. Research has indicated that partial replacement of clinker with bagasse ash (10–30%) can preserve or enhance mechanical strength while reducing environmental impact [146]. Bagasse ash can be utilized as a filler in the production of ceramics capable of withstanding temperatures of up to 1600 °C, thereby providing a local substitute for conventional refractory materials [147]. The research has demonstrated that ash can be utilized as a filler in polymer composites or glass matrices, thereby enhancing their thermal resistance and longevity [148].

5.1. Bagasse Ash: Technical, Regulatory, and Sustainability Issues in Construction

The use of bagasse ash in construction and mechanical applications presents several technical, administrative, and sustainability challenges [149]. A primary issue is the variability in ash composition and fineness, which depends on the type of fuel utilized for combustion, as well as operational parameters. This variability directly impacts the pozzolanic activity of the ash, thereby affecting the mechanical quality, durability, and overall efficacy of the final material—be it concrete or ceramics. For example, guidelines such as ASTM C618 (USA) [150] and EN 450 (Europe) [151,152] specify requirements for pozzolanic materials, including chemical composition and fineness, but these are not always tailored to the unique characteristics of bagasse ash, limiting its acceptance and application. This regulatory fragmentation hampers commercialization by raising certification costs, delaying project approvals, and reducing competitiveness against established materials like fly ash, potentially limiting market penetration in global construction sectors. Also, increasing the substitution rate of bagasse ash in cementitious networks requires careful calibration to balance cost efficiency with long-term durability and mechanical performance [153]; too high a substitution level can compromise structural integrity under certain conditions. Moreover, pre-treatment processes like smashing, crushing, or chemical activation are essential to improve ash reactivity and consistency [154], but these steps significantly increase handling costs and mechanical complexity, requiring energy inputs and additional gear, which can hinder adaptability. Variations in ash quality due to feedstock and combustion conditions lead to inconsistent performance in concrete and ceramic items, affecting properties such as quality, permeability, and lifespan [155]. Hence, establishing precise control over raw material quality and treatment strategies is pivotal to guarantee consistency, optimize performance, and meet regulatory standards [156], especially for long-term solidity in sticky or forceful situations. Thorough testing and approval are essential to ensure that bagasse ash-based materials can dependably contribute to sustainable development practices around the world [157]. To promote harmonization, stakeholders could advocate for unified standards through ISO committees, integrating bagasse ash into existing pozzolan

classifications, and funding cross-regional trials to align with sustainability goals like UN SDGs, thereby boosting commercialization.

5.2. Optimization and Sustainability of Bagasse Ash for Advanced Materials

To maximize the potential of bagasse ash as a sustainable resource for advanced materials, it is essential to optimize its treatment processes, including grinding, activation, and chemical treatments, to enhance its pozzolanic reactivity [104]. The grinding process increases particle fineness and surface area, which improves reactivity and facilitates better dispersion within composite systems. Chemical activation, such as acid or alkali treatments and surface modifications like silanization, further enhances surface properties, promoting stronger bonding and tailored performance in applications [158]. Precise characterization of the ash's composition, particle size distribution, and mechanical properties ensures consistency, repeatability, and quality control. These pretreated ashes can then be incorporated into hybrid formulations alongside fibers, nanomaterials, or support agents, which collectively improve mechanical strength, thermal stability, and durability [159]. This systematic approach influences the final properties of the materials, expanding their use in high-performance applications such as refractory materials, thermal insulators, or additive manufacturing, and supports the development of eco-responsible, sustainable solutions grounded in circular economy principles [146].

5.3. Challenges and Prospects for Sustainable Use of Bagasse Ash in Cement and Ceramics

Environmental benefits

CO_2 Emissions reduction

The incorporation of sugarcane bagasse ash (SCBA) as a supplementary cementitious material (SCM) in cement production significantly reduces CO_2 emissions, addressing the cement industry's contribution to approximately 5–8% of global CO_2 emissions [160]. Studies demonstrate that replacing cement with SCBA can reduce emissions by 3.8% to 12.3% depending on replacement levels (5%, 10%, and 15%, respectively). For instance, in a study from Khyber Pakhtunkhwa, concrete mixes with 10% SCBA (SCBA-P10) achieved a 7.89% reduction in CO_2 emissions compared to control mixes, while maintaining comparable mechanical strength [161]. In the Philippines, utilizing 125 kt of SCBA annually could reduce CO_2 emissions by approximately 94 kt, equivalent to replacing 3 million 40 kg bags of cement [162]. Additionally, SCBA's use in alkali-activated binders can decrease CO_2 emissions by up to 70% compared to traditional Portland cement production, due to lower energy requirements in processing [151]. These reductions align with global decarbonization goals and support carbon credit mechanisms like the Clean Development Mechanism (CDM), where certified emission reduction (CER) credits can be earned, as demonstrated in Brazilian studies [152].

Raw material savings

SCBA, a byproduct of sugarcane processing, reduces the demand for virgin raw materials in cement and ceramic production, promoting resource conservation [163]. Globally, cement production consumes over 4 billion tons of raw materials annually, including limestone and clay. By substituting 10–20% of cement with SCBA, the need for limestone extraction is reduced, preserving natural resources and minimizing environmental degradation from mining. In ceramics, SCBA can replace quartz due to its high silica content (up to 76.3%), reducing reliance on mined silica sources [164]. For example, incorporating 5 wt.% SCBA in brick formulations has been shown to maintain mechanical properties while reducing raw material use by 3–10%. Furthermore, diverting SCBA from landfills avoids disposal costs (e.g., USD 53.72/ton in the U.S.) and mitigates land and water pollution, enhancing circular economy practices [165]. The abundant availability of SCBA,

with Brazil alone producing over 2.5 million tonnes annually, underscores its potential as a sustainable feedstock for large-scale applications [32].

Industrial prospects and steps for Large-Scale Production
Challenges to overcome

1. *Variability in composition*: SCBA's chemical composition varies significantly due to differences in sugarcane origin, burning conditions (temperature and duration), and regional soil properties [166]. Silica content ranges from 59.2% to 87.7%, with some samples containing high levels of unburnt carbon or crystalline silica, reducing pozzolanic activity [167]. This variability complicates consistent performance in cement and ceramics.
2. *Processing requirements:* Raw SCBA often contains fibrous particles and unburnt carbon, requiring sieving, grinding, and calcination to enhance pozzolanic properties [168]. For instance, grinding SCBA to a fineness comparable to cement (e.g., 45 min in a ball mill) increases its reactivity but adds processing costs.
3. *Lack of standardization:* The absence of universal standards for SCBA use in cement and ceramics hinders industrial adoption. While ASTM C618 specifies requirements for pozzolanic materials, SCBA's variable composition often fails to meet these criteria without preprocessing, limiting its acceptance compared to established SCMs like fly ash or slag [169,170].
4. *Long-Term Performance Data:* Limited studies on the long-term durability of SCBA-blended materials, particularly under aggressive environments (e.g., chloride or sulfate exposure), create uncertainty for industrial applications.

Steps for scaling up production
Standardized processing protocols:

Develop consistent preprocessing methods, such as controlled burning at 700–900 °C to minimize carbon content and ensure amorphous silica formation. Sieving through a 200 sieve (75 μm) and milling to achieve a specific surface area comparable to cement (per ASTM C204) should be standardized [171].

Implement quality control measures to monitor SCBA's chemical and physical properties, ensuring compliance with standards like ASTM C618, which requires a minimum strength activity index of 75% [172].

Regional pilot projects:

Establish pilot plants in major sugarcane-producing regions (e.g., Brazil, India, Thailand) to test SCBA integration at semi-industrial scales. These projects can validate optimal replacement levels (10–20% for cement, 5–20% for ceramics) and assess economic feasibility [173]. For example, Brazil's 2.5 million tonnes of SCBA could replace 6% of its cement production.

Collaborate with local sugar industries to streamline SCBA collection and processing, reducing transportation and landfill costs [174].

Development of industry standards:

Work with standardization bodies (e.g., ASTM, ISO) to create specific guidelines for SCBA as an SCM, addressing acceptable ranges for silica content, loss on ignition (LOI), and particle size [175]. This would enhance industrial confidence and facilitate regulatory approval.

Compare SCBA's performance with established SCMs like fly ash and slag to build trust, as demonstrated in studies showing SCBA's comparable or superior pozzolanic activity at 10–20% replacement [169].

Investment in processing infrastructure:

Invest in scalable grinding and calcination equipment to handle large volumes of SCBA. For instance, vibrating cup mills or ball mills can achieve the required fineness for industrial use [176].

Integrate SCBA processing with existing cement plant operations to reduce costs, leveraging waste heat from kilns for calcination [177].

Long-term testing and certification:

Conduct extensive durability tests (e.g., chloride penetration, sulfate resistance) over extended periods to confirm SCBA's performance in real-world conditions [178]. Studies show improved chloride resistance with ultrafine SCBA, but more data is needed for ceramics.

Pursue certifications like CDM credits to incentivize adoption, as demonstrated in Brazil, where SCBA use supports carbon credit trading under UNFCCC frameworks [179].

Supply chain integration:

Develop partnerships between sugar mills, cement manufacturers, and ceramic producers to create a reliable SCBA supply chain [180]. For example, India's sugarcane production (83.13 MT in Maharashtra alone) offers a stable SCBA source for local industries.

Address logistical challenges by optimizing transportation and storage, ensuring SCBA quality during long-distance transport or long-term storage [32].

The sustainable use of SCBA in cement and ceramics offers significant environmental benefits, including CO_2 emissions reductions of up to 12.3% and savings in raw materials like limestone and quartz [181]. However, industrial-scale adoption requires overcoming challenges related to composition variability, processing needs, and standardization. By implementing standardized processing, regional pilot projects, industry standards, infrastructure investments, long-term testing, and supply chain integration, SCBA can transition from a niche material to a widely accepted SCM, supporting sustainable construction and circular economy goals [168].

6. Disposable Plates Made from Bagasse Pulp

The use of bagasse pulp for manufacturing disposable plates and utensils offers an environmentally friendly alternative to conventional plastic and polystyrene products, widely used in events, picnics, and takeaway services [169]. Sugarcane bagasse, a lignocellulosic fibrous residue from sugarcane processing, can be transformed into non-toxic, biodegradable materials that support waste reduction. This approach also promotes the valorization of agricultural waste, contributing to the development of a zero-waste industry. The global market for biodegradable packaging, including products such as disposable plates, is projected to reach approximately $15 billion by 2027, driven by increasing consumer demand for sustainable options and tightening environmental regulations. This growth highlights the significant economic opportunity for innovative materials like bagasse pulp. The primary advantages of producing disposable utensils from bagasse pulp include biodegradability and compostability under standard conditions, which help prevent long-term plastic pollution. Typically, raw bagasse is used directly in the production of plates and cutlery, reducing the need for complex pretreatment processes. However, to meet hygiene and safety standards, additional processes such as heat treatment, agglomeration, or chemical treatments (e.g., bonding, drying, or sterilization) may be necessary. Further development of advanced chemical and biochemical methods will enhance the production of derivatives such as paper, biochemicals, and bioethanol, expanding the application scope of bagasse-based materials [170].

Schematic Diagram: Process of Manufacturing Bagasse-Based Disposable Plates
[Bagasse] → [Pulping] → [Molding] → [Processing] → [Finished Product].

6.1. Challenges and Prospects for Bagasse Pulp Plates: Strength, Safety, and Acceptability

Plastic plates manufactured from bagasse pulp typically exhibit reduced water and impact resistance in comparison to conventional plastics, necessitating treatment or the incorporation of additives [182]. It is imperative that the pulp undergoes a drying process, followed by treatment to mitigate the risk of mold growth or decomposition during storage. Compliance with local and international food safety standards necessitates the implementation of effective sterilization processes [183]. In large-scale production, it is imperative to regulate product consistency, drying time, and the quality of the bond between fibers without the use of harmful substances [184]. While these costs are generally modest, it is essential to optimize them in order to maintain competitiveness with plastics and mitigate cost escalation in the event of increased demand [185]. The adoption of biodegradable packaging is influenced by consumer perceptions and regulatory frameworks [186].

6.2. Improvement of Bagasse Pulp Plates: Reinforcement, Treatment, and Certification

In order to enhance the mechanical properties and longevity of bagasse pulp plates, a variety of approaches can be adopted [187]. The development of compositions containing natural binders or biopolymers has the potential to enhance their water and impact resistance, thereby improving their overall performance. Furthermore, the incorporation of eco-friendly surface treatments, such as hydrophobic or anti-mold coatings, has been demonstrated to enhance moisture resistance and prolong the lifespan of these materials [188]. With regard to the manufacturing process, the incorporation of advanced techniques such as extrusion, injection molding, or low-temperature compression has the potential to reduce energy consumption while enhancing the efficiency of mass production [189]. Pulp can also be valorized by creating biodegradable composites by mixing it with other biomaterials or nanomaterials, with the aim of improving their mechanical and functional performance [190]. The development of dedicated certifications that ensure food safety and biodegradability, in addition to complying with current standards, would be crucial to stimulating their commercial integration and consolidating consumer confidence [191].

6.3. Bagasse Pulp Plates: Technical and Regulatory Challenges for Sustainable Production

The utilization of bagasse pulp in the fabrication of disposable plates demonstrates evident promise with respect to sustainability, the mitigation of plastic waste, and the enhancement of agricultural value creation [192]. Nevertheless, mechanical strength, particularly in relation to moisture, persists as a substantial technical challenge. The majority of extant studies concentrate on prototypes or small-scale production, with a need for validation at an industrial scale. It is imperative that regulations and standards be revised to ensure quality, food safety, and biodegradability. Several countries have already established stringent regulations in this domain; for example, the European Union's EN 13432 standard certifies compostability and biodegradability [193,194], while Canada's CSA Z317.13 standard emphasizes safety and environmental performance for biodegradable products [195]. Similarly, Japan's Green Procurement Law encourages the use of environmentally friendly materials in packaging and food service items [195]. These examples underscore the importance of harmonized regulatory frameworks to facilitate the wider adoption of sustainable bagasse pulp plates.

7. Manufacturing Paper from Bagasse Pulp

Globally, approximately 800 million tons of sugarcane are produced annually, generating nearly 200 million tons of bagasse as a byproduct. This widespread availability makes bagasse an abundant and underutilized resource ideal for large-scale pulp production [196]. Bagasse pulp is a promising alternative to traditional wood pulp for paper production due to its renewable nature and potential cost savings [119]. Its use enhances the sustainability of the paper industry, particularly in regions where wood is scarce or degraded [197]. Bagasse residue is frequently used to manufacture recycled or lightweight paper for applications such as packaging, toilet paper, or printing paper. The production of bagasse pulp relies primarily on chemical methodologies, including soda, kraft, or sulfite, conducted in high-temperature, high-pressure digesters [198]. The soda technique, the most traditional, involves using approximately 12 to 16% sodium hydroxide at 165 °C for 15 to 18 min. Pre-shredding is essential to remove the pith, which constitutes 30–35% of the total weight, and to optimize fiber quality [199]. The fibers produced, measuring 1 to 1.2 mm, are shorter than traditional wood pulp fibers (3 mm), resulting in reduced mechanical strength, particularly in tear resistance. The pulp is commonly bleached to produce white or high-quality paper, but this process increases costs. To address this mechanical weakness, bleached or recycled conifer fibers or reinforcing agents, such as molasses, are often incorporated to improve strength and water retention capacity [200]. Papers made from bagasse pulp are primarily suited for non-structural or low-grammage applications. Although their tensile and tear strength are lower than those of wood pulp paper, their superior durability and biodegradability make them suitable for various applications [199]. These papers typically exhibit reduced tear resistance due to the predominance of shorter fibers. Water retention capacity (WRV) varies depending on the treatments applied, which affects their suitability for packaging or sanitary paper [201].

7.1. Challenges of Bagasse Pulp: Strength, Recycling, and Standardization

The presence of short and degraded fibers is a significant factor in reducing mechanical strength, particularly for high-end paper and structural applications [202]. The use of chemicals, such as soda, kraft, or sulfite, increases costs and environmental impact, particularly for liquid waste disposal [203]. Variability in pith consistency and bagasse quality, depending on season and geographical location, introduces inconsistencies into the process. The recyclability of bagasse pulp is limited due to fiber degradation, requiring additives or supplementary processes [32]. Certification for food contact or biodegradability remains unstandardized globally [204].

7.2. Optimizing Bagasse Conversion Processes for Sustainable, High-Performance Paper

Optimizing the bagasse-to-fiber conversion process is essential for developing more efficient and environmentally friendly papers [205]. Improving processing methodologies, such as shredding, bleaching, and drying, through greener, cost-effective techniques reduces the ecological footprint and enhances profitability [206]. Specifically, environmentally benign enzymatic treatments offer a promising alternative to conventional chemical methods, reducing hazardous effluents and energy consumption while improving fiber fibrillation, brightness, and surface properties [207]. Incorporating extended fibers or employing nanotechnologies, such as nanocellulose or nanoclay, is shown to enhance the mechanical strength of paper, as well as its resistance to moisture and mechanical stress [194]. Targeted chemical or enzymatic treatments can further improve fibrillation, moisture resistance, and overall durability, contributing to higher-quality products [195]. Additionally, evaluating the pith as a raw material, either as a feedstock for biochemical industries or an energy source, offers opportunities to lower production costs while

utilizing an underexploited resource [208]. Finally, studies focusing on standardization and certification of bagasse paper, particularly regarding biodegradability, food safety, and recyclability, are crucial to ensure compliance with international standards and foster greater market acceptance [209].

7.3. Bagasse-Based Paper: Eco-Design Challenges and Prospects

Although the production of paper from bagasse pulp is an eco-friendly option for many applications, it is hindered by the lower quality of short fibers, moisture sensitivity, and the need for chemical treatment [210]. Ongoing research aims to improve mechanical properties while minimizing ecological impact and enhancing economic competitiveness.

Market trends

The global demand for eco-friendly and biodegradable packaging and paper products is rising rapidly, driven by increasing consumer awareness and stricter environmental regulations [211]. The biodegradable packaging market is projected to reach over $15 billion by 2027, with a compound annual growth rate (CAGR) of approximately 7–8% [212]. This growth is supported by policies promoting sustainable materials and the shift away from plastic packaging, particularly in regions such as Europe, North America, and parts of Asia [210]. The increasing adoption of bio-based papers, including those made from agricultural residues like bagasse, reflects a broader shift toward circular economy practices [213]. Consequently, developing high-quality, cost-effective bagasse-based papers aligned with eco-design principles is a strategic focus for industry stakeholders aiming to capture this expanding market segment [214].

8. Nano-Cellulose from Bagasse

Nano-cellulose, a polysaccharide fiber derived from pure cellulose, possesses a nanometric structure (nanofibrils, nanocrystals) with excellent mechanical, optical, and barrier properties, making it ideal for composites, packaging, films, and energy storage [215]. Derived from bagasse, a byproduct containing 40–50% cellulose, nano-cellulose supports sustainable material design by recycling agricultural waste. It is produced through methods such as acid hydrolysis, ball milling, or enzymatic treatment, forming nanocrystals (NCC), nanofibrils (NFC), or microfibrils (MFC). Traditional methods often involve solvents, high costs, and environmental concerns [216]. Li et al. (2012) introduced an eco-friendly, cost-effective high-pressure homogenization (HPH) method, reducing energy use and improving dispersion in polymers [217]. Nano-cellulose enhances polymer strength, heat stability, and barrier properties and creates transparent, durable, biodegradable films with low permeability [218]. Barbosa et al. (2017) demonstrated that bagasse-derived nano-cellulose in natural rubber improves thermo-mechanical resistance and biodegradability [219]. Compatible with various polymer matrices, nano-cellulose is used in energy storage, sensors, and filter membranes due to its dimensional stability, chemical inertness, and low thermal expansion [219].

8.1. Nano-Cellulose: Technical Challenges and Industrial Issues

To enable large-scale production of nano-cellulose, developing cost-effective, environmentally sustainable, and efficient methods is essential [220]. Traditional chemical processes, such as acid hydrolysis, are effective in producing high-quality nano-cellulose but are associated with high costs, with production expenses ranging from $15– $30 per kilogram, depending on raw material and process scale [221]. These methods also pose environmental hazards due to the use of strong acids and the generation of chemical effluents requiring treatment, which increases the environmental footprint and disposal costs [222]. In contrast, mechanical or hybrid processes, such as high-pressure homogenization (HPH),

microfluidization, or enzymatic treatments, are relatively cleaner, with lower chemical usage, but still require significant energy inputs, with consumption reaching 10–20 MJ per kilogram of nano-cellulose [223]. While these methods reduce chemical waste, they require further optimization to achieve uniform dispersion and consistent quality, which impacts the performance of resulting composites [224]. Ensuring surface compatibility within polymer matrices is a key challenge in industrial applications; this often necessitates surface modification treatments or coupling agents, such as silanes or surfactants, which add to manufacturing costs and complexity. Additionally, nano-cellulose must retain its properties under processing conditions—resistance to moisture, heat, and mechanical stress remains critical, especially for applications in energy storage, packaging, or biocomposites [225]. From a regulatory perspective, current standards for nanomaterials are still evolving. Clear guidelines on toxicity, biodegradability, and stability are urgently needed, particularly for applications involving food contact or energy storage. Existing regulations in regions like the European Union and the United States focus on nanomaterial safety assessment but lack specific standards for nano-cellulose, creating uncertainties that hinder large-scale commercialization [226]. Finally, the high costs associated with nano-scale production, often 10–50 times higher than traditional cellulose processing, pose a significant barrier to industrial adoption [227]. Overcoming this obstacle requires innovations in processing technology, economies of scale, and standardized regulatory frameworks to ensure safety and environmental sustainability [228].

8.2. Sustainable Production and Integration of Nano-Cellulose in Composites

The integration of nano-cellulose into composites is essential for developing high-performance, eco-friendly materials [228]. Cost-effective, solvent-free manufacturing methods—such as mechanical, enzymatic, or heat-assisted processes—minimize environmental impact and reduce costs [229]. Optimizing nano-cellulose dispersion within polymer matrices, using surfactants, compatibilizers, or surface treatments, enhances interfacial adhesion and compatibility [230]. Surface modification techniques, including silane-based agents (e.g., aminosilanes, alkylsilanes) for covalent or hydrogen bonding and titanate or zirconate coupling agents for thermal stability, are critical for uniform dispersion and strength in hydrophobic polymers [231,232]. Compatibilizers, such as maleic anhydride-grafted polypropylene (PP-g-MA), bridge hydrophilic nano-cellulose and hydrophobic polymers, while surfactants, such as fatty acids or alkylamines, reduce surface tension and prevent agglomeration [233,234]. Enzymatic modifications or acetylation improve moisture resistance by altering hydroxyl groups [231]. These treatments enhance compatibility and stability for applications, such as sensors and filtration, but must align with green chemistry principles using non-toxic, biodegradable agents [132]. Eco-friendly strategies and effective compatibilizers are vital for leveraging nano-cellulose in sustainable, durable materials for energy, health, and environmental applications.

8.3. Bagasse Nanocellulose: Challenges and Prospects for the Industry

Converting bagasse to nano-cellulose holds significant promise for a wide range of applications, including composites, packaging, and energy storage systems [132]. Nevertheless, several key challenges must be addressed to realize its full industrial potential. Firstly, reducing production costs is critical, which can be achieved by developing cost-effective extraction methods, such as mechanical, enzymatic, or hybrid approaches, that lower energy consumption and minimize chemical use while maximizing yield and quality [235]. Secondly, establishing standardized, flexible protocols is crucial to ensure consistent nanoscale properties, such as size, shape, and durability, thus facilitating quality control, certification, and broader industrial adoption [236]. Thirdly, developing universal safety standards

and certifications—covering toxicity, biodegradability, and recyclability—is imperative to ensure regulatory compliance and promote the use of nano-cellulose in food contact applications and other sensitive sectors [145]. Finally, fostering the development of local value chains in bagasse-producing countries, such as those in Latin America, Asia, and Africa, can stimulate economic growth, reduce reliance on imports, and support sustainable resource use, creating an integrated and robust industrial ecosystem for nano-cellulose [237].

9. Biochemicals from Bagasse

In addition to the biochemical method, involving acid hydrolysis and fermentation, a thermomechanical route can produce various chemical products from bagasse, including succinic acid, furfural, lignosulfonates, vanillin, bioethanol, enzymes, and oligosaccharides [238].

9.1. Succinic Acid

Succinic acid ($C_4H_6O_4$) plays a pivotal role in green chemistry, serving as a raw material for synthesizing polymers, solvents, and pharmaceutical products [239]. The biochemical conversion of bagasse, a byproduct of sugarcane processing, offers a sustainable alternative. This method involves preliminary treatment of lignocellulose, followed by fermentation using microorganisms such as Actinobacillus succinogenes, Mannheimia succiniciproducens, or recombinant Escherichia coli [239]. Lignin, typically isolated at the end of the process, can be used as a biofuel. The synthesis of succinic acid is closely linked to fermentation conditions, including pH, temperature, sugar content, and nitrogen source. Research indicates that optimizing co-fermentation of hexose and pentose sugars improves efficiency [240,241]. Genetic engineering of microorganisms to enhance tolerance to inhibitors, combined with xylose use, represents an emerging trend [242]. However, yields remain limited, typically exceeding 50%.

9.2. Furfural

As shown by Yazdizadeh et al. (2016), furfural is produced through xylose dehydration following hemicellulose hydrolysis [243]. Furfural is a key component in manufacturing solvents, additives, and fuels [244]. The conventional approach uses dilute acids (H_2SO_4, HCl), but this generates toxic byproducts and causes corrosion [245]. Alternative catalyst-free methods, such as hydrothermal or microwave processes, and nanostructured catalysts, like graphene or metal oxides, are being explored to optimize yields [245]. Yields vary significantly, ranging from 20 to 50%, depending on conditions. Inhibitor formation and product decomposition pose significant challenges. Improving catalyst cost and stability is essential.

9.3. Lignosulfonates from Lignin

Ramnani et al. (2005) produced lignosulfonates by sulfonating the liquor from alkaline digestion of bagasse [246]. This water-soluble product exhibits surfactant, dispersant, and binding properties, finding applications in water treatment, construction, and agriculture [196]. Lignin, a byproduct of the process, is often underutilized.

9.4. Vanillin from Lignin

Qi et al. (2019) demonstrated that oxidizing lignin from bagasse yields vanillin, an aromatic compound ($C_8H_8O_3$) used in food flavoring and as a pharmaceutical intermediate [247]. The reaction occurs at elevated temperatures in the presence of oxygen, followed by purification through extraction [248]. Converting lignin from bagasse to vanillin supports green chemistry principles. However, the process faces challenges, including low yields (generally < 30%), high purification costs, and ongoing development. Producing chemicals like succinic acid, furfural, lignosulfonates, and vanillin from lignocellulose

expands the range of bagasse-derived bioproducts. Most processes are at technological readiness levels (TRL) 4–5, nearing industrial standards [249]. Yields are often modest, with costs, waste management, inhibitors, and toxic byproducts posing significant challenges [250]. Modulating decomposition or conversion reactions, particularly for vanillin and furfural, remains a challenge [251]. Ongoing research focuses on optimizing catalyst stability and large-scale process control. Industrial scale-up faces obstacles related to regulatory challenges and product standardization [252].

9.5. Integrated Biomass Valorization: Challenges and Strategies for Sustainable Chemical Production

Enhancing the stability and selectivity of catalysts used in xylose-to-furfural conversion is critical for process optimization [253]. Biotechnology can play a key role in developing efficient, inhibitor-resistant microorganisms for producing succinic acid or vanillin [232]. Optimizing the integrated valorization of lignin, pentoses, and glucose maximizes the use of biomass fractions, improving overall profitability. Integrating pretreatment, catalytic reactions, and purification with mixed techniques enhances process viability and competitiveness while accounting for economic factors [2]. Converting bagasse into succinic acid, furfural, lignosulfonates, and vanillin offers a promising avenue for the bioeconomy [233]. However, technological and economic challenges must be addressed to ensure long-term industrialization. Research should prioritize increasing productivity, improving process reliability, reducing costs, and mitigating environmental impact within controlled parameters [254].

9.6. Bioethanol from Bagasse, Sugarcane Tops and Molasses

Bioethanol production from sugarcane bagasse, tops, and molasses involves saccharification, fermentation, and distillation, offering a renewable fuel alternative [255]. Acid hydrolysis breaks down lignocellulose into fermentable sugars but generates inhibitors that reduce efficiency, while enzymatic hydrolysis targets cellulose and hemicellulose, producing fewer inhibitors at higher costs [256,257]. Fermentation typically uses conventional yeast for glucose, with specialized strains required for xylose to enhance overall yield [258]. Key challenges include optimizing sugar conversion, minimizing inhibitors, overcoming structural barriers like lignin, and managing costs and regulatory hurdles related to bioenergy certification, waste management, and emissions.

9.6.1. Optimizing the Valorization of Polysaccharides: Challenges and Industrial Prospects

Enzymatic hydrolysis and purification are costly, and efficient fermentation of pentose sugars remains challenging [259]. Understanding and mitigating inhibitor formation during pretreatment is critical for improving process efficiency. Robust microorganisms capable of withstanding industrial conditions are essential for process viability. High initial investment and adherence to stringent regulatory standards are necessary for sustainable industrial-scale production.

9.6.2. Integrated Biotechnologies for the Sustainable Recovery of Lignocellulosic Biomass

Developing microorganisms, such as genetically modified yeasts or bacteria, capable of fermenting both glucose and xylose while resisting inhibitors is a key research priority [260]. Refining pretreatment techniques, such as low-temperature hydrolysis or combined extraction methods, can reduce inhibitor production. More efficient, cost-effective, and resilient enzymes are needed to enhance process performance [125]. Integrating hydrolysis and fermentation into a continuous process could streamline operations and reduce costs. Comprehensive recovery of co-products, like lignin and organic acids, is essen-

tial for economic viability, supported by life-cycle assessments to ensure ecological and economic sustainability.

9.6.3. Production of Bioethanol from Bagasse: Technological Challenges and Industrial Prospects

Bioethanol from bagasse and sugarcane byproducts holds significant potential, particularly in regions with abundant feedstock. However, managing inhibitors from pretreatment, improving xylose fermentation efficiency, and controlling costs are critical challenges. Advances in biotechnology, process engineering, and enzyme development are necessary to enhance competitiveness and enable sustainable industrial-scale production.

9.7. Enzymes Produced from Sugarcane Bagasse

The enzymatic processing of sugarcane bagasse focuses on microorganisms producing enzymes, such as cellulases, xylanases, hemicellulases, lignases, and esterases, crucial for lignocellulose breakdown in bioenergy and biomaterial production. These enzymes enable efficient bioconversion, but large-scale production remains challenging due to high costs and the need for thermal stability and pH optimization. Diverse enzyme mixtures adapt to bagasse's unique composition, enhancing decomposition. Advances in biotechnology and fermentation improve enzyme productivity and consistency. On-site enzyme production during fermentation or pretreatment supports cost-effective processes. However, regulatory frameworks, quality control, and cultivation costs limit standardization and efficiency in industrial applications.

9.7.1. Enzymatic and Biotechnological Optimization for the Industrial Production of Biocatalysts

To enhance their efficacy in industrial contexts, refining microbial strains and enzyme combinations is essential to improve decomposition potential. Additionally, integrating genetic engineering, large-scale fermentation, and on-site production improves cost-effectiveness and production economics. Optimizing enzyme formulations enhances their stability and reusability in industrial processes. Standardizing production, purification, and formulation processes is crucial to comply with legal standards, ensuring enzyme quality and safety.

9.7.2. Thermostable Enzymes and Co-Cultures: Innovations for Integrated Biomass Degradation

Developing thermostable enzymes resistant to inhibition is critical to improving efficiency in industrial contexts. Engineering high-productivity microorganisms or using co-culture systems can enhance enzyme production. Developing advanced enzyme cocktails for the simultaneous degradation of cellulose, hemicellulose, and lignin is a priority to improve overall process efficiency. Additionally, integrating nanotechnology techniques can significantly enhance enzyme efficiency. Large-scale, cost-effective enzyme production lines are essential to ensure commercial viability and competitiveness.

9.7.3. Enzyme Production from Bagasse: Challenges and Prospects for Industrialization

Enzyme production from bagasse is a pivotal stage in its biotechnological valorization. Despite significant research advancements leading to effective strains and cocktails, primarily in academic settings, industrialization is hindered by costs, stability, and standardization. Advances in genetic engineering, bioproduction, and expertise in formulation and regulation are crucial for effectively utilizing these enzymes in the bioeconomy.

9.8. Oligosaccharides Produced

Oligosaccharides are bioactive precursors with applications in nutrition, health, environmental chemistry, and biotechnology. Producing these materials from bagasse primarily involves pretreatment techniques designed to disrupt the complex polysaccharide structure, thus breaking it into shorter chains. Various techniques have been explored, including alkaline hydrolysis, steam auto-hydrolysis, and specific enzymes.

9.8.1. Pre-Treatment Methods and Experimental Results

Applying the alkaline method with the fungus Thermoascus aurantiacus yields a conversion rate consistently exceeding 37%. This straightforward process leverages the fungus's inherent enzymatic activity, promoting integrated valorization. Combining the alkaline approach with Pichia stipitis yeast provides an economical solution; however, conversion is limited to about 32%, requiring additional procedures to improve yield. High-temperature steam hydrolysis, without enzymes, yields less and may produce inhibitory compounds. Variable conversion rates highlight the need for meticulous control over processing conditions. Toxic or inhibitory byproducts, such as furfural and acetaldehyde, limit the recovery of oligosaccharides. Industrialization faces challenges, including scalability, enzyme and chemical agent stability, and financial constraints. Achieving conversion rates >40% is critical for industrial competitiveness.

9.8.2. Optimization of Bagasse Pre-Treatment and Enzymatic Degradation Processes: Strategies for Sustainable Industrial Valorization

Enhancing pretreatment conditions, including time, temperature, and chemical agent concentration, is essential to optimize conversion while minimizing inhibitor production. Developing or isolating thermotolerant enzymes is crucial for improving degradation efficiency. Using integrated methodologies, such as simultaneous hydrolysis and fermentation or extraction techniques, enhances biomass valorization. Biotechnology offers a promising strategy to increase the resilience of microbes or enzymes to inhibitory byproducts. Implementing life-cycle analysis is vital to improve overall sustainability. Converting bagasse into oligosaccharides holds significant potential due to its benefits [261]. However, current yields, ranging from 28 to 37%, are relatively low. While steam or alkaline hydrolysis is simple, improving its efficiency is critical for industrial competitiveness. Key challenges include variable experimental conditions, inhibitory compounds, and the need for scale control. Research should prioritize optimizing conditions, advancing enzymatic processes, and integrating innovative approaches to increase productivity and reduce costs [262].

10. Bioelectricity from Bagasse and Cane Residues

Sugarcane bagasse is widely used for energy production in Brazil, India, and Thailand through cogeneration, pyrolysis, gasification, and bioethanol production, promoting energy independence and reducing greenhouse gas emissions [263]. These methods enhance sugar mill profitability and lower carbon footprints. Cogeneration and combustion achieve 30–40% energy efficiency, but high investment costs for gasification and pyrolysis infrastructure limit profitability, especially in capital-scarce regions. Managing co-products, such as biochar and tar, requires careful planning for environmental sustainability. Bagasse quality, particularly its moisture and composition, significantly affects energy yields. Strict regulatory compliance is essential to control emissions and ensure safety, while seasonal and geographical variability challenges industrial planning.

10.1. Mixed Thermochemical Technologies for the Sustainable Recovery of Bagasse

Developing mixed technologies combining pyrolysis, gasification, and fermentation is essential for optimizing the valorization of products, such as bioethanol, biochar, and biogas, derived from bagasse [264]. Optimizing the management of byproducts, particularly using biochar as an agricultural amendment or absorbent while minimizing deleterious tar formation during pyrolysis, is crucial. Incorporating these methodologies into biorefineries can facilitate systems where energy, biofuels, and high-value products are used simultaneously, thus ensuring optimal biomass exploitation. Developing advanced catalysts and efficient reactors is critical to enhance productivity, reduce energy consumption, and control the formation of scale or inhibitors [241]. These factors collectively improve overall sustainability. Finally, sustainable management, governed by rigorous criteria for emissions, safety, and waste recycling, is essential to secure regulatory and ecological approval while ensuring responsible use of these technologies.

10.2. Bagasse Energy Optimization: Challenges and Industrial Prospects

Using bagasse as an energy source is a stable sector, yet it has yet to be fully optimized [242]. The technological sophistication of steam boiler and cogeneration systems is demonstrated by the proliferation of industrial projects employing these technologies. However, expanding into pyrolysis, gasification, and bioethanol production poses significant technological and financial challenges. Research should focus on improving yields, reducing costs, and managing co-products effectively. These efforts are instrumental in facilitating a transition to a more sustainable and circular bioeconomy. Table 2 comprehensively outlines the advantages, disadvantages, Technology Readiness Levels (TRL), and cost estimates for various sugarcane bagasse applications, including adsorbents, composites, ash, biochemicals, bioethanol, enzymes, oligosaccharides, and bioelectricity, highlighting their sustainability potential and technical challenges. Figure 3, generated using the Matplotlib library in Python, visualizes the TRL and estimated costs for these applications, as outlined in Table 2, providing a clear comparison of their developmental stages and economic viability. Figure 3 It offers a comprehensive breakdown of sugarcane bagasse applications, showcasing its multifaceted utilization across industries, such as bioenergy, agriculture, and manufacturing, in 2024. Figure 4 offers a detailed comparison of cost ranges across various sugarcane bagasse usage categories, highlighting economic variations in its industrial applications for 2024.

Table 2. Sugarcane Bagasse (SCB) Applications with Precise Cost Estimations.

Usage Category	Advantages	Disadvantages	TRL	Estimated Costs	References
Adsorbents: Chemical/Physical Bioadsorbents	Low cost, recyclable, effective for metals/dyes	Requires chemical treatment, limited regeneration	3–4	0.5–2 $/kg (chemicals: 0.3–1 $/kg; processing: 0.2–1 $/kg)	[112,265]
Adsorbents: Activated Carbon	High surface area (536.5 m^2/g), thermal stability	High production/energy costs	4–5	1–3 $/kg ($H_3PO_4$ activation: 0.5–1.5 $/kg; steam: 0.5–1.5 $/kg)	[66,114]
Adsorbents: Ion Exchange Resins	Good selectivity, regenerable	Manufacturing complexity	3–4	2–5 $/kg (resin synthesis: 1–3 $/kg; equipment: 1–2 $/kg)	[266]
Adsorbents: Nanocatalysts/Zeolites	High efficiency, versatile (catalysis/adsorption)	Synthesis costs, scalability issues	3	5–10 $/kg (nanomaterial synthesis: 3–7 $/kg; energy: 2–3 $/kg)	[109]
Adsorbents: Biochar (Soil/Carbon Sequestration)	Improves soil fertility, sequesters carbon	Variable yield, production costs	3–4	200–500 $/tonne ($0.22–0.55 $/kg; pyrolysis: 100–300 $/tonne)	[267]

Table 2. *Cont.*

Usage Category	Advantages	Disadvantages	TRL	Estimated Costs	References
Adsorbents: Biochar (Solid Fuel/Energy)	Renewable energy source, syngas production	Lower energy density, requires pretreatment	3–4	0.3–0.8 $/kg (pyrolysis: 0.2–0.5 $/kg; drying: 0.1–0.3 $/kg)	[268]
Adsorbents: Biochar (Electrochemistry/Filtration)	High conductivity, desalination potential	Needs treatment, variable costs	3–4	1–5 $/kg (functionalization: 0.5–3 $/kg; equipment: 0.5–2 $/kg)	[32]
Composites: Flexible Packaging	Eco-friendly, customizable, lightweight	Limited mechanical/barrier properties	3–4	0.5–1.5 $/kg (pulp processing: 0.3–0.8 $/kg; additives: 0.2–0.7 $/kg)	[126]
Composites: Non-Structural Applications	Biodegradable, low cost	Unsuitable for high mechanical loads	3–4	0.4–1 $/kg (pulp: $0.2–0.5 $/kg; molding: 0.2–0.5 $/kg)	[130]
Composites: Reinforced Thermoplastics	Good strength, thermal stability with additives	Reduced stability without additives	3–4	1–2.5 $/kg (PLA matrix: 0.7–1.5 $/kg; additives: 0.3–1 €/kg)	[165,269]
Composites: Nanocomposites	Improved stability, barrier properties	High costs, dispersion challenges	3	3–8 €/kg (nanoclay/graphene: 2–5 $/kg; processing: 1–3 $/kg)	[143,144]
Ash: Partial Cement Substitute	Reduces emissions, valorizes waste	Reduced strength at high substitution (>30%)	3–4	0.1–0.3 $/kg (grinding: 0.05–0.15 $/kg; transport: 0.05–0.15 $/kg)	[163,165]
Ash: High-Temperature Ceramic Additive	Resists 1600 °C, good insulation	Requires pretreatment, limited compatibility	3–4	0.5–1.5 $/kg (calcination: 0.3–0.8 $/kg; blending: 0.2–0.7 $/kg)	[157]
Ash: Polymer/Glass Composite Filler	Enhances thermal resistance, durability	Dispersion challenges, treatment costs	3	1–3 $/kg (surface treatment: 0.5–1.5 $/kg; mixing: 0.5–1.5 $/kg)	[144,270]
Disposable Plates: Utensils	Eco-friendly, biodegradable, low cost	Lower strength, hygroscopic, needs drying	3–4	0.3–0.8 $/kg (pulp: 0.2–0.5 $/kg; molding/drying: 0.1–0.3 $/kg)	[196]
Paper: Packaging/Hygienic	Renewable, biodegradable, low-cost pulp	Lower strength, shorter fibers	3–4	0.5–1.2 $/kg (soda pulping: 0.3–0.7 $/kg; bleaching: 0.2–0.5 $/kg)	[230,232,271]
Paper: Printing/High-Quality	Affordable, local use	Low tear resistance, poor for thin paper	2–3	0.4–1 $/kg (pulping: 0.3–0.6 $/kg; additives: 0.1–0.4 $/kg)	[214]
Paper: Recycled/Composite	Valorizes recycling, improved mechanics	Fiber degradation, additive needs	3	0.5–1.5 $/kg (recycling: 0.3–0.8 $/kg; additives: 0.2–0.7 $/kg)	[215]
Biochemicals: Succinic Acid	Sustainable, versatile for polymers/pharma	Low conversion (<50%), inhibitor issues	4–5	2–5 $/kg (fermentation: 1–3 $/kg; purification: 1–2 $/kg)	[272,273]
Biochemicals: Furfural	Key for solvents/fuels, 20–50% yield	Toxic byproducts, catalyst stability	4–5	1.5–4 $/kg (hydrolysis: 1–2.5 $/kg; catalysts: 0.5–1.5 $/kg)	[274,275]
Biochemicals: Lignosulfonates	Water-soluble, surfactant/dispersant	Underutilized lignin byproduct	4–5	0.8–2 $/kg (sulfonation: 0.5–1.2 $/kg; purification: 0.3–0.8 $/kg)	[212,276]
Biochemicals: Vanillin	Food/pharma use, green chemistry	Low yield (<30%), high purification cost	4–5	10–20 $/kg (oxidation: 5–10 $/kg; purification: 5–10 $/kg)	[277,278].
Bioethanol	Renewable fuel, easy storage	Inhibitor formation, high enzyme costs	3–4	0.8–2 $/L (enzymes: 0.4–1 $/L; fermentation: 0.4–1 $/L)	[279–281]
Enzymes: Cellulases	Robust, well-studied for cellulose breakdown	High costs, byproduct inhibition	4	10–20 $/kg (fermentation: 7–14 $/kg; purification: 3–6 $/kg)	[20,282]

Table 2. *Cont.*

Usage Category	Advantages	Disadvantages	TRL	Estimated Costs	References
Enzymes: Hemicellulases	Enhances hemicellulose degradation	Limited industrial expression	3–4	5–15 $/kg (fermentation: 3–9 $/kg; purification: 2–6 $/kg)	[283]
Enzymes: Lignases/Esterases	Facilitates lignin breakdown	Low stability in industrial settings	3	8–18 $/kg (fermentation: 5–11 $/kg; purification: 3–7 $/kg)	[284]
Enzymes: Accessory Enzymes	Optimizes degradation process	Production needs improvement	3–4	5–15 $/kg (fermentation: 3–9 $/kg; purification: 2–6 $/kg)	[285,286]
Oligosaccharides: Alkaline + Pichia stipitis	Simple, low-cost, biorefinery-compatible	Moderate conversion (31.8%), purification needs	3	1–3 $/kg (alkaline treatment: 0.5–1.5 $/kg; fermentation: 0.5–1.5 $/kg)	[257]
Oligosaccharides: Alkaline + Thermoascus aurantiacus	Higher efficiency (37.1%)	Long duration, high energy costs	3	1.5–4 $/kg (alkaline treatment: 0.7–2 $/kg; fermentation: 0.8–2 $/kg)	[258]
Oligosaccharides: Steam Auto-Hydrolysis	Enzyme-free, easy integration	Low yield (28%), inhibitory byproducts	3	2–5 $/kg (hydrolysis: 1.5–3.5 $/kg; purification: $0.5–1.5/kg)	[280]
Bioelectricity: Cogeneration	Reliable, reduces fossil fuel use	Pollution if uncontrolled, limited efficiency	4–5	1000–2000 $/kW (initial: 800–1500 $/kW; operational: 200–500 $/kW)	[287,288],
Bioelectricity: Pyrolysis	Produces biochar, bio-oil, gases	Variable yields, byproduct management	3–4	0.5–1.5 $/kg (pyrolysis: 0.3–0.9 $/kg; byproduct handling: 0.2–0.6 $/kg)	[24,62]
Bioelectricity: Gasification	Flexible syngas for engines/turbines	Tar formation, high maintenance	3–4	500–1000 $/kW (equipment: 400–800 $/kW; maintenance: 100–200 $/kW)	[289]
Bioelectricity: Bioethanol Fermentation	Renewable fuel, storable	Inhibitor issues, high costs	3–4	0.8–2 $/L (enzymes: 0.4–1 $/L; fermentation: 0.4–1 $/L)	[290,291]
Bioelectricity: Bio-oil/Bio-huile	Biofuel, agricultural residues	Variable yields, high processing costs	3	0.6–1.8 $/kg (pyrolysis/HTC: 0.4–1.2 $/kg; purification: 0.2–0. 6 $/kg)	[74,101,282]

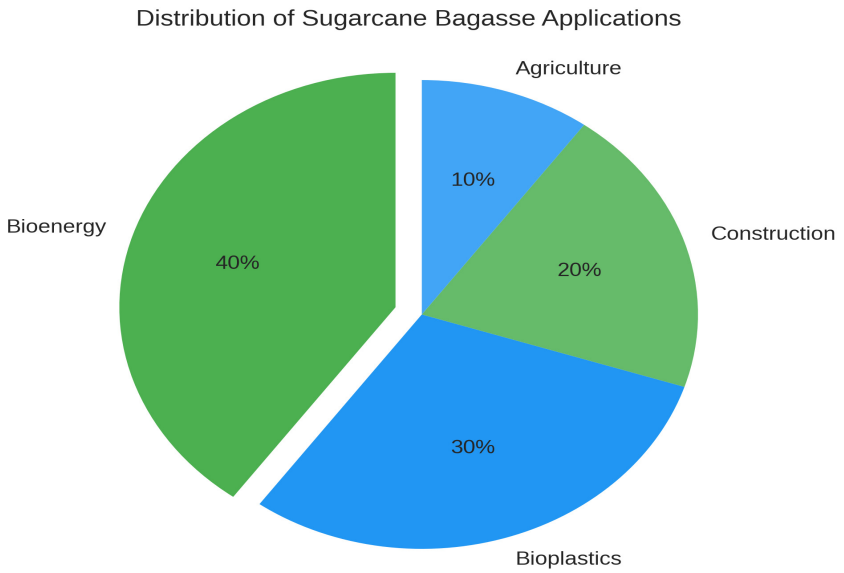


Figure 3. Distribution of sugarcane bagasse applications.

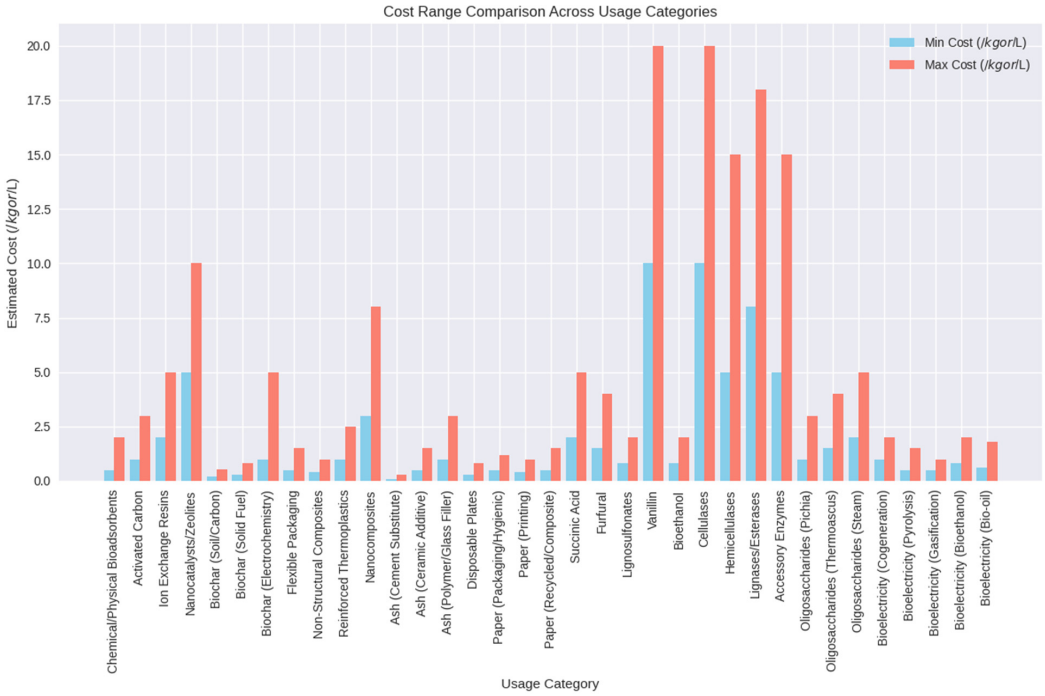


Figure 4. Cost range comparison across usage categories.

This graphical summary strengthens the manuscript's presentation, facilitating better understanding for researchers, stakeholders, and policymakers on SCB's role in sustainable development. Figure 5 illustrates the diverse applications of sugarcane bagasse and its derived products, encompassing bioenergy, bioplastics, animal feed, paper production, and construction materials.

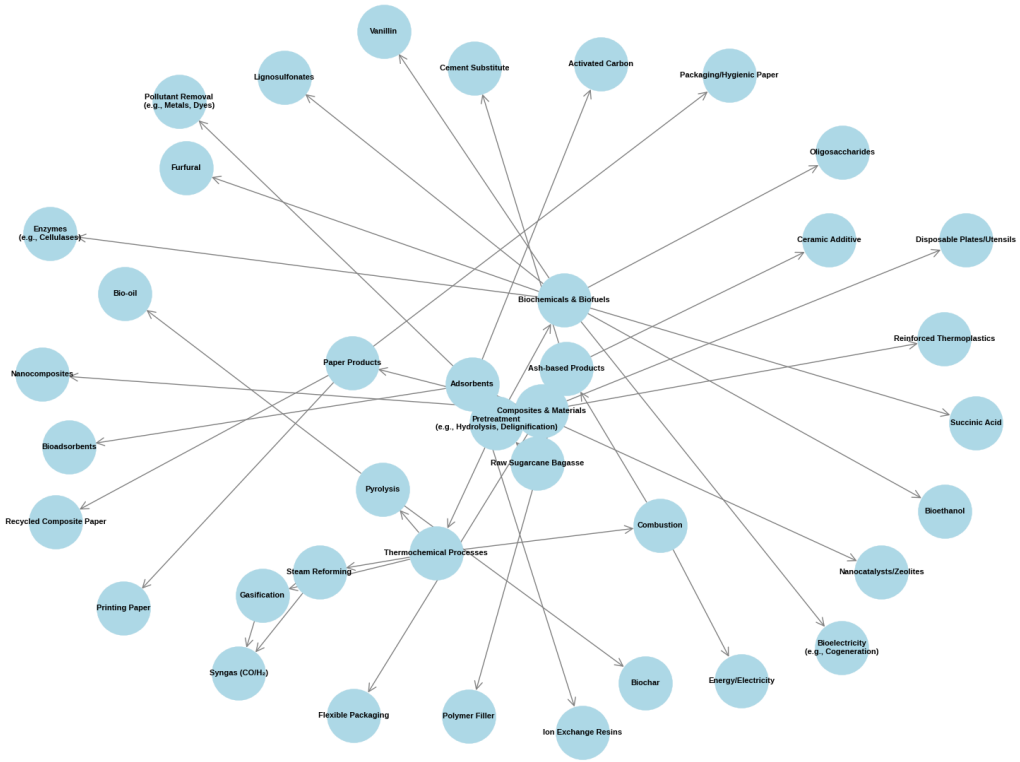


Figure 5. Applications of Sugarcane Bagasse and Derived Products.

11. Technical-Economic Analysis

The prevailing wisdom in the field is that bagasse is an economically viable resource that has applications in bioenergy, eco-friendly chemistry, and power generation. Profitability is closely linked to the specific context, initial investments, consumer markets, and legislation. The sector is poised for significant advancements in combustion and cogeneration, as evidenced by the current state of several industrial projects. The diversification of applications (electricity, bioethanol, biochar, gas) is a key factor in enhancing economic optimization, with the caveat that the local context must be taken into account. The evaluation of residues (e.g., straw, leaves, and pith) and by-products (e.g., biochar, gas, and oils) has been demonstrated to enhance overall profitability. The thermochemical conversion (i.e., combustion, pyrolysis, and gasification) is typically limited to 30–40%, which restricts its economic viability. The implementation of advanced technologies, such as gasification and advanced pyrolysis, necessitates the acquisition of costly equipment that is challenging to amortize, particularly in regions characterized by low purchasing power. The recovery and disposal of bio-oil, bio-tar, and bio-char must be conducted in accordance with specific protocols to ensure environmental safety and sustainability. The regulation of emissions, particularly in the context of combustion or pyrolysis, entails the imposition of supplementary expenses associated with environmental control measures. The quality of bagasse is contingent upon factors such as season, moisture content, and composition, which complicates the development of industrial plans [292]. The fluctuating market prices of electricity, fuel, or carbon credits can significantly influence long-term profitability. The comparative analysis highlights the benefits of sugarcane bagasse due to its low ash content and high cellulose, making it a flexible feedstock for bioethanol, bioenergy, and biocomposites [36]. Although rice straw and husks face challenges with higher ash content, they present distinct opportunities for silica-based applications. The balanced characteristics of wheat straw support various biorefinery pathways. Incorporating these residues into sequential biorefinery systems, where bagasse emphasizes bioethanol and energy production, rice residues are aimed at creating adsorbents, and wheat straw is dedicated to biogas, can enhance resource efficiency and align with sustainable development objectives [32]. This comparison emphasizes the supportive functions of agricultural residues in sustainable valorization. Subsequent studies should concentrate on enhancing pretreatment techniques and creating comprehensive biorefinery frameworks to maximize the potential of these resources [37].

11.1. Mixed Technologies for Sustainable Biomass Recovery: Optimization and Management of Co-Products

The development of improved biomass valorization methods involves the integration of diverse technologies, such as pyrolysis, gasification, fermentation, and integrated cogeneration. The objective of this integration is to enhance the performance and diversify the range of products derived from these processes. Furthermore, the effective management of co-products is imperative. For instance, biochar can be utilized as a fertilizer or an absorbent, while tar can be converted into a raw material for the production of catalysts or biochemicals. This approach fosters the development of a circular economy. It is imperative to persist in the enhancement of our technological aptitude in gasification and pyrolysis units, across both modest and substantial scales, to ensure their stability, reliability, and profitability. These attributes are paramount for their successful integration into industrial applications.

The integration of these methodologies within bioprocesses facilitates the establishment of production chains wherein the generation of energy, biofuels, and high-value-added products coexist, thereby promoting diversification of revenue sources and economic stabil-

ity. Finally, the enhancement of environmental standards, particularly with respect to the reduction in particulates, NO_x, SO_x, and the management of harmful waste, is imperative to ensure the sustainable development of these technologies. A comprehensive life-cycle assessment could facilitate the evaluation of their environmental and economic impact, thereby guiding technological decisions towards more sustainable and efficient options.

11.2. Technical and Economic Assessment of Bagasse Recovery: Industrial Opportunities and Challenges

A technical and economic analysis of bagasse exploitation reveals that it represents a key resource for the production of sustainable energy and chemicals, particularly in developing countries [293,294]. In certain contexts, electrical cogeneration has emerged as a well-established and lucrative enterprise. Conversely, second-generation processes such as pyrolysis, gasification, and fermentation continue to necessitate considerable financial investment and technological advancements to enhance their competitiveness in the market [294]. Large-scale industrialization will require a focus on varied utilization, by-product recovery, and cost control, while taking into account environmental restrictions.

Distinctive Features and Contributions of This Review

With an emphasis on recent developments (2020–2025), this review of the creative uses of sugarcane bagasse (SCB) distinguishes itself from previous research by providing a thorough, integrative analysis of SCB valorization across a variety of industries, including bioenergy, bioplastics, construction, adsorbents, and agriculture. This study synthesizes various pathways, highlighting interdisciplinary approaches and their alignment with circular economy principles, in contrast to previous reviews, such as those by Shabbirahmed et al. [125]. and Ajala et al. [295,296], which mainly focused on specific applications like bioethanol or composites. It offers a comprehensive viewpoint on scaling SCB-based innovations by combining techno-economic studies, environmental impact assessments, and regulatory concerns in a unique way. For example, this analysis examines worldwide trends, including case studies from Brazil, India, and China, which account for around 70% of global SCB output [297,298], whereas earlier research such as Konde et al. [295,296], concentrated on biorefinery potential in certain locations (e.g., India). It also discusses new topics that have not received enough attention in previous reviews, like SCB-derived nanomaterials (such as carbon dots and nanocellulose) and their uses in water treatment and sensing [299,300]. This review provides a new comparison approach by contrasting processing methods (such as gasification, pyrolysis, and enzymatic hydrolysis) with updated Technology Readiness Levels (TRLs) and cost estimations. It also fills in holes in earlier research that frequently ignored regulatory frameworks by suggesting practical policy solutions like harmonized standards (like EN 13432) and incentives like Brazil's RenovaBio. These contributions offer policymakers, industry stakeholders, and researchers a roadmap for advancing SCB valorization in a sustainable manner.

12. Future Research and Policy Implications

To fully realize sugarcane bagasse (SCB) as a renewable resource within a circular economy, future research and policy must address specific technical, economic, and environmental gaps to enable scalable and sustainable valorization. Below, we outline precise research gaps and targeted directions, alongside policy recommendations, to guide advancements in SCB utilization.

12.1. Technical Research Gaps and Directions

Gap 1: Inefficient Pretreatment Methods: Current pretreatment methods, such as acid or enzymatic hydrolysis, are energy-intensive and produce inhibitors that reduce sugar yields for biofuels and bioproducts like polyhydroxyalkanoates (PHAs) [301,302].

Research direction 1: Develop low-cost, eco-friendly pretreatment techniques, such as biological pretreatment using fungal or bacterial co-cultures, to enhance sugar recovery without generating inhibitors. Optimize enzyme cocktails for SCB's complex lignocellulosic structure to improve bioconversion efficiency and reduce energy inputs.

Gap 2: Limited Scalability of Nanomaterial Applications: SCB-derived nanomaterials, such as nanocellulose and carbon dots, show promise for sensing and water treatment but lack consistent particle size control and functionalization, hindering industrial applications [303,304].

Research direction 2: Investigate scalable synthesis methods for SCB-derived nanomaterials, focusing on precise control of particle size and surface chemistry through green chemical processes. Conduct pilot-scale studies to validate their performance in real-world applications like pollutant detection or water purification.

Gap 3: Scalability Challenges in Integrated Biorefineries: Integrated biorefineries co-producing biofuels, biochemicals, and bioplastics face issues with high moisture content and tar formation in processes like steam explosion and hydrothermal treatment, limiting scalability [305].

Research direction 3: Design modular biorefinery systems with integrated steam explosion and hydrothermal processes optimized for SCB's variable composition. Develop tar mitigation strategies, such as catalytic cracking or bio-based filtration, to enhance process stability and scalability [306].

12.2. Economic and Commercialization Gaps and Directions

Gap 1: High Costs and Feedstock Variability: Pretreatment and enzyme costs remain a significant barrier to economic viability, exacerbated by inconsistent SCB quality across regions, making cost parity with fossil-based alternatives challenging [302,303].

Research direction 1: Conduct techno-economic analyses to identify cost-reduction strategies, such as enzyme recycling systems or low-cost pretreatment alternatives. Develop standardized preprocessing protocols to normalize SCB feedstock quality, ensuring consistent yields and reducing operational costs [302,303].

12.3. Environmental and Policy Gaps and Directions

Gap 1: Limited Policy Support and Standardization: The absence of harmonized standards for SCB-derived products, such as bioplastics, and insufficient policy incentives in high-sugarcane regions like Brazil and India hinder commercialization and environmental benefits [307,308].

Research and Policy Direction 1: Establish global standards for SCB-derived bioproducts, aligning with frameworks like EN 13432 for bioplastics, to build market trust and facilitate trade. Advocate for region-specific policies, such as subsidies, tax incentives, and decarbonization credits inspired by programs like RenovaBio, to promote SCB diversion from landfills and support sustainable bioeconomies [308,309]. Foster collaborative ecosystems under initiatives like the EU Green Deal to drive innovation and scalability through public–private partnerships [309].

12.4. Integrated Strategies for Sustainable Bioeconomies

Addressing these gaps requires interdisciplinary efforts combining biotechnology, process engineering, and policy innovation. The research should prioritize pilot-scale validation of integrated biorefinery systems to confirm technical and economic feasibil-

ity under real-world conditions. The collaborative research networks should focus on developing resilient microbial strains and scalable nanomaterial production to expand SCB applications. The policy frameworks must incentivize sustainable practices, such as waste-to-resource conversion, and support standardized quality metrics to ensure market acceptance.The recent studies highlight the potential of these strategies to position SCB as a cornerstone of sustainable bioeconomies, reducing reliance on fossil resources and enhancing environmental outcomes [125].

13. Conclusions

In summary, this review highlights SCB's transformative potential as a versatile, renewable resource for bioenergy, bioplastics, adsorbents, construction materials, and agricultural applications, advancing circular economy principles through waste minimization and reduced environmental impacts. By providing a comprehensive, comparative analysis of processing technologies—unlike prior reviews that focused narrowly on individual pathways—this work underscores recent innovations, such as enhanced gasification efficiencies and nanocellulose composites, while addressing scalability and economic viability. Challenges like pretreatment optimization, regulatory gaps, and commercialization barriers persist, but opportunities for GHG reductions (40–70%) and resource savings position SCB as a cornerstone for sustainable industries.

Looking forward, advancing SCB valorization requires interdisciplinary R&D in AI-optimized processes, hybrid biorefineries, and nanotechnology to enhance yields and reduce costs. Policymakers should prioritize harmonized standards (e.g., via ISO/FAO collaborations) and incentives like carbon credits to facilitate global adoption, particularly in major producers like Brazil and India. Future research should focus on life-cycle assessments integrating climate resilience and social equity, ensuring SCB contributes to equitable, low-carbon transitions by 2030 and beyond. Ultimately, realizing SCB's full potential will drive green innovation, supporting UN Sustainable Development Goals for a resilient bioeconomy.

Author Contributions: All authors have read and agreed to the published version of the manuscript. S.N.—Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing—original draft, Visualization, Project administration; O.T.—Conceptualization, Methodology, Supervision, Resources, Writing—review and editing, Funding acquisition; Y.A.—Investigation, Software, Resources, Validation, Writing—review and editing; E.F.L.—Investigation, Validation, Resources, Writing—review and editing; L.G.—Formal analysis, Validation, Visualization, Writing—review and editing.

Funding: The research was funded by Hassan II University of Casablanca through the Ben M'Sick Faculty of Sciences.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript: SCB: Sugarcane bagasse; CAGR: Compound annual growth rate; GHG: Greenhouse gas.

References

1. Sheikhdavoodi, M.J.; Almassi, M.; Ebrahimi-Nik, M.; Kruse, A.; Bahrami, H. Gasification of sugarcane bagasse in supercritical water; evaluation of alkali catalysts for maximum hydrogen production. *J. Energy Inst.* **2015**, *88*, 450–458. [CrossRef]
2. Ajala, E.O.; Ighalo, J.O.; Ajala, M.A.; Adeniyi, A.G.; Ayanshola, A.M. Sugarcane bagasse: A biomass sufficiently applied for improving global energy, environment and economic sustainability. *Bioresour. Bioprocess.* **2021**, *8*, 87. [CrossRef] [PubMed]

3. Yin, C.-Y. Prediction of higher heating values of biomass from proximate and ultimate analyses. *Fuel* **2011**, *90*, 1128–1132. [CrossRef]
4. Ajala, E.O.; Olonade, Y.O.; Ajala, M.A.; Akinpelu, G.S. Lactic Acid Production from Lignocellulose—A Review of Major Challenges and Selected Solutions. *ChemBioEng Rev.* **2020**, *7*, 38–49. [CrossRef]
5. Lee, J.Y. Water-Food-Energy Challenges in the Face of a Growing Sugar Industry in Central India. Ph.D. Thesis, Stanford University, Stanford, CA, USA, 2024.
6. Barbosa, F.d.S.; Coelho, R.D.; Barros, T.H.d.S.; Lizcano, J.V.; Fraga Júnior, E.F.; Santos, L.d.C.; Leal, D.P.V.; Ribeiro, N.L.; Costa, J.d.O. Sugarcane water productivity for bioethanol, sugar and biomass under deficit irrigation. *AgriEngineering* **2024**, *6*, 1117–1132. [CrossRef]
7. Rizzioli, F. Recovery of Biofuels, Biobased Products and Nutrients in Agricultural Biogas Plants. Ph.D. Thesis, University of Verona, Verona, Italy, 2025.
8. Pereira, L.G.; Ramos, N.P.; Pighinelli, A.L.M.; Novaes, R.M.; Seabra, J.E.; Debiasi, H.; Hirakuri, M.H.; Folegatti, M.I. State-Level Inventories and Life Cycle GHG Emissions of Corn, Soybean, and Sugarcane Produced in Brazil. *Sustainability* **2025**, *17*, 8482. [CrossRef]
9. Karp, S.G.; Woiciechowski, A.L.; Soccol, V.T.; Soccol, C.R. Pretreatment strategies for delignification of sugarcane bagasse: A review. *Braz. Arch. Biol. Technol.* **2013**, *56*, 679–689. [CrossRef]
10. Sun, J.-X.; Sun, X.-F.; Sun, R.-C.; Fowler, P.; Baird, M.S. Inhomogeneities in the chemical structure of sugarcane bagasse lignin. *J. Agric. Food Chem.* **2003**, *51*, 6719–6725. [CrossRef]
11. Antunes, F.A.F.; Chandel, A.K.; Brumano, L.P.; Terán Hilares, R.; Peres, G.F.D.; Ayabe, L.E.S.; Sorato, V.S.; Santos, J.R.; Santos, J.C.; Da Silva, S.S. A novel process intensification strategy for second-generation ethanol production from sugarcane bagasse in fluidized bed reactor. *Renew. Energy* **2018**, *124*, 189–196. [CrossRef]
12. Cao, S.; Aita, G.M. Enzymatic hydrolysis and ethanol yields of combined surfactant and dilute ammonia treated sugarcane bagasse. *Bioresour. Technol.* **2013**, *131*, 357–364. [CrossRef]
13. Zhu, Z.; Rezende, C.A.; Simister, R.; McQueen-Mason, S.J.; Macquarrie, D.J.; Polikarpov, I.; Gomez, L.D. Efficient sugar production from sugarcane bagasse by microwave assisted acid and alkali pretreatment. *Biomass Bioenergy* **2016**, *93*, 269–278. [CrossRef]
14. Nosratpour, M.J.; Karimi, K.; Sadeghi, M. Improvement of ethanol and biogas production from sugarcane bagasse using sodium alkaline pretreatments. *J. Environ. Manag.* **2018**, *226*, 329–339. [CrossRef] [PubMed]
15. Canilha, L.; Carvalho, W.; Felipe, M.D.G.D.A.; Silva, J.B.d.A.e.; Giulietti, M. Ethanol Production from Sugarcane Bagasse Hydrolysate Using Pichia stipitis. *Appl. Biochem. Biotechnol.* **2010**, *161*, 84–92. [CrossRef] [PubMed]
16. Velmurugan, R.; Muthukumar, K. Utilization of sugarcane bagasse for bioethanol production: Sono-assisted acid hydrolysis approach. *Bioresour. Technol.* **2011**, *102*, 7119–7123. [CrossRef]
17. Veza, I.; Muhamad Said, M.F.; Latiff, Z.A. Recent advances in butanol production by acetone-butanol-ethanol (ABE) fermentation. *Biomass Bioenergy* **2021**, *144*, 105919. [CrossRef]
18. Prasad, S.D. Butanol Production from Residues of Sugar and Timber and Estimation of Butanol Production Potential in Fiji. In *School of Engineering and Physics*; University of the South Pacific Suva: Suva, Fiji, 2020.
19. Yue, T.; Jiang, D.; Zhang, Z.; Zhang, Y.; Li, Y.; Zhang, T.; Zhang, Q. Recycling of shrub landscaping waste: Exploration of bio-hydrogen production potential and optimization of photo-fermentation bio-hydrogen production process. *Bioresour. Technol.* **2021**, *331*, 125048. [CrossRef]
20. Carvalho, W.; Santos, J.; Canilha, L.; Silva, S.; Perego, P.; Converti, A. Xylitol production from sugarcane bagasse hydrolysate: Metabolic behaviour of Candida guilliermondii cells entrapped in Ca-alginate. *Biochem. Eng. J.* **2005**, *25*, 25–31. [CrossRef]
21. Borges, E.R.; Pereira, N., Jr. Succinic acid production from sugarcane bagasse hemicellulose hydrolysate by Actinobacillus succinogenes. *J. Ind. Microbiol. Biotechnol.* **2011**, *38*, 1001–1011. [CrossRef]
22. Gómez, E.O.; Cortez, L.A.B.; Lora, E.S.; Sanchez, C.G.; Bauen, A. Preliminary tests with a sugarcane bagasse fueled fluidized-bed air gasifier. *Energy Convers. Manag.* **1999**, *40*, 205–214. [CrossRef]
23. Pellegrini, L.F.; de Oliveira, S., Jr. Exergy analysis of sugarcane bagasse gasification. *Energy* **2007**, *32*, 314–327. [CrossRef]
24. Gabra, M.; Pettersson, E.; Backman, R.; Kjellström, B. Evaluation of cyclone gasifier performance for gasification of sugar cane residue—Part 1: Gasification of bagasse. *Biomass Bioenergy* **2001**, *21*, 351–369. [CrossRef]
25. Mavukwana, A.; Jalama, K.; Ntuli, F.; Harding, K. Simulation of Sugarcane Bagasse Gasification using Aspen Plus. In Proceedings of the International Conference on Chemical and Environmental Engineering (ICCEE), Johannesburg, South Africa, 15–16 April 2013; Volume 1516, pp. 70–74.
26. Dellepiane, D.; Bosio, B.; Arato, E. Clean energy from sugarcane waste: Feasibility study of an innovative application of bagasse and barbojo. *J. Power Sources* **2003**, *122*, 47–56. [CrossRef]
27. Zayer Kabeh, K.; Prussi, M.; Chiaramonti, D. Advances in Bio-Hydrogen Production: A Critical Review of Pyrolysis Gas Reforming. *Appl. Sci.* **2025**, *15*, 3995. [CrossRef]

28. Rijo, B.; Nobre, C.; Brito, P.; Ferreira, P. An Overview of the Thermochemical Valorization of Sewage Sludge: Principles and Current Challenges. *Energies* **2024**, *17*, 2417. [CrossRef]
29. Yabandeh, S.; Hajinezhad, A.; Moosavian, S.F.; Fattahi, R. Modeling and Simulation of Waste Tire-Based Power Generation System using Aspen Plus. *Results Eng.* **2025**, *28*, 107326. [CrossRef]
30. Kumar, D.; Jain, V.; Shanker, G.; Srivastava, A. Citric acid production by solid state fermentation using sugarcane bagasse. *Process Biochem.* **2003**, *38*, 1731–1738. [CrossRef]
31. Sengupta, P.; Manna, I. Advanced high-temperature structural materials in petrochemical, metallurgical, power, and aerospace sectors—An overview. *Future Landsc. Struct. Mater. India* **2022**, *1*, 79–131.
32. Hiranobe, C.T.; Gomes, A.S.; Paiva, F.F.; Tolosa, G.R.; Paim, L.L.; Dognani, G.; Cardim, G.P.; Cardim, H.P.; dos Santos, R.J.; Cabrera, F.C. Sugarcane bagasse: Challenges and opportunities for waste recycling. *Clean Technol.* **2024**, *6*, 662–699. [CrossRef]
33. Santana, H.E.; Jesus, M.; Santos, J.; Rodrigues, A.C.; Pires, P.; Ruzene, D.S.; Silva, I.P.; Silva, D.P. Lignocellulosic biomass gasification: Perspectives, challenges, and methods for tar elimination. *Sustainability* **2025**, *17*, 1888. [CrossRef]
34. Makepa, D.C.; Chihobo, C.H. Barriers to commercial deployment of biorefineries: A multi-faceted review of obstacles across the innovation chain. *Heliyon* **2024**, *10*, e32649. [CrossRef]
35. Shibukawa, V.P.; Ramos, L.; Cruz-Santos, M.M.; Prado, C.A.; Jofre, F.M.; de Arruda, G.L.; da Silva, S.S.; Mussatto, S.I.; dos Santos, J.C. Impact of product diversification on the economic sustainability of second-generation ethanol biorefineries: A critical review. *Energies* **2023**, *16*, 6384. [CrossRef]
36. Mubarak Alqahtani, A. Sweet sorghum and bagasse: A comprehensive review of feedstock traits, conversion processes, and economic viability for bioethanol and biogas production. *Biofuels* **2024**, *15*, 575–585. [CrossRef]
37. Pandey, A.; Sharma, Y.C. Advancements in biomass valorization in integrated biorefinery systems. *Biofuels Bioprod. Biorefin.* **2024**, *18*, 2078–2090. [CrossRef]
38. Waheed, Q.M.K.; Williams, P.T. Hydrogen Production from High Temperature Pyrolysis/Steam Reforming of Waste Biomass: Rice Husk, Sugar Cane Bagasse, and Wheat Straw. *Energy Fuels* **2013**, *27*, 6695–6704. [CrossRef]
39. Adeniyi, A.G.; Ighalo, J.O.; Abdulsalam, A. Modeling of integrated processes for the recovery of the energetic content of sugar cane bagasse. *Biofuels Bioprod. Biorefin.* **2019**, *13*, 1057–1067. [CrossRef]
40. Osada, M.; Yamaguchi, A.; Hiyoshi, N.; Sato, O.; Shirai, M. Gasification of Sugarcane Bagasse over Supported Ruthenium Catalysts in Supercritical Water. *Energy Fuels* **2012**, *26*, 3179–3186. [CrossRef]
41. Zhu, M.; Wang, Q.; Wang, S. Recent Advances and Future Perspectives in Catalyst Development for Efficient and Sustainable Biomass Gasification: A Comprehensive Review. *Sustainability* **2025**, *17*, 7370. [CrossRef]
42. Małozięć, K. Modelling Hydrothermal Liquefaction Process. Master's Thesis, School of Engineering Science, Kemiantekniikka, Finnish University of Applied Sciences, Tampere, Finland, 2025.
43. Kumar, A.; Sharma, K.; Yadav, V.; Banerjee, D.K. *Hydrogen Horizons: Tech, Trends, and Tomorrow*; Book Saga Publications: Maharashtra, India, 2025.
44. Gyandoh, E.S. Techno-Economic Analysis (TEA) and Life-Cycle Assessment (LCA) of Sustainable Aviation Fuel (SAF) Production Through Circular Economy (CE) Practices: A Focus on Supply Chain Optimization and Policy Implications. Ph.D. Thesis, The University of New Mexico, Albuquerque, NM, USA, 2025.
45. Naquash, A.; Hameed, Z.; Qyyum, M.A.; Khan, Z.; Al-Muhtaseb, A.H.; Riaz, A.; Lee, M. Biohydrogen and biomethane production from biomass gasification: Compositional analysis, recent advancements, challenges, and prospects. *Process Saf. Environ. Prot.* **2025**, *194*, 1526–1537. [CrossRef]
46. Akhtar, M.S.; Naseem, M.T.; Ali, S.; Zaman, W. Metal-Based Catalysts in Biomass Transformation: From Plant Feedstocks to Renewable Fuels and Chemicals. *Catalysts* **2025**, *15*, 40. [CrossRef]
47. Ungureanu, N.; Vlăduț, N.-V.; Biriș, S.-Ș.; Ionescu, M.; Gheorghiță, N.-E. Municipal Solid Waste Gasification: Technologies, Process Parameters, and Sustainable Valorization of By-Products in a Circular Economy. *Sustainability* **2025**, *17*, 6704. [CrossRef]
48. Yadav, A.; Mittal, R.; Bishnoi, N.R. Nanomaterial-Based Immobilization in Industrial Biocatalysis: Prospects, Gaps, and Challenges. In *Enzyme Immobilization with Nanomaterials: Applications and Challenges*; ACS Publications: Washington, DC, USA, 2025; pp. 81–103, ISBN 1947-5918.
49. Khalil, M.I.; Jhanjhi, N.; Humayun, M.; Sivanesan, S.; Masud, M.; Hossain, M.S. Hybrid smart grid with sustainable energy efficient resources for smart cities. *Sustain. Energy Technol. Assess.* **2021**, *46*, 101211. [CrossRef]
50. Borkertas, S.; Viskelis, J.; Viskelis, P.; Streimikyte, P.; Gasiunaite, U.; Urbonaviciene, D. Fungal biomass fermentation: Valorizing the food industry's waste. *Fermentation* **2025**, *11*, 351. [CrossRef]
51. Silva, J.; Rocha, C.; Soria, M.; Madeira, L.M. Catalytic steam reforming of biomass-derived oxygenates for H2 production: A review on Ni-based catalysts. *Chem. Eng.* **2022**, *6*, 39. [CrossRef]
52. Mather, T.N.; Siva, N.; Jauregui, M.; Klatte, H.; Lambert, J.D.; Anderson, C.T. Preparation and compositional analysis of Lignocellulosic plant biomass as a precursor for food production during food crises. *Curr. Protoc.* **2024**, *4*, e1090. [CrossRef]

53. Isahak, W.N.R.W.; Al-Amiery, A. Catalysts driving efficiency and innovation in thermal reactions: A comprehensive review. *Green Technol. Sustain.* **2024**, *2*, 100078. [CrossRef]
54. Zafeer, M.K.; Menezes, R.A.; Venkatachalam, H.; Bhat, K.S. Sugarcane bagasse-based biochar and its potential applications: A review. *Emergent Mater.* **2024**, *7*, 133–161. [CrossRef]
55. Tan, Z.; Li, Y.; Chen, F.; Liu, J.; Zhong, J.; Guo, L.; Zhang, R.; Chen, R. Challenges and perspectives of the conversion of lignin waste to high-value chemicals by pyrolysis. *Processes* **2024**, *12*, 589. [CrossRef]
56. Al Arni, S.; Bosio, B.; Arato, E. Syngas from sugarcane pyrolysis: An experimental study for fuel cell applications. *Renew. Energy* **2010**, *35*, 29–35. [CrossRef]
57. Carrier, M.; Hugo, T.; Gorgens, J.; Knoetze, H. Comparison of slow and vacuum pyrolysis of sugar cane bagasse. *J. Anal. Appl. Pyrolysis* **2011**, *90*, 18–26. [CrossRef]
58. Erlich, C.; Björnbom, E.; Bolado, D.; Giner, M.; Fransson, T.H. Pyrolysis and gasification of pellets from sugar cane bagasse and wood. *Fuel* **2006**, *85*, 1535–1540. [CrossRef]
59. Garcáa-Pèrez, M.; Chaala, A.; Roy, C. Vacuum pyrolysis of sugarcane bagasse. *J. Anal. Appl. Pyrolysis* **2002**, *65*, 111–136. [CrossRef]
60. Ounas, A.; Aboulkas, A.; Bacaoui, A.; Yaacoubi, A. Pyrolysis of olive residue and sugar cane bagasse: Non-isothermal thermogravimetric kinetic analysis. *Bioresour. Technol.* **2011**, *102*, 11234–11238. [CrossRef]
61. Darmstadt, H.; Garcia-Perez, M.; Chaala, A.; Cao, N.-Z.; Roy, C. Co-pyrolysis under vacuum of sugar cane bagasse and petroleum residue: Properties of the char and activated char products. *Carbon* **2001**, *39*, 815–825. [CrossRef]
62. Herath Bandara, S.J. Exploring the Potential of Biochar in Enhancing US Agriculture. *Reg. Sci. Environ. Econ.* **2025**, *2*, 23. [CrossRef]
63. Peters, M.A.; Alves, C.T.; Onwudili, J.A. A review of current and emerging production technologies for biomass-derived sustainable aviation fuels. *Energies* **2023**, *16*, 6100. [CrossRef]
64. El-Halwagi, M.M. *Sustainable Design Through Process Integration: Fundamentals and Applications to Industrial Pollution Prevention, Resource Conservation, and Profitability Enhancement*; Elsevier: Amsterdam, The Netherlands, 2025; ISBN 0-443-16040-6.
65. Ayub, Y.; Zhou, J.; Shen, W.; Ren, J. Innovative valorization of biomass waste through integration of pyrolysis and gasification: Process design, optimization, and multi-scenario sustainability analysis. *Energy* **2023**, *282*, 128417. [CrossRef]
66. Athira, G.; Bahurudeen, A.; Appari, S. Thermochemical Conversion of Sugarcane Bagasse: Composition, Reaction Kinetics, and Characterisation of By-Products. *Sugar Tech* **2021**, *23*, 433–452. [CrossRef]
67. Hou, Y. A Comprehensive Review of Fuels Used in Combustion Processes. Bachelor's Thesis, Hebei University of Technology, Tianjin, China, 2024.
68. Ramajo-Escalera, B.; Espina, A.; García, J.; Sosa-Arnao, J.; Nebra, S. Model-free kinetics applied to sugarcane bagasse combustion. *Thermochim. Acta* **2006**, *448*, 111–116. [CrossRef]
69. Ahmad, E.; Jäger, N.; Apfelbacher, A.; Daschner, R.; Hornung, A.; Pant, K.K. Integrated thermo-catalytic reforming of residual sugarcane bagasse in a laboratory scale reactor. *Fuel Process. Technol.* **2018**, *171*, 277–286. [CrossRef]
70. Chen, W.-H.; Ye, S.-C.; Sheen, H.-K. Hydrothermal carbonization of sugarcane bagasse via wet torrefaction in association with microwave heating. *Bioresour. Technol.* **2012**, *118*, 195–203. [CrossRef]
71. Munir, S.; Daood, S.S.; Nimmo, W.; Cunliffe, A.M.; Gibbs, B.M. Thermal analysis and devolatilization kinetics of cotton stalk, sugar cane bagasse and shea meal under nitrogen and air atmospheres. *Bioresour. Technol.* **2009**, *100*, 1413–1418. [CrossRef]
72. Ryzhchenko, O. *Environmental and Health Impacts of Agricultural Waste Combustion for Bioenergy: A Toxicity and Emission Review*; National University of Civil Protection of Ukraine: Kharkiv, Ukraine, 2024; Volume 6, pp. 45–58. [CrossRef]
73. Khobragade, D.S. Biomass–An Environmental Concern. In *Plant Biomass Derived Materials: Sources, Extractions, and Applications*; John Wiley and Sons: Hoboken, NJ, USA, 2024; pp. 1–22.
74. Omwenga, S.C. An Evaluation of Renewable Energy Adoption in Kenya. A Case Study of Biomass Briquette Production and its Use in Industrial Boiler Operations. Ph.D. Thesis, University of Nairobi, Nairobi, Kenya, 2018.
75. Nunes, L.J. Exploring the present and future of biomass recovery units: Technological innovation, policy incentives and economic challenges. *Biofuels* **2024**, *15*, 375–387. [CrossRef]
76. Makepa, D.C.; Chihobo, C.H. Sustainable pathways for biomass production and utilization in carbon capture and storage—A review. *Biomass Convers. Biorefin.* **2025**, *15*, 11397–11419. [CrossRef]
77. Perera, W.; Hosan, K.; Wijesekara, R.; Priyadarshana, H.; Abeysinghe, S.; Amarasinghe, A.; Koswattage, K. Biogas Purification Technologies: A Comparative Review of Methods and Accessibility for Sustainable Energy Applications. *J. Agric. Value Addit.* **2025**, *8*, 44–73. [CrossRef]
78. Wu, M.; Wei, K.; Jiang, J.; Xu, B.B.; Ge, S. Advancing green sustainability: A comprehensive review of biomass briquette integration for coal-based energy frameworks. *Int. J. Coal Sci. Technol.* **2025**, *12*, 44. [CrossRef]
79. Bharti, R.; Thakur, A.; Verma, M.; Sharma, R. *Environmental and Health Impacts of Air Pollution: A State of Art Review on the Strategy to Control Air Pollution*; AIP Publishing LLC: Melville, NY, USA, 2025; Volume 2807, p. 50006.

80. Kim, C.; Park, K.; Lee, H.; Im, J.; Ususky, D.; Tak, K.; Park, D.; Chung, W.; Han, D.; Yoon, J. Accelerating the net-zero economy with CO_2-hydrogenated formic acid production: Process development and pilot plant demonstration. *Joule* **2024**, *8*, 693–713. [CrossRef]
81. Kpalo, S.Y.; Zainuddin, M.F.; Manaf, L.A.; Roslan, A.M. A review of technical and economic aspects of biomass briquetting. *Sustainability* **2020**, *12*, 4609. [CrossRef]
82. Tawo, O.E.; Mbamalu, M.I. Advancing waste valorization techniques for sustainable industrial operations and improved environmental safety. *Int. J. Sci. Res. Arch* **2025**, *14*, 127–149. [CrossRef]
83. Jorapur, R.; Rajvanshi, A.K. Sugarcane leaf-bagasse gasifiers for industrial heating applications. *Biomass Bioenergy* **1997**, *13*, 141–146. [CrossRef]
84. Lourinho, G.; Alves, O.; Garcia, B.; Rijo, B.; Brito, P.; Nobre, C. Costs of gasification technologies for energy and fuel production: Overview, analysis, and numerical estimation. *Recycling* **2023**, *8*, 49. [CrossRef]
85. Li, J.; Chen, H.; Cao, J.; Jin, Z.; Pan, P.; Xu, G.; Wang, X. Energy, Exergy, Economic, and Environmental (4E) Analysis of a Hybrid Sludge-Biomass Power System via Integrated Hydrocharization and Co-Gasification. *Energy* **2025**, *335*, 137945. [CrossRef]
86. Gao, N.; Salisu, J.; Quan, C.; Williams, P. Modified nickel-based catalysts for improved steam reforming of biomass tar: A critical review. *Renew. Sustain. Energy Rev.* **2021**, *145*, 111023. [CrossRef]
87. Khandelwal, K.; German, C.S.; Dalai, A.K. Technoeconomic analysis of supercritical water gasification of canola straw for hydrogen production. *Int. J. Hydrog. Energy* **2024**, *96*, 1067–1078. [CrossRef]
88. Kruesi, M.; Jovanovic, Z.R.; dos Santos, E.C.; Yoon, H.C.; Steinfeld, A. Solar-driven steam-based gasification of sugarcane bagasse in a combined drop-tube and fixed-bed reactor—Thermodynamic, kinetic, and experimental analyses. *Biomass Bioenergy* **2013**, *52*, 173–183. [CrossRef]
89. Boujjat, H.; Rodat, S.; Abanades, S. Techno-economic assessment of solar-driven steam gasification of biomass for large-scale hydrogen production. *Processes* **2021**, *9*, 462. [CrossRef]
90. He, D.; Ma, H.; Hu, D.; Wang, X.; Dong, Z.; Zhu, B. Biochar for sustainable agriculture: Improved soil carbon storage and reduced emissions on cropland. *J. Environ. Manag.* **2024**, *371*, 123147. [CrossRef]
91. Zandersons, J.; Gravitis, J.; Kokorevics, A.; Zhurinsh, A.; Bikovens, O.; Tardenaka, A.; Spince, B. Studies of the Brazilian sugarcane bagasse carbonisation process and products properties. *Biomass Bioenergy* **1999**, *17*, 209–219. [CrossRef]
92. Humidity Sensor Market: Size Share & Trends Analysis Report by Type (Absolute Humidity Sensor, Relative Humidity Sensor), by End Use (Automotive, Industrial), by Region, and Segment Forecasts, 2025–2030. Grand View Research, Market Analysis Report. 2025. Available online: https://www.grandviewresearch.com/industry-analysis/humidity-sensor-market (accessed on 25 March 2025).
93. Asadullah, M.; Rahman, M.A.; Ali, M.M.; Rahman, M.S.; Motin, M.A.; Sultan, M.B.; Alam, M.R. Production of bio-oil from fixed bed pyrolysis of bagasse. *Fuel* **2007**, *86*, 2514–2520. [CrossRef]
94. Drugkar, K.; Rathod, W.; Sharma, T.; Sharma, A.; Joshi, J.; Pareek, V.K.; Ledwani, L.; Diwekar, U. Advanced separation strategies for up-gradation of bio-oil into value-added chemicals: A comprehensive review. *Sep. Purif. Technol.* **2022**, *283*, 120149. [CrossRef]
95. Inayat, A.; Ahmed, A.; Tariq, R.; Waris, A.; Jamil, F.; Ahmed, S.F.; Ghenai, C.; Park, Y.-K. Techno-economical evaluation of bio-oil production via biomass fast pyrolysis process: A review. *Front. Energy Res.* **2022**, *9*, 770355. [CrossRef]
96. Wills, V.C.; Rodriguez, J.K. Waste valorization: Harnessing biogas plant residues for fuel production. *Sustain. Energy Fuels* **2025**, *9*, 2045–2062. [CrossRef]
97. Pratiti, R. Household air pollution related to biomass cook stove emissions and its interaction with improved cookstoves. *AIMS Public Health* **2021**, *8*, 309. [CrossRef]
98. US EIA. *Assumptions to the Annual Energy Outlook 2020: Electricity Market Module*; US EIA: Washington, DC, USA, 2020; Volume 8.
99. Zhang, J.; Li, G.; Borrion, A. Life cycle assessment of electricity generation from sugarcane bagasse hydrochar produced by microwave assisted hydrothermal carbonization. *J. Clean. Prod.* **2021**, *291*, 125980. [CrossRef]
100. Valle, S.O.F.; López, D.M.M.; Plata, F.J.C.; Ángeles, E.L.; Camas, G.d.c.S. Catalytic Gasification of Biomass: Materials, Products and Other Considerations. In *Gasification—Current Technologies and Future Prospect*; De Gruyter: Berlin, Germany, 2025.
101. Phang, F.J.F.; Chew, J.J.; Chakraborty, S.; Sunarso, J. Synthesis of Hydrochars via Wet Torrefaction of Biomass for Sustainable Energy Production: A Life Cycle Assessment Study. *ACS Sustain. Chem. Eng.* **2025**, *13*, 2884–2892. [CrossRef]
102. Adelodun, B.; Ajibade, F.O.; Ighalo, J.O.; Odey, G.; Ibrahim, R.G.; Kareem, K.Y.; Bakare, H.O.; Tiamiyu, A.O.; Ajibade, T.F.; Abdulkadir, T.S.; et al. Assessment of socioeconomic inequality based on virus-contaminated water usage in developing countries: A review. *Environ. Res.* **2021**, *192*, 110309. [CrossRef] [PubMed]
103. Eletta, O.A.A.; Adeniyi, A.G.; Ighalo, J.O.; Onifade, D.V.; Ayandele, F.O. Valorisation of Cocoa (*Theobroma cacao*) pod husk as precursors for the production of adsorbents for water treatment. *Environ. Technol. Rev.* **2020**, *9*, 20–36. [CrossRef]
104. Xavier, A.L.P.; Adarme, O.F.H.; Furtado, L.M.; Ferreira, G.M.D.; da Silva, L.H.M.; Gil, L.F.; Gurgel, L.V.A. Modeling adsorption of copper(II), cobalt(II) and nickel(II) metal ions from aqueous solution onto a new carboxylated sugarcane bagasse. Part II: Optimization of monocomponent fixed-bed column adsorption. *J. Colloid Interface Sci.* **2018**, *516*, 431–445. [CrossRef]

105. Wannahari, R.; Sannasi, P.; M Nordin, M.; Mukhtar, H. Sugarcane bagasse derived nano magnetic adsorbent composite (SCB-NMAC) for removal of Cu2+ from aqueous solution. *ARPN J. Eng. Appl. Sci.* **2018**, *13*, 1–9.
106. Abdullah, A.L.; Salleh, M.M.; Mazlina, M.S.; Noor, M.; Osman, M.; Wagiran, R.; Sobri, S. Azo dye removal by adsorption using waste biomass: Sugarcane bagasse. *Int. J. Eng. Technol.* **2005**, *2*, 8–13.
107. Brandão, P.C.; Souza, T.C.; Ferreira, C.A.; Hori, C.E.; Romanielo, L.L. Removal of petroleum hydrocarbons from aqueous solution using sugarcane bagasse as adsorbent. *J. Hazard. Mater.* **2010**, *175*, 1106–1112. [CrossRef]
108. Moisés, M.P.; da Silva, C.T.P.; Meneguin, J.G.; Girotto, E.M.; Radovanovic, E. Synthesis of zeolite NaA from sugarcane bagasse ash. *Mater. Lett.* **2013**, *108*, 243–246. [CrossRef]
109. Mathur, A.K.; Majumder, C.B.; Chatterjee, S. Combined removal of BTEX in air stream by using mixture of sugar cane bagasse, compost and GAC as biofilter media. *J. Hazard. Mater.* **2007**, *148*, 64–74. [CrossRef]
110. Kamran, U.; Shezad, N.; Park, S.-J.; Rhee, K.Y.; You, S.; Akhtar, F. Solvent-free valorization of sugarcane bagasse fibers into nitrogen-doped microporous carbons: Efficient contenders for selective carbon dioxide capture. *J. CO2 Util.* **2025**, *92*, 103033. [CrossRef]
111. Fei, Y.; Hu, Y.H. Design, synthesis, and performance of adsorbents for heavy metal removal from wastewater: A review. *J. Mater. Chem. A* **2022**, *10*, 1047–1085. [CrossRef]
112. Akhtar, M.S.; Ali, S.; Zaman, W. Innovative adsorbents for pollutant removal: Exploring the latest research and applications. *Molecules* **2024**, *29*, 4317. [CrossRef] [PubMed]
113. Al Ali, M. *Advanced Techniques in Porous Structure Design for Additive Manufacturing*; John Wiley & Sons: Hoboken, NJ, USA, 2025; ISBN 1-394-31268-7.
114. Dey, N.; Bhardwaj, S.; Maji, P.K. Recent breakthroughs in the valorization of lignocellulosic biomass for advancements in the construction industry: A Review. *RSC Sustain.* **2025**, *3*, 3307–3357. [CrossRef]
115. Singh, A.V.; Chandrasekar, V.; Prabhu, V.M.; Bhadra, J.; Laux, P.; Bhardwaj, P.; Al-Ansari, A.A.; Aboumarzouk, O.M.; Luch, A.; Dakua, S.P. Sustainable bioinspired materials for regenerative medicine: Balancing toxicology, environmental impact, and ethical considerations. *Biomed. Mater.* **2024**, *19*, 060501. [CrossRef]
116. Almaraz-Sánchez, I.; Amaro-Reyes, A.; Acosta-Gallegos, J.A.; Mendoza-Sánchez, M. Processing agroindustry by-products for obtaining value-added products and reducing environmental impact. *J. Chem.* **2022**, *2022*, 3656932. [CrossRef]
117. Henning, L.M.; Abdullayev, A.; Vakifahmetoglu, C.; Simon, U.; Bensalah, H.; Gurlo, A.; Bekheet, M.F. Review on polymeric, inorganic, and composite materials for air filters: From processing to properties. *Adv. Energy Sustain. Res.* **2021**, *2*, 2100005. [CrossRef]
118. Mukesh, M.; Anwar, S.; Gulshan, A.; Ali, M.; Ali, K.M.; Guo, Y. Pilot-Scale Evaluation and Production Feasibility of Sustainable Antimicrobial Paper from Sugarcane Bagasse. *Int. J. Environ. Agric. Biotechnol.* **2025**, *10*, 595671. [CrossRef]
119. Abegunde, S.M.; Idowu, K.S.; Adejuwon, O.M.; Adeyemi-Adejolu, T. A review on the influence of chemical modification on the performance of adsorbents. *Resour. Environ. Sustain.* **2020**, *1*, 100001. [CrossRef]
120. Iwuozor, K.O.; Okoro, H.K.; Adeniyi, A.G.; Zvinowanda, C.; Ngila, J.C.; Emenike, E.C. Sugarcane bagasse adsorbents: Bibliometric insights and the influence of chemical treatment on adsorption performance in aqueous solution. *Sugar Tech* **2024**, *26*, 333–351. [CrossRef]
121. Mahmud, M.A.; Anannya, F.R. Sugarcane bagasse—A source of cellulosic fiber for diverse applications. *Heliyon* **2021**, *7*, e07771. [CrossRef]
122. Bantacut, T.; Romli, M.; Noor, E. Biomass by-product from crystal sugar production: A comparative study between Ngadirejo and Mauritius sugar mill. In Proceedings of the IOP Conference Series: Earth and Environmental Science; IOP Publishing: Bristol, UK, 2018; Volume 141, p. 12009.
123. Guerra, S.P.S.; Denadai, M.S.; Saad, A.L.M.; Spadim, E.R.; da Costa, M.X.R. Chapter 3—Sugarcane: Biorefinery, technology, and perspectives. In *Sugarcane Biorefinery, Technology and Perspectives*; Santos, F., Rabelo, S.C., De Matos, M., Eichler, P., Eds.; Academic Press: Oxford, UK, 2020; pp. 49–65, ISBN 978-0-12-814236-3.
124. Shabbirahmed, A.M.; Haldar, D.; Dey, P.; Patel, A.K.; Singhania, R.R.; Dong, C.-D.; Purkait, M.K. Sugarcane bagasse into value-added products: A review. *Environ. Sci. Pollut. Res.* **2022**, *29*, 62785–62806. [CrossRef]
125. Versino, F.; García, M.A. Particle Size Distribution Effect on Cassava Starch and Cassava Bagasse Biocomposites. *ACS Sustain. Chem. Eng.* **2019**, *7*, 1052–1060. [CrossRef]
126. Stroescu, M.; Romina, A.; Mureșan, C.C. A Comprehensive Review on Sugarcane Bagasse in Food Packaging: Properties, Applications, and Future Prospects. *Hop Med. Plants* **2024**, *32*, 169–184. [CrossRef]
127. López-Maldonado, E.A.; Solangi, A.R.; Granados-Chinchilla, F. *Nanobiotechnology for Sustainable Food Management*; CRC Press: Boca Raton, FL, USA, 2024; ISBN 1-040-13052-6.
128. Edo, G.I.; Mafe, A.N.; Ali, A.; Akpoghelie, P.O.; Yousif, E.; Isoje, E.F.; Igbuku, U.A.; Zainulabdeen, K.; Owheruo, J.O.; Essaghah, A.E.A. Advancing sustainable food packaging: The role of green nanomaterials in enhancing barrier properties. *Food Eng. Rev.* **2025**, *17*, 573–607. [CrossRef]

129. Huerta-Cardoso, O.; Durazo-Cardenas, I.; Longhurst, P.; Simms, N.J.; Encinas-Oropesa, A. Fabrication of agave tequilana bagasse/PLA composite and preliminary mechanical properties assessment. *Ind. Crops Prod.* **2020**, *152*, 112523. [CrossRef]
130. Sekar, S.; Suresh Kumar, S.; Vigneshwaran, S.; Velmurugan, G. Evaluation of mechanical and water absorption behavior of natural fiber-reinforced hybrid biocomposites. *J. Nat. Fibers* **2022**, *19*, 1772–1782. [CrossRef]
131. Antony Jose, S.; Cowan, N.; Davidson, M.; Godina, G.; Smith, I.; Xin, J.; Menezes, P.L. A comprehensive review on cellulose Nanofibers, nanomaterials, and composites: Manufacturing, properties, and applications. *Nanomaterials* **2025**, *15*, 356. [CrossRef]
132. Guimarães, J.L.; Frollini, E.; da Silva, C.G.; Wypych, F.; Satyanarayana, K.G. Characterization of banana, sugarcane bagasse and sponge gourd fibers of Brazil. *Ind. Crops Prod.* **2009**, *30*, 407–415. [CrossRef]
133. Chaharmahali, M.; Hamzeh, Y.; Ebrahimi, G.; Ashori, A.; Ghasemi, I. Effects of nano-graphene on the physico-mechanical properties of bagasse/polypropylene composites. *Polym. Bull.* **2014**, *71*, 337–349. [CrossRef]
134. Kord, B.; Ravanfar, P.; Ayrilmis, N. Influence of Organically Modified Nanoclay on Thermal and Combustion Properties of Bagasse Reinforced HDPE Nanocomposites. *J. Polym. Environ.* **2017**, *25*, 1198–1207. [CrossRef]
135. Barra, G.; Guadagno, L.; Raimondo, M.; Santonicola, M.G.; Toto, E.; Vecchio Ciprioti, S. A comprehensive review on the thermal stability assessment of polymers and composites for aeronautics and space applications. *Polymers* **2023**, *15*, 3786. [CrossRef]
136. Jamwal, V.; Mittal, A. Recent progresses in nanocomposite films for food-packaging applications: Synthesis strategies, technological advancements, potential risks and challenges. *Food Rev. Int.* **2024**, *40*, 3634–3665. [CrossRef]
137. Ferreira, P.S.; Scopel, E.; Pinto, L.O.; Rezende, C.A. Hydrophobic and Robust Sugarcane Bagasse-Based Biosorbents for Oil Spill Cleanup: Synergy of Hydrothermal Treatment and Cellulose Nanofibril Reinforcement. *ACS Sustain. Resour. Manag.* **2025**, *2*, 853–863. [CrossRef]
138. Ashiwaju, B.I.; Orikpete, O.F.; Fawole, A.A.; Alade, E.Y.; Odogwu, C. A step toward sustainability: A review of biodegradable packaging in the pharmaceutical industry. *Matrix Sci. Pharma* **2023**, *7*, 73–84. [CrossRef]
139. Rahman, M.M.; Khan, K.H.; Parvez, M.M.H.; Irizarry, N.; Uddin, M.N. Polymer nanocomposites with optimized nanoparticle dispersion and enhanced functionalities for industrial applications. *Processes* **2025**, *13*, 994. [CrossRef]
140. Jayalath, S.U.; Alwis, A.P.D. PHA, the Greenest Plastic So Far: Advancing Microbial Synthesis, Recovery, and Sustainable Applications for Circularity. *ACS Omega* **2025**, *10*, 32564–32586. [CrossRef]
141. Pandey, S.; Choudhry, S.; Singh, A. Multifunctional Biopolymers: Types, Preparation, and Industrial Applications. *Multifunct. Mater. Eng. Biol. Appl.* **2025**, *1*, 393–418.
142. Silva, R.R.A.; Marques, C.S.; Arruda, T.R.; Teixeira, S.C.; de Oliveira, T.V. Biodegradation of polymers: Stages, measurement, standards and prospects. *Macromol* **2023**, *3*, 371–399. [CrossRef]
143. Abdelhamid, H.N. Nanotechnology and Biopolymers: A Perfect Synergy for Modern Applications. *Mater. Sci.* **2024**, preprint. [CrossRef]
144. Singh, A.; Kaur, S.; Thakur, H.; Rashi; Kashyap, S.; Lyudmila, A.; Mudgal, G. Unveiling the transformative power of smart cellulosic nanomaterials: Revisiting potential promises to sustainable future. In *Functionalized Cellulose Materials: Sustainable Manufacturing and Applications*; Springer: Berlin/Heidelberg, Germany, 2025; pp. 1–42.
145. Agrawal, K.M.; Barve, B.R.; Khan, S.S. Biogas from pressmud. *IOSR J. Mech. Civ. Eng.* **2013**, *1*, 37–41.
146. Sholokhova, A.; Varžinskas, V.; Rutkaitė, R. Valorization of Agro-waste in Bio-based and Biodegradable Polymer Composites: A Comprehensive Review with Emphasis on Europe Perspective. *Waste Biomass Valorization* **2025**, *16*, 1537–1571. [CrossRef]
147. da Silva, M.; Bastos, R.; Soares, M.; Cerri, B.; Bettani, S.; de Jesus, G.; Ragazzo, G.; Santos, N. Biopolymers in Sugarcane Vinasse Treatment and Valorization. In *Agricultural Waste: Environmental Impact, Useful Metabolites and Energy Production*; Springer: Berlin/Heidelberg, Germany, 2023; pp. 167–186.
148. Rashid, A.B.; Haque, M.; Islam, S.M.; Labib, K.R.U. Nanotechnology-enhanced fiber-reinforced polymer composites: Recent advancements on processing techniques and applications. *Heliyon* **2024**, *10*, e24692. [CrossRef] [PubMed]
149. Faheem, M.; Khan, K.A. Harnessing sustainable biocomposites: A review of advances in greener materials and manufacturing strategies. *Polym. Bull.* **2025**, *82*, 8827–8870. [CrossRef]
150. Paiva, C.L.; Ugaya, C.M. Environmental impacts assessment in packaging and its contribution to reducing food waste. *Clean. Circ. Bioecon.* **2024**, *8*, 100083. [CrossRef]
151. Villalba, V.; Kuiper, H.; Gill, E. Review on thermal and mechanical challenges in the development of deployable space optics. *J. Astron. Telesc. Instrum. Syst.* **2020**, *6*, 10902. [CrossRef]
152. Hong, H.; Xiao, R.; Guo, Q.; Liu, H.; Zhang, H. Quantitively Characterizing the Chemical Composition of Tailored Bagasse Fiber and Its Effect on the Thermal and Mechanical Properties of Polylactic Acid-Based Composites. *Polymers* **2019**, *11*, 1567. [CrossRef]
153. Kusuma, H.S.; Permatasari, D.; Umar, W.K.; Sharma, S.K. Sugarcane bagasse as an environmentally friendly composite material to face the sustainable development era. *Biomass Convers. Biorefin.* **2024**, *14*, 26693–26706. [CrossRef]
154. Goyal, A.; Anwar, A.; Kunio, H.; Hidehiko, O. Properties of Sugarcane Bagasse Ash and Its Potential as Cement-Pozzolana Binder. In *Proceedings of the 12th International Conference on Structural and Geotechnical Engineering*; Ain Shams University, Faculty of Engineering: Cairo, Egypt, 2007; pp. 10–12.

155. Natarajan, S.; Subramaniyam, S.T.; Kumaravel, V. Fabrication of hydrophobic coatings using sugarcane bagasse waste ash as silica source. *Appl. Sci.* **2019**, *9*, 190. [CrossRef]
156. Souza, A.; Teixeira, S.; Santos, G.; Costa, F.; Longo, E. Reuse of sugarcane bagasse ash (SCBA) to produce ceramic materials. *J. Environ. Manag.* **2011**, *92*, 2774–2780. [CrossRef] [PubMed]
157. Guna, V.; Ilangovan, M.; Hu, C.; Venkatesh, K.; Reddy, N. Valorization of sugarcane bagasse by developing completely biodegradable composites for industrial applications. *Ind. Crops Prod.* **2019**, *131*, 25–31. [CrossRef]
158. Jang, J.K.; Kalina, R.D.; Al-Shmaisani, S.; Ferron, R.D.; Juenger, M.C. Assessing Pozzolanicity of supplementary cementitious materials using ASTM standard test methods. *Adv. Civ. Eng. Mater.* **2022**, *11*, 485–499. [CrossRef]
159. Mahmudul Hasan, M. Investigation of Bagasse Ash as a Partial Supplementary Cementitious Material. Master's Thesis, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh, 2018.
160. Assumptor, O.M.; Masika, E.; Thiong'o, K. Probing Optimal Blends of Pozzolans to Develop Supplementary Cementing Material Within Busia County, Kenya. Ph.D. Thesis, Kenyatta University, Nairobi, Kenya, 2024.
161. Nassiri, S.; Butt, A.A.; Mateos, A.; Roy, S.; Filani, I.; Zarei, A.; Pandit, G.; Haider, M.M.; Harvey, J. *Identification of Likely Alternative Supplementary Cementitious Materials in California: A Review of Supplies, Technical Performance in Concrete, Economic, and Climatic Considerations*; University of California: Davis, CA, USA, 2024.
162. Capuano, R. Mechanochemistry: Versatile and Functional Strategy for the Realization and the Recycling of Multi-Phase Materials. Ph.D. Thesis, University of Brescia, Brescia, Italy, 2023.
163. Keskin, T.; Yilmaz, E.; Kasap, T.; Sari, M.; Cao, S. Toward viable industrial solid residual waste recycling: A review of its innovative applications and future perspectives. *Minerals* **2024**, *14*, 943. [CrossRef]
164. Qamar, S.Z.; Al-Hinai, N.; Márquez, F.P.G. *Quality Control and Quality Assurance: Techniques and Applications*; BoD–Books on Demand: Norderstedt, Germany, 2024; ISBN 0-85014-024-2.
165. Onsongo, S.K.; Olukuru, J.; Munyao, O.M.; Mwabonje, O. The role of agricultural ashes (rice husk ash, coffee husk ash, sugarcane bagasse ash, palm oil fuel ash) in cement production for sustainable development in Africa. *Discov. Sustain.* **2025**, *6*, 62. [CrossRef]
166. Singh, A.B.; Khandelwal, C.; Dangayach, G.S. Advancements in healthcare materials: Unraveling the impact of processing techniques on biocompatibility and performance. *Polym.-Plast. Technol. Mater.* **2024**, *63*, 1608–1644. [CrossRef]
167. Chen, S. Thermomechanical Pulp Fines as Additives for 3D Printing Filaments. Master's Thesis, University of British Columbia, Vancouver, BC, Canada, 2024.
168. Yaseen, N. Exploring the potential of sugarcane bagasse ash as a sustainable supplementary cementitious material: Experimental investigation and statistical analysis. *Results Chem.* **2024**, *10*, 101723. [CrossRef]
169. Ullah, M.F.; Tang, H.; Ullah, A.; Toth, Z.; Ahmad, M.; Alzlfawi, A. Mechanical and environmental performance of sugarcane Bagasse Ash from Khyber Pakhtunkhwa in sustainable concrete. *Sci. Rep.* **2025**, *15*, 24571. [CrossRef]
170. Gudia, S.E.L.; Go, A.W.; Giduquio, M.B.; Juanir, R.G.; Jamora, J.B.; Gunarto, C.; Tabañag, I.D.F. Sugarcane bagasse ash as a partial replacement for cement in paste and mortar formulation–A case in the Philippines. *J. Build. Eng.* **2023**, *76*, 107221. [CrossRef]
171. Patil, P.P.; Katare, V.D. Development of sustainable alkali-activated binder for building products using sugarcane bagasse ash: A review. *Mater. Today Proc.* 2023, *in press*. [CrossRef]
172. Hauser, P.D.; Fonseca, R.T. Global cooperation and challenges of sustainable development: CDM results and lessons learned for the design of new financial mechanisms. In *Environment and Natural Resources*; Institute of Applied Economic Research: Rio de Janeiro, Brazil, 2019.
173. Gbadeyan, O.J.; Sibiya, L.; Mpongwana, N.; Linganiso, L.Z.; Linganiso, E.C.; Deenadayalu, N. Manufacturing of building materials using agricultural waste (sugarcane bagasse ash) for sustainable construction: Towards a low carbon economy. A review. *Int. J. Sustain. Eng.* **2023**, *16*, 368–382. [CrossRef]
174. Chop, H.; Arnold, B.J. Utilization of Coal Wastes for the Production of Ceramic Materials: A Review. *Min. Metall. Explor.* **2025**, *42*, 1001–1023. [CrossRef]
175. Francioso, V.; Lemos-Micolta, E.D.; Elgaali, H.H.; Moro, C.; Rojas-Manzano, M.A.; Velay-Lizancos, M. Valorization of sugarcane bagasse ash as an alternative SCM: Effect of particle size, temperature-crossover effect mitigation & cost analysis. *Sustainability* **2024**, *16*, 9370. [CrossRef]
176. Zaheer, M.M.; Tabish, M. The durability of concrete made up of sugar cane bagasse ash (SCBA) as a partial replacement of cement: A review. *Arab. J. Sci. Eng.* **2023**, *48*, 4195–4225. [CrossRef]
177. Aziz, A.A.; Nassar, H.F.; Al-Shemy, M.T.; Mohamed, O. Boosting the mechanical performance and fire resistivity of white ordinary portland cement pastes via biogenic mesoporous silica nanoparticles. *Sci. Rep.* **2025**, *15*, 2909. [CrossRef]
178. Moraes, J.d.; Cordeiro, G.; Akasaki, J.; Vieira, A.; Payá, J. Improving the reactivity of a former ground sugarcane bagasse ash produced by autogenous combustion through employment of two different additional grinding procedures. *Constr. Build. Mater.* **2021**, *270*, 121471. [CrossRef]
179. Suraneni, P.; Burris, L.; Shearer, C.R.; Hooton, R.D. ASTM C618 fly ash specification: Comparison with other specifications, shortcomings, and solutions. *ACI Mater. J.* **2021**, *118*, 157–167. [CrossRef]

180. Sadoon, A.; Bassuoni, M.; Ghazy, A. Assessment of Oat Husk Ash from Cold Climates as a Supplementary Cementitious Material. *J. Mater. Civ. Eng.* **2025**, *37*, 04025371. [CrossRef]
181. Kalkan, Ö.F. Effect of Grinding Chemicals and Aids on the Grinding Efficiency and the Performance of Portland Cement. Master's Thesis, Middle East Technical University, Ankara, Turkiye, 2023.
182. Matias, D.R.M.R.d.A. Optimization of Energy Consumption in the Ceramics Industry: A Techno-Economic Analysis. Master's Thesis, Politecnico di Milano, Milan, Italy, 2023.
183. Singh, N.; Sharma, R.; Yadav, K. Sustainable solutions: Exploring Supplementary Cementitious Materials in Construction. *Iran. J. Sci. Technol. Trans. Civ. Eng.* **2025**, *49*, 2191–2224. [CrossRef]
184. Ferraro, C.C.; Paris, J.M.; Riding, K.A.; Townsend, T.G.; Bueno, E.T. *Evaluation of Silica-Based Materials for Use in Portland Cement Concrete*; Florida Department of Transportation: Tallahassee, FL, USA, 2021.
185. Caibin, W. Ball Grinding Process. In *The ECPH Encyclopedia of Mining and Metallurgy*; Springer: Berlin/Heidelberg, Germany, 2024; pp. 117–118.
186. Alaneme, G.U.; Olonade, K.A.; Esenogho, E.; Lawan, M.M.; Dintwa, E. Artificial intelligence prediction of the mechanical properties of banana peel-ash and bagasse blended geopolymer concrete. *Sci. Rep.* **2024**, *14*, 26151. [CrossRef] [PubMed]
187. Alsarhan, H.; Al-Fakih, A. Performance and sustainability of industrial by-products-based alkali-activated concrete: A review. *Multiscale Multidiscip. Model. Exp. Des.* **2025**, *8*, 1–25. [CrossRef]
188. Paul, A.; Nair, R. Carbon Emission Trading—A Critical Analysis. *J. Environ. Law Policy* **2024**, *12*, 145–162.
189. Murugesan, T.; Athira, G.; Vidjeapriya, R.; Bahurudeen, A. Sustainable opportunities for sugar industries through potential reuse of sugarcane bagasse ash in blended cement production. *Sugar Tech* **2021**, *23*, 949–963. [CrossRef]
190. Yarra, A.; Nakkeeran, G.; Roy, D.; Alaneme, G.U. Evaluation of SCBA-replaced cement for carbon credits and reduction in CO2 emissions. *Discov. Appl. Sci.* **2025**, *7*, 114. [CrossRef]
191. Mohammadi, A.; Ramezanianpour, A.M. Investigating the environmental and economic impacts of using supplementary cementitious materials (SCMs) using the life cycle approach. *J. Build. Eng.* **2023**, *79*, 107934. [CrossRef]
192. Dybka-Stępień, K.; Antolak, H.; Kmiotek, M.; Piechota, D.; Koziróg, A. Disposable food packaging and serving materials—Trends and biodegradability. *Polymers* **2021**, *13*, 3606. [CrossRef]
193. Konde, K.S.; Nagarajan, S.; Kumar, V.; Patil, S.V.; Ranade, V.V. Sugarcane bagasse based biorefineries in India: Potential and challenges. *Sustain. Energy Fuels* **2021**, *5*, 52–78. [CrossRef]
194. Singh, S.P.; Jawaid, M.; Chandrasekar, M.; Senthilkumar, K.; Yadav, B.; Saba, N.; Siengchin, S. Sugarcane wastes into commercial products: Processing methods, production optimization and challenges. *J. Clean. Prod.* **2021**, *328*, 129453. [CrossRef]
195. *Global Strategy for Food Safety 2022–2030: Towards Stronger Food Safety Systems and Global Cooperation*; World Health Organization: Geneva, Switzerland, 2022; ISBN 92-4-005768-4.
196. Karim, A.; Raji, Z.; Habibi, Y.; Khalloufi, S. A review on the hydration properties of dietary fibers derived from food waste and their interactions with other ingredients: Opportunities and challenges for their application in the food industry. *Crit. Rev. Food Sci. Nutr.* **2024**, *64*, 11722–11756. [CrossRef]
197. Kumar, B.; Pimentel, J.; Cano-Londoño, N.A.; Ruiz-Mercado, G.J.; Deak, C.T.; Cabezas, H. Designing cost-effective supply chains for plastics at the end-of-life. *J. Clean. Prod.* **2025**, *501*, 145227. [CrossRef]
198. Moshood, T.D.; Mahmud, F.; Nawanir, G.; Ahmad, M.H.; Mohamad, F.; AbdulGhani, A. Sustainable adoption of biodegradable plastics: A quantitative analysis of determinants and consumer behaviour in developing economies. *Manag. Environ. Qual. Int. J.* **2025**, *36*, 706–740. [CrossRef]
199. Etuk, S.E.; Robert, U.W.; Agbasi, O.E.; Inyang, N.J. Evaluation of thermophysical and strength properties of composite panels produced from sugarcane bagasse and waste newspapers. *Adv. Mater. Sci.* **2023**, *23*, 19–31. [CrossRef]
200. Barthwal, S.; Uniyal, S.; Barthwal, S. Nature-inspired superhydrophobic coating materials: Drawing inspiration from nature for enhanced functionality. *Micromachines* **2024**, *15*, 391. [CrossRef]
201. Czepiel, M.; Bańkosz, M.; Sobczak-Kupiec, A. Advanced injection molding methods. *Materials* **2023**, *16*, 5802. [CrossRef]
202. Haile, A.; Gelebo, G.G.; Tesfaye, T.; Mengie, W.; Mebrate, M.A.; Abuhay, A.; Limeneh, D.Y. Pulp and paper mill wastes: Utilizations and prospects for high value-added biomaterials. *Bioresour. Bioprocess.* **2021**, *8*, 35. [CrossRef]
203. Hielm, A.; Sampson, G.; Pampin, M.P.; Treweek, J.; McCord, M.; Newsom, M.D.; Thorning, A.; Monaghan, J.; De Olde, E.; Heilandt, T. *Improving Standards and Certification in Agri-Food Supply Chains: Ensuring Safety, Sustainability and Social Responsibility*; Burleigh Dodds Science Publishing: Cambridge, UK, 2024; Volume 148, ISBN 1-80146-452-9.
204. Hossam, Y.; Fahim, I.S. Towards a circular economy: Fabrication and characterization of biodegradable plates from sugarcane waste. *Front. Sustain. Food Syst.* **2023**, *7*, 1220324. [CrossRef]
205. Afshar, S.V.; Boldrin, A.; Christensen, T.H.; Corami, F.; Daugaard, A.E.; Rosso, B.; Hartmann, N.B. Disintegration of commercial biodegradable plastic products under simulated industrial composting conditions. *Sci. Rep.* **2025**, *15*, 8569. [CrossRef]
206. Domínguez-Solera, E.; Gadaleta, G.; Ferrero-Aguar, P.; Navarro-Calderón, Á.; Escrig-Rondán, C. The biodegradability of plastic products for agricultural application: European regulations and technical criteria. *Clean Technol.* **2025**, *7*, 11. [CrossRef]

207. Santos, T.J.C.d. Organization and Management of Maintenance Indexed to Risk Factors in Healthcare Environment. Master's Thesis, Polytechnic Institute of Coimbra, Coimbra, Portugal, 2017.
208. Thapliyal, D.; Karale, M.; Diwan, V.; Kumra, S.; Arya, R.K.; Verros, G.D. Current status of sustainable food packaging regulations: Global perspective. *Sustainability* **2024**, *16*, 5554. [CrossRef]
209. Bijimol, B.I.; Elias, L.; Sreelekshmy, B.R.; Shibli, S.M.A. Effective Exploitation of Sugarcane Byproducts and Industrial Effluents for Strategic Energy Applications: A Review on Recent Developments and Approaches with Special Reference to Microbial Fuel Cells. *ACS Appl. Bio Mater.* **2025**, *8*, 3657–3690. [CrossRef]
210. Ding, Z.; Grundmann, P. Understanding system interdependencies in sustainable paper production from residue grass biomass: Insights from fuzzy cognitive mapping. *Sci. Rep.* **2025**, *15*, 1398. [CrossRef] [PubMed]
211. Rainey, T.J.; Covey, G. Pulp and paper production from sugarcane bagasse. In *Sugarcane-Based Biofuels and Bioproducts*; John Wiley and Sons: Hoboken, NJ, USA, 2016; pp. 259–280.
212. Andrade, M.F.; Colodette, J.L. Dissolving pulp production from sugar cane bagasse. *Ind. Crops Prod.* **2014**, *52*, 58–64. [CrossRef]
213. Ashori, A.; Marashi, M.; Ghasemian, A.; Afra, E. Utilization of sugarcane molasses as a dry-strength additive for old corrugated container recycled paper. *Compos. Part B Eng.* **2013**, *45*, 1595–1600. [CrossRef]
214. Sharma, M.; Durães, L.; Soares, B.; Alves, J.L.; Ferreira, P.J. Strengthening of sustainable packaging: Impact of microfibrillated cellulose in the presence of industrial white-water. *Cellulose* **2025**, *32*, 4387–4401. [CrossRef]
215. Sathish, M.; Radhika, N.; Venuvanka, N.; Rajeshkumar, L. A review on sustainable properties of plant fiber-reinforced polymer composites: Characteristics and properties. *Polym. Int.* **2024**, *73*, 887–943. [CrossRef]
216. Rajan, K.; Berton, P.; Rogers, R.D.; Shamshina, J.L. Is Kraft Pulping the Future of Biorefineries? A Perspective on the Sustainability of Lignocellulosic Product Development. *Polymers* **2024**, *16*, 3438. [CrossRef]
217. Li, J.; Wei, X.; Wang, Q.; Chen, J.; Chang, G.; Kong, L.; Su, J.; Liu, Y. Homogeneous isolation of nanocellulose from sugarcane bagasse by high pressure homogenization. *Carbohydr. Polym.* **2012**, *90*, 1609–1613. [CrossRef]
218. Zhong, Z.-W. Processes for environmentally friendly and/or cost-effective manufacturing. *Mater. Manuf. Process.* **2021**, *36*, 987–1009. [CrossRef]
219. Barbosa, L.d.S.N.S.; Hytönen, E.; Vainikka, P. Carbon mass balance in sugarcane biorefineries in Brazil for evaluating carbon capture and utilization opportunities. *Biomass Bioenergy* **2017**, *105*, 351–363. [CrossRef]
220. Khan, M.F. Recent advances in microbial enzyme applications for sustainable textile processing and waste management. *Sci* **2025**, *7*, 46. [CrossRef]
221. El-Feky, M.; Badawy, A.H.; Helal, Y. Nanotechnology-Enabled Innovations in Cement: Enhancing Durability, and Impact Load Resistance with Nanocellulose, Nano Silica, and Nano Clay Additives. *Egypt. J. Chem.* **2025**, *68*, 223–231. [CrossRef]
222. Shen, D.; Chen, L.; Wu, S.; Chen, K.; Qi, D.; Zhu, S. Fibrillation in cellulose-based Lyocell: Chemical insights, engineering solutions and emerging challenges. *Carbohydr. Polym.* **2025**, *363*, 123722. [CrossRef]
223. Kichonge, B.; Kivevele, T. Viability of non-edible oilseed plants and agricultural wastes as feedstock for biofuels production: A techno-economic review from an African perspective. *Biofuels Bioprod. Biorefin.* **2023**, *17*, 1382–1410. [CrossRef]
224. Markevičiūtė, Z. Creation of a Biodegradable Paper-Based Packaging Material with Additives Enhancing Biodegradability in the Context of the Circular Economy. Ph.D. Thesis, Kaunas University of Technology, Kaunas, Lithuania, 2025.
225. Kumar, B. A Comprehensive Analysis of Sugarcane Bagasse as a Sustainable Solution for Environmentally Friendly Paper Manufacturing. In *The Economics of Learning: Shaping Student Welfare and Society*; Board of Editors, Ed.; Bharti Publications: New Delhi, India, 2024; pp. 24–35, ISBN 978-81-976277-2-9.
226. Yadav, M.; Maurya, A.K.; Chaurasia, S.K. Eco-friendly polymer composites for green packaging: Environmental policy, governance and legislation. In *Sustainable Packaging Strengthened by Biomass*; Elsevier: Amsterdam, The Netherlands, 2025; pp. 317–346.
227. Moutinho, L.G.; Soares, E.; Oliveira, M. Bio-based thermoplastic composites reinforced with natural fillers for sustainable packaging: A comprehensive review. *Polym. Compos.* **2025**, *46*, 9703–9727. [CrossRef]
228. Priya, A.; Alagumalai, A.; Balaji, D.; Song, H. Bio-based agricultural products: A sustainable alternative to agrochemicals for promoting a circular economy. *RSC Sustain.* **2023**, *1*, 746–762. [CrossRef]
229. Chandel, S.; Shaji, A.; Chutturi, M. Life Cycle Assessment of Biocomposites: Environmental Impacts and Sustainability Perspectives. In *Innovations and Applications of Advanced Biomaterials in Healthcare and Engineering*; IGI Global Scientific Publishing: Hershey, PA, USA, 2025; pp. 439–502.
230. Omran, A.A.B.; Mohammed, A.A.; Sapuan, S.; Ilyas, R.; Asyraf, M.; Rahimian Koloor, S.S.; Petrů, M. Micro-and nanocellulose in polymer composite materials: A review. *Polymers* **2021**, *13*, 231. [CrossRef]
231. Mandal, A.; Chakrabarty, D. Isolation of nanocellulose from waste sugarcane bagasse (SCB) and its characterization. *Carbohydr. Polym.* **2011**, *86*, 1291–1299. [CrossRef]
232. Lee, W.; Kim, J.; Lee, T.G. Certifications and testing methods for biodegradable plastics. *Rev. Chem. Eng.* **2025**, *41*, 125–146. [CrossRef]

233. Trache, D.; Tarchoun, A.F.; Derradji, M.; Hamidon, T.S.; Masruchin, N.; Brosse, N.; Hussin, M.H. Nanocellulose: From fundamentals to advanced applications. *Front. Chem.* **2020**, *8*, 392. [CrossRef]
234. Catarino, M.L.; Sampaio, F.; Gonçalves, A.L. Sustainable Wet Processing Technologies for the Textile Industry: A Comprehensive Review. *Sustainability* **2025**, *17*, 3041. [CrossRef]
235. Rao, H.J.; Singh, S.; Ramulu, P.J.; Singh, N.; Santos, T.F.; Santos, C.M.; Nadar, N.R.; Kumar, G.D. Nature-inspired nano cellulose materials, advancements in nano cellulose preparation and versatile applications. In *Nanocellulose-Sources, Preparations, and Applications*; IntechOpen: London, UK, 2024; ISBN 1-83769-259-9.
236. Pascoli, D.U. *Nanocellulose Production from Low-Cost Agricultural Residues: Process Development, Economic Assessment, and Process Robustness*; University of Washington: Washington, DC, USA, 2022; ISBN 979-8-3514-3969-3.
237. Afolalu, S.A.; Ikumapayi, O.M.; Ogedengbe, T.S.; Kazeem, R.A.; Ogundipe, A.T. Waste pollution, wastewater and effluent treatment methods—An overview. *Mater. Today Proc.* **2022**, *62*, 3282–3288. [CrossRef]
238. Krexner, T.; Bauer, A.; Zollitsch, W.; Weiland, K.; Bismarck, A.; Mautner, A.; Medel-Jiménez, F.; Gronauer, A.; Kral, I. Environmental life cycle assessment of nano-cellulose and biogas production from manure. *J. Environ. Manag.* **2022**, *314*, 115093. [CrossRef] [PubMed]
239. Fekiač, J.J.; Krbata, M.; Kohutiar, M.; Janík, R.; Kakošová, L.; Breznická, A.; Eckert, M.; Mikuš, P. Comprehensive Review: Optimization of Epoxy Composites, Mechanical Properties, & Technological Trends. *Polymers* **2025**, *17*, 271. [CrossRef]
240. Silva, F.A.; Dourado, F.; Gama, M.; Poças, F. Nanocellulose bio-based composites for food packaging. *Nanomaterials* **2020**, *10*, 2041. [CrossRef]
241. Tofanica, B.-M.; Mikhailidi, A.; Fortună, M.E.; Rotaru, R.; Ungureanu, O.C.; Ungureanu, E. Cellulose Nanomaterials: Characterization Methods, Isolation Techniques, and Strategies. *Crystals* **2025**, *15*, 352. [CrossRef]
242. Castellanos, H.G.; Aryanfar, Y.; Mohtaram, S.; Keçebaş, A.; Karaca-Dolgun, G.; Ahmad, S.; Asiri, A.N.M.; Islam, S. The efficacy of nano-cellulose-based composites in heavy metal removal from wastewater: A comprehensive review. *J. Chem. Technol. Biotechnol.* **2025**, *100*, 291–312. [CrossRef]
243. Yazdizadeh, M.; Nasr, M.J.; Safekordi, A. A new catalyst for the production of furfural from bagasse. *RSC Adv.* **2016**, *6*, 55778–55785. [CrossRef]
244. Franca-Oliveira, G.; Fornari, T.; Hernández-Ledesma, B. A review on the extraction and processing of natural source-derived proteins through eco-innovative approaches. *Processes* **2021**, *9*, 1626. [CrossRef]
245. Abdel-Hakim, A.; Mouradb, R.M. Nanocellulose and its polymer composites: Preparation, characterization, and applications. *Russ. Chem. Rev* **2023**, *92*, 5076. [CrossRef]
246. Ramnani, P.; Singh, R.; Gupta, R. Keratinolytic potential of Bacillus licheniformis RG1: Structural and biochemical mechanism of feather degradation. *Can. J. Microbiol.* **2005**, *51*, 191–196. [CrossRef] [PubMed]
247. Qi, X.; Wei, W.; Shen, J.; Dong, W. Salecan polysaccharide-based hydrogels and their applications: A review. *J. Mater. Chem. B* **2019**, *7*, 2577–2587. [CrossRef]
248. Harrats, C.; Groeninckx, G. Reactive Processing of Polymer Blend Using Reactive Compatibilization and Dynamic Crosslinking: Phase Morphology Control and Microstructure–Property Relations. *Modif. Blending Synth. Nat. Macromol.* **2004**, *175*, 155–199.
249. Chen, S.; Ding, L.; Hou, J.; Wang, J. Glucose-Based Surfactants for the Oil and Gas Industry: A Review. *Energy Fuels* **2025**, *47*, 16100–16131. [CrossRef]
250. Singh, S.; Johri, P.; Trivedi, M.; Lopez-Sanchez, P. *Green Biotechnology for Herbal and Medicinal Plant Metabolites*; CRC Press: Boca Raton, FL, USA, 2025; ISBN 1-040-34011-3.
251. Sharmile, N.; Chowdhury, R.R.; Desai, S. A comprehensive review of quality control and reliability research in micro–nano technology. *Technologies* **2025**, *13*, 94. [CrossRef]
252. Bechthold, I.; Bretz, K.; Kabasci, S.; Kopitzky, R.; Springer, A. Succinic acid: A new platform chemical for biobased polymers from renewable resources. *Chem. Eng. Technol.* **2008**, *31*, 647–654. [CrossRef]
253. Corona-González, R.I.; Varela-Almanza, K.M.; Arriola-Guevara, E.; Martínez-Gómez, Á.d.J.; Pelayo-Ortiz, C.; Toriz, G. Bagasse hydrolyzates from *Agave tequilana* as substrates for succinic acid production by *Actinobacillus succinogenes* in batch and repeated batch reactor. *Bioresour. Technol.* **2016**, *205*, 15–23. [CrossRef]
254. Chen, J.; Yang, S.; Alam, M.d.A.; Wang, Z.; Zhang, J.; Huang, S.; Zhuang, W.; Xu, C.; Xu, J. Novel biorefining method for succinic acid processed from sugarcane bagasse. *Bioresour. Technol.* **2021**, *324*, 124615. [CrossRef]
255. Gottardo, S.; Mech, A.; Drbohlavová, J.; Małyska, A.; Bøwadt, S.; Sintes, J.R.; Rauscher, H. Towards safe and sustainable innovation in nanotechnology: State-of-play for smart nanomaterials. *NanoImpact* **2021**, *21*, 100297. [CrossRef]
256. Dulie, N.W.; Woldeyes, B.; Demsash, H.D. Synthesis of lignin-carbohydrate complex-based catalyst from Eragrostis tef straw and its catalytic performance in xylose dehydration to furfural. *Int. J. Biol. Macromol.* **2021**, *171*, 10–16. [CrossRef]
257. Trung, T.Q.; Thinh, D.B.; Anh, T.N.M.; Nguyet, D.M.; Quan, T.H.; Viet, N.Q.; Tuan, T.T.; Dat, N.M.; Nam, H.M.; Hieu, N.H. Synthesis of furfural from sugarcane bagasse by hydrolysis method using magnetic sulfonated graphene oxide catalyst. *Vietnam J. Chem.* **2020**, *58*, 245–250. [CrossRef]

258. Yu, S.-B.; Lin, F.; Tian, J.; Yu, J.; Zhang, D.-W.; Li, Z.-T. Water-soluble and dispersible porous organic polymers: Preparation, functions and applications. *Chem. Soc. Rev.* **2022**, *51*, 434–449. [CrossRef] [PubMed]
259. Mohamed, A.T. *Design and Investment of High Voltage Nanodielectrics*; IGI Global: Hershey, PA, USA, 2020; ISBN 1-7998-3830-7.
260. Zhang, Y.; Luan, H.; Qiu, W.; Zhang, X.; Wang, H.; Liu, M.; Song, P. Advances in vanillin synthesis: Focusing on microbial synthesis pathways and prospects. *World J. Microbiol. Biotechnol.* **2025**, *41*, 1–20. [CrossRef] [PubMed]
261. Buchner, G.A.; Stepputat, K.J.; Zimmermann, A.W.; Schomäcker, R. Specifying technology readiness levels for the chemical industry. *Ind. Eng. Chem. Res.* **2019**, *58*, 6957–6969. [CrossRef]
262. Kumar, V.; Yadav, S.K.; Kumar, J.; Ahluwalia, V. A critical review on current strategies and trends employed for removal of inhibitors and toxic materials generated during biomass pretreatment. *Bioresour. Technol.* **2020**, *299*, 122633. [CrossRef]
263. D'Arrigo, P.; Rossato, L.A.; Strini, A.; Serra, S. From waste to value: Recent insights into producing vanillin from lignin. *Molecules* **2024**, *29*, 442. [CrossRef]
264. Yılbaşı, Z. Biofuels, E-Fuels, and Waste-Derived Fuels: Advances, Challenges, and Future Directions. *Sustainability* **2025**, *17*, 6145. [CrossRef]
265. Dulie, N.W.; Woldeyes, B.; Demsash, H.D. Xylose Release from Sugarcane Bagasse via Acid-Catalyzed Hydrothermal Reaction and Its Conversion into Furfural Using Teff (Eragrostis tef) Straw-Based Catalyst. *Waste Biomass Valorization* **2022**, *13*, 955–965. [CrossRef]
266. Banerjee, G.; Chattopadhyay, P. Vanillin biotechnology: The perspectives and future. *J. Sci. Food Agric.* **2019**, *99*, 499–506. [CrossRef]
267. Singh, M.; Kumar, S.; Ali, H.; Singh, S.; Kansal, S.K. Valorization of lignocellulosic biomass into high-value chemicals: Forging a route towards the circular economy. In *Energy Materials*; CRC Press: Boca Raton, FL, USA, 2024; pp. 98–133, ISBN 1-003-26977-X.
268. Alemde, V. Innovative process technologies: Advancing efficiency and sustainability through optimization and control. *Int. J. Res. Publ. Rev.* **2025**, *6*, 1941–1955. [CrossRef]
269. Formann, S.; Hahn, A.; Janke, L.; Stinner, W.; Sträuber, H.; Logroño, W.; Nikolausz, M. Beyond sugar and ethanol production: Value generation opportunities through sugarcane residues. *Front. Energy Res.* **2020**, *8*, 579577. [CrossRef]
270. Qi, B.; Chen, X.; Shen, F.; Su, Y.; Wan, Y. Optimization of enzymatic hydrolysis of wheat straw pretreated by alkaline peroxide using response surface methodology. *Ind. Eng. Chem. Res.* **2009**, *48*, 7346–7353. [CrossRef]
271. Sindhu, R.; Kuttiraja, M.; Binod, P.; Janu, K.U.; Sukumaran, R.K.; Pandey, A. Dilute acid pretreatment and enzymatic saccharification of sugarcane tops for bioethanol production. *Bioresour. Technol.* **2011**, *102*, 10915–10921. [CrossRef] [PubMed]
272. Sadik, M.W.; Halema, A.A. Production of ethanol from molasses and whey permeate using yeasts and bacterial strains. *Int. J. Curr. Microbiol. App. Sci* **2014**, *3*, 804–818.
273. Domingues, R.; Bondar, M.; Palolo, I.; Queirós, O.; de Almeida, C.D.; Cesário, M.T. Xylose metabolism in bacteria—Opportunities and challenges towards efficient lignocellulosic biomass-based biorefineries. *Appl. Sci.* **2021**, *11*, 8112. [CrossRef]
274. Sobti, R.; Sharma, A.; Soni, S.K. Applications of Biotechnological Techniques in Mitigating Environmental Concerns. In *Genomic, Proteomics, and Biotechnology*; CRC Press: Boca Raton, FL, USA, 2022; pp. 249–312.
275. Paschoa, J.L.; Avila, P.F.; Ramalho, E.X.; Silva, M.F.; Bueno, D.; Goldbeck, R. Production and purification of xylooligossaccharides from sugarcane bagasse and antioxidant potential assessment for functional ingredient application in the food industry. *Ind. Crops Prod.* **2024**, *208*, 117844. [CrossRef]
276. Bloch, P.-Y. Industrialisation of the Production of a Technological Innovation with a Significant Environmental Gain Potential: Application to Bio-Enzymatic Cells. Ph.D. Thesis, University of Grenoble Alpes, Saint-Martin-d'Hères, France, 2024.
277. Arshad, M.; Ahmed, S. Cogeneration through bagasse: A renewable strategy to meet the future energy needs. *Renew. Sustain. Energy Rev.* **2016**, *54*, 732–737. [CrossRef]
278. Su, G.; Jiang, P.; Zhou, H.; Zulkifli, N.W.M.; Ong, H.C.; Ibrahim, S. Integrated production of methanol and biochar from bagasse and plastic waste: A three-in-one solution for carbon sequestration, bioenergy production, and waste valorization. *Energy Convers. Manag.* **2024**, *307*, 118344. [CrossRef]
279. Lynd, L.R.; Beckham, G.T.; Guss, A.M.; Jayakody, L.N.; Karp, E.M.; Maranas, C.; McCormick, R.L.; Amador-Noguez, D.; Bomble, Y.J.; Davison, B.H. Toward low-cost biological and hybrid biological/catalytic conversion of cellulosic biomass to fuels. *Energy Environ. Sci.* **2022**, *15*, 938–990. [CrossRef]
280. Osaki, M.R. An energy optimization model comparing the use of sugarcane bagasse for power or ethanol production. *Ind. Crops Prod.* **2022**, *187*, 115284. [CrossRef]
281. Preparing an Ion Exchange Resin from Sugarcane Bagasse to Remove Reactive Dye from Wastewater. EBSCOhost. Available online: https://openurl.ebsco.com/contentitem/gcd:31830969?sid=ebsco:plink:crawler&id=ebsco:gcd:31830969 (accessed on 19 August 2025).

282. Rodier, L.; Bilba, K.; Onésippe, C.; Arsène, M.-A. Utilization of bio-chars from sugarcane bagasse pyrolysis in cement-based composites. *Ind. Crops Prod.* **2019**, *141*, 111731. [CrossRef]
283. Okonkwo, C.A.; Menkiti, M.C.; Obiora-Okafo, I.A.; Ezenwa, O.N. Controlled pyrolysis of sugarcane bagasse enhanced mesoporous carbon for improving capacitance of supercapacitor electrode. *Biomass Bioenergy* **2021**, *146*, 105996. [CrossRef]
284. Ramaraj, B. Mechanical and thermal properties of polypropylene/sugarcane bagasse composites. *J. Appl. Polym. Sci.* **2007**, *103*, 3827–3832. [CrossRef]
285. Janjaturaphan, S.; Wansom, S. Pozzolanic activity of industrial sugar cane bagasse ash. *Suranaree J. Sci. Technol.* **2010**, *17*, 487–498.
286. Jaturapiree, A.; Saowapark, T.; Sukrat, K.; Chaichana, E. Hydrothermal Extraction of Cellulose from Sugarcane Bagasse for Production of Biodegradable Food Containers. *Recycling* **2025**, *10*, 110. [CrossRef]
287. Jackson de Moraes Rocha, G.; Martin, C.; Soares, I.B.; Souto Maior, A.M.; Baudel, H.M.; Moraes de Abreu, C.A. Dilute mixed-acid pretreatment of sugarcane bagasse for ethanol production. *Biomass Bioenergy* **2011**, *35*, 663–670. [CrossRef]
288. Wanderley, M.C.d.A.; Martín, C.; Rocha, G.J.d.M.; Gouveia, E.R. Increase in ethanol production from sugarcane bagasse based on combined pretreatments and fed-batch enzymatic hydrolysis. *Bioresour. Technol.* **2013**, *128*, 448–453. [CrossRef]
289. Gottschalk, L.M.F.; Oliveira, R.A.; Bon, E.P.d.S. Cellulases, xylanases, β-glucosidase and ferulic acid esterase produced by *Trichoderma* and *Aspergillus* act synergistically in the hydrolysis of sugarcane bagasse. *Biochem. Eng. J.* **2010**, *51*, 72–78. [CrossRef]
290. Manavalan, T.; Manavalan, A.; Thangavelu, K.P.; Heese, K. Secretome analysis of *Ganoderma lucidum* cultivated in sugarcane bagasse. *J. Proteom.* **2012**, *77*, 298–309. [CrossRef]
291. Lamounier, K.F.R.; Rodrigues, P.O.; Pasquini, D.; Baffi, M.A. Saccharification of Sugarcane Bagasse Using an Enzymatic Extract Produced by Aspergillus fumigatus. *J. Renew. Mater.* **2018**, *6*, 169–175. [CrossRef]
292. Mohammadi, A.; Nasernejad, B. Enzymatic degradation of anthracene by the white rot fungus Phanerochaete chrysosporium immobilized on sugarcane bagasse. *J. Hazard. Mater.* **2009**, *161*, 534–537. [CrossRef] [PubMed]
293. Mazutti, M.; Bender, J.P.; Treichel, H.; Luccio, M.D. Optimization of inulinase production by solid-state fermentation using sugarcane bagasse as substrate. *Enzym. Microb. Technol.* **2006**, *39*, 56–59. [CrossRef]
294. Rajagopalan, G.; Krishnan, C. α-Amylase production from catabolite derepressed Bacillus subtilis KCC103 utilizing sugarcane bagasse hydrolysate. *Bioresour. Technol.* **2008**, *99*, 3044–3050. [CrossRef] [PubMed]
295. Bian, J.; Peng, F.; Peng, X.-P.; Peng, P.; Xu, F.; Sun, R.-C. Structural features and antioxidant activity of xylooligosaccharides enzymatically produced from sugarcane bagasse. *Bioresour. Technol.* **2013**, *127*, 236–241. [CrossRef]
296. Brienzo, M.; Carvalho, W.; Milagres, A.M.F. Xylooligosaccharides Production from Alkali-Pretreated Sugarcane Bagasse Using Xylanases from Thermoascus aurantiacus. *Appl. Biochem. Biotechnol.* **2010**, *162*, 1195–1205. [CrossRef]
297. Acosta Fernandez, R.A.; Viviescas, P.; Sandoval, M.; Nabarlatz, D. Autohydrolysis of sugar cane bagasse and empty fruit bunch: Kinetics model and analysis of xylo-oligosaccharides yield. *Chem. Eng. Trans.* **2018**, *65*, 307–312. [CrossRef]
298. Silalertruksa, T.; Gheewala, S.H.; Pongpat, P. Sustainability assessment of sugarcane biorefinery and molasses ethanol production in Thailand using eco-efficiency indicator. *Appl. Energy* **2015**, *160*, 603–609. [CrossRef]
299. Adeniyi, A.G.; Ighalo, J.O. Biosorption of pollutants by plant leaves: An empirical review. *J. Environ. Chem. Eng.* **2019**, *7*, 103100. [CrossRef]
300. Xiong, W. Bagasse composites: A review of material preparation, attributes, and affecting factors. *J. Thermoplast. Compos. Mater.* **2018**, *31*, 1112–1146. [CrossRef]
301. Thaha, A.N.; Ghamari, M.; Jothiprakash, G.; Velusamy, S.; Karthikeyan, S.; Ramesh, D.; Sundaram, S. High Impact Biomass Valorization for Second Generation Biorefineries in India: Recent Developments and Future Strategies for Sustainable Circular Economy. *Biomass* **2025**, *5*, 16. [CrossRef]
302. Chandel, A.K.; Da Silva, S.S.; Carvalho, W.; Singh, O.V. Sugarcane bagasse and leaves: Foreseeable biomass of biofuel and bio-products. *J. Chem. Technol. Biotechnol.* **2012**, *87*, 11–20. [CrossRef]
303. Khoo, R.; Chow, W.; Ismail, H. Sugarcane bagasse fiber and its cellulose nanocrystals for polymer reinforcement and heavy metal adsorbent: A review. *Cellulose* **2018**, *25*, 4303–4330. [CrossRef]
304. Adeleye, A.T.; Odoh, C.K.; Enudi, O.C.; Banjoko, O.O.; Osiboye, O.O.; Odediran, E.T.; Louis, H. Sustainable synthesis and applications of polyhydroxyalkanoates (PHAs) from biomass. *Process Biochem.* **2020**, *96*, 174–193. [CrossRef]
305. Hassan, S.; Ngo, T.; Ball, A.S. Valorisation of sugarcane bagasse for the sustainable production of polyhydroxyalkanoates. *Sustainability* **2024**, *16*, 2200. [CrossRef]
306. Guttman, L.; Neori, A.; Israel, A.; Shpige, M. Development of polyculture and integrated multi-trophic aquaculture (IMTA) in Israel: A review. *Isr. J. Aquac.-Bamidgeh* **2017**, *69*, 1385. [CrossRef]
307. Mod, B.; Baskar, A.V.; Bahadur, R.; Tavakkoli, E.; Van Zwieten, L.; Singh, G.; Vinu, A. From cane to nano: Advanced nanomaterials derived from sugarcane products with insights into their synthesis and applications. *Sci. Technol. Adv. Mater.* **2024**, *25*, 2393568. [CrossRef]

308. Branco, R.H.; Serafim, L.S.; Xavier, A.M. Second generation bioethanol production: On the use of pulp and paper industry wastes as feedstock. *Fermentation* **2018**, *5*, 4. [CrossRef]
309. Koller, M.; Mukherjee, A. A new wave of industrialization of PHA biopolyesters. *Bioengineering* **2022**, *9*, 74. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.