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Forest biomass valorization in Brazil: innovations in biorefineries and opportunities for a low-carbon economy

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Abstract – The objective of this review was to analyze the role of forest biomass valorization in bioeconomy and global energy transition. This study presents the contributions of emerging technologies to the production of sustainable products and their alignment with Brazil's international climate commitments, particularly the goals outlined for COP30. Given that fossil fuel combustion accounts for nearly 80% of global greenhouse gas emissions, the search for renewable energy alternatives has become a strategic priority. Biorefineries have emerged as a key pathway for converting plant- and animal-based biomass into bioenergy and renewable chemical compounds. Brazil stands out for its extensive availability of forest and agro-industrial residues, which strengthens its potential to generate high-value-added products and promote sustainable industrial practices. By-products such as lignin, nanocellulose, and agroforestry residues show a significant potential for the development of innovative materials that contribute to decarbonization strategies. The integration of Brazil's biomass resources with technological innovation may position the country as a global leader in advancing sustainable bio-based solutions.

Index terms: circular economy, emission reduction, innovation, lignocellulose, renewable bioresources, sustainability.

Valorização de biomassa florestal no Brasil: inovações em biorrefinarias e oportunidades para uma economia de baixo carbono

Resumo – O objetivo desta revisão foi analisar o papel da valorização da biomassa florestal na bioeconomia e na transição energética global. Este estudo apresenta as contribuições das tecnologias emergentes para a produção de produtos sustentáveis e sua relação com os compromissos climáticos internacionais do Brasil, em especial as metas estabelecidas para a COP30. Considerando-se que a queima de combustíveis fósseis é responsável por cerca de 80% das emissões globais de gases de efeito estufa, a busca por alternativas de energia renovável tornou-se uma prioridade estratégica. As biorrefinarias surgiram como um caminho chave para converter biomassa de origem vegetal e animal em bioenergia e compostos químicos renováveis. O Brasil se destaca pela ampla disponibilidade de resíduos florestais e agroindustriais, o que reforça seu potencial para gerar produtos de alto valor agregado e promover práticas industriais sustentáveis. Subprodutos como lignina, nanocelulose e resíduos agroflorestais mostram potencial significativo para o desenvolvimento de materiais inovadores que contribuem para estratégias de descarbonização. A integração dos recursos de biomassa do Brasil com a inovação tecnológica pode posicionar o país como líder global no avanço de soluções sustentáveis de base biológica.

Termos para indexação: economia circular, redução de emissões, inovação, lignocelulose, biorrecursos renováveis, sustentabilidade.

Introduction

Projections of the global population indicate that the Earth will have 9.8 billion inhabitants by 2050, which will intensify the demand for food and energy, allowing critical challenges and potential conflicts, if no effective measures are taken (Flies et al., 2018). The reliance on fossil fuels exacerbates these challenges, since CO_2 emissions from combustion of these fuels accounts for approximately 80% of greenhouse gases, making them one of the main contributors to climate change (Gür, 2024). To mitigate these impacts and ensure a more sustainable economy, decarbonization of the energy matrix has become a global strategic goal.

Biorefineries emerge as a promising alternative, since they enable the sustainable use of plant and animal biomass, reducing the dependence on fossil fuels and contributing to energy diversification and climate change mitigation (Raina et al., 2024). The growth of this market reflects this trend, with projections indicating that the sector may reach USD 1.1 trillion by 2027, driven by increasing demand for advanced biofuels, bioenergy, and renewable chemicals (Abdullah et al., 2024). Furthermore, international commitments, such as the Paris Agreement and the guidelines established at COP26 (Conference of the Parties) and the COP30, held in Brazil in 2025, underscore the strategic importance of biorefineries in the global energy transition (Pattanaik & Nayak, 2023).

Agribusiness, circular economy and biorefineries

Agribusiness is composed of a network of economic agents that form the agro-industrial system, which is subdivided into production chains that require logistical integration between industry, agricultural production, and the consumer market. This system encompasses activities that allow of the transformation of raw materials into products (Figure 1) (Stein et al., 2019).

Currently, agribusiness is a complex fusion of economic activities derived from agriculture, livestock, and the forestry sector, accounting for about one-third of the gross domestic product (GDP) (Silva et al., 2021). Within these activities, agroindustry stands out. Due to technological advances and growing demands for sustainable solutions, agroindustry plays a key role in the consolidation of biorefineries, which have emerged as integrated and efficient models for biomass utilization (Vaz-Junior, 2020). Compared to other industrial sectors, agroindustry presents certain peculiarities given the characteristics of its raw materials, such as seasonality, perishability, and heterogeneity (Vaz-Junior, 2020).

Thus, biorefineries have emerged as integrated industrial units, usually located near agricultural zones, capable of full utilization of plant biomass,

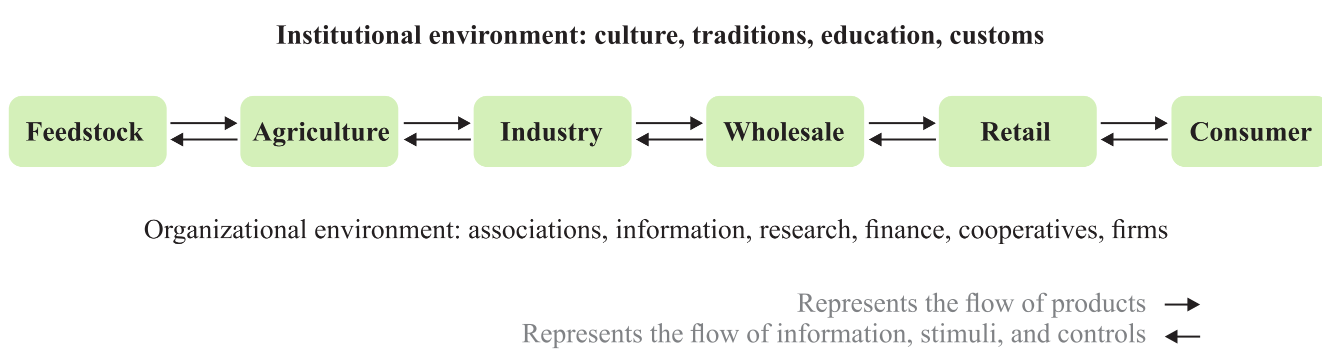

Figure 1. Stages of the agro-industrial value chain. Source: adapted from Nassar (2001).

whose conversion is promoted by these units into a variety of high-value-added products, such as biofuels, chemicals, and materials (Solarte-Toro & Cardona Alzate, 2023). In this context, the efficient management of losses and waste along the production chain becomes essential.

Losses and waste carry important conceptual distinctions depending on the stage at which they occur (FAO, 2021). In the agrifood sector, losses occur during the stages of production (on-farm), post-harvest, logistics, and processing, generally associated with agricultural practices, climatic conditions, phytopathological issues, mechanical damage, inadequate processing, or reduced industrial efficiency, among other factors (FAO, 2021). Waste refers to the reduction or disposal of products during distribution and final consumption stages, usually resulting from excessive consumption, improper storage practices, or disposal based on aesthetic standards (FAO, 2021). Thus, when biomass reduction or disposal occurs in the earlier stages of the chain, up to industrial processing, the term “losses” is conventionally used (Figure 2).

Integrated into the logic of the bioeconomy, several initiatives have sought to valorize residue of sugarcane, one of the most important agro-industrial crops in Brazil, not only because of sugar and ethanol production, but also because of its by-products, such as straw, bagasse, and vinasse (Sari et al., 2021). Bagasse is an abundant lignocellulosic residue, which is extensively studied in second-generation ethanol production through enzymatic hydrolysis and fermentation, allowing of increased output without expanding cultivated areas (Sari et al., 2021). Moreover, straw and bagasse have been used as biomass for bioelectricity generation, contributing to the diversification of Brazil’s energy matrix (Magalhães, 2019; Sari et al., 2021). Vinasse, a by-product of the fermentation process, can be reused as a biofertilizer, promoting nutrient return to the soil, and improving crop efficiency (Magalhães, 2019).

Other residues, such as sawdust, wood dust, and chips, produced by the timber and pulp industries, have emerged as important inputs for bioenergy production, reducing dependence on fossil fuel (Ahmad et al., 2024). The conversion of these materials into solid biofuels, such as pellets, or even into cellulosic ethanol, provides viable and environmentally responsible energy alternatives (Calvin et al., 2021). Simultaneously, the transformation of sawdust into biomaterials and biocomposites found new applications in civil construction, furniture, and packaging industries, fostering circularity and innovation (Sari et al., 2021).

Coffee residue from the production chain, such as husks, spent coffee grounds, and coffee powder, offer a wide range of possibilities. Husks can be converted into briquettes or pellets for energy use, while the spent grounds, rich in bioactive compounds, such as polyphenols and flavonoids, have been explored by the cosmetics and pharmaceutical industries for their antioxidant potential (Magalhães, 2019). Additionally, solid residue from processing can be used as substrates for the production of industrial enzymes, such as cellulase, with applications in the textile and food industries (Ahmad et al., 2024).

Traditionally discarded, husk and mesocarp from coconut production have gained prominence. When used as biomass, these materials allow of the generation of renewable bioenergy (Sari et al., 2021). Coconut fiber is considered a promising raw material for the production of bioplastics and compostable materials, offering a viable alternative to petroleum-derived synthetic polymers (Ahmad et al., 2024). Residual oil, still present after primary extraction, can also be incorporated into cosmetic formulations, showing the versatility of this residue (Magalhães, 2019).

Residue generated during the soybean processing, such as meal, husks, and by-products from oil extraction, are considered strategic. Soybean meal can be converted into biodiesel and ethanol, due to its high lipid and carbohydrate contents (Calvin et al., 2021). Furthermore,

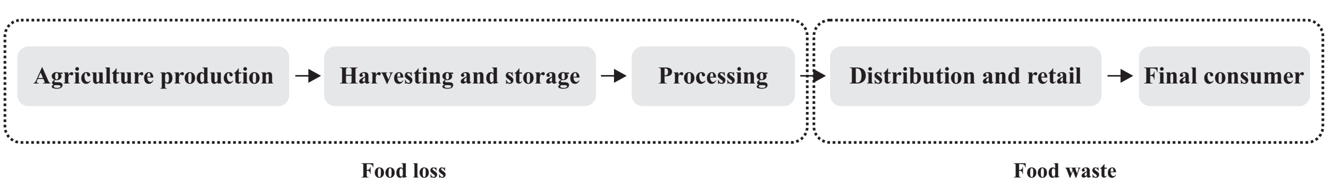

Figure 2. Food losses and waste in the production chain. Source: adapted from FAO (2019).

it has a broad applicability in the production of plant-based proteins for human and animal consumption, meeting the growing demand for alternatives to animal-based proteins (Magalhães, 2019).

Biomass conversion

The biomass energy conversion can be classified into two major categories: biochemical and thermochemical processes (Seo et al., 2022; Yaashikaa et al., 2022). Biochemical platforms use microorganisms and enzymatic processes to transform pretreated biomass into biofuels (Seo et al., 2022). Additionally, hybrid platforms integrate the advantages of both routes, enhancing overall conversion efficiency (Yaashikaa et al., 2022). Biorefinery techniques not only improve the efficiency of conversion processes, but also make it possible the production of more sustainable and lower-cost materials, adding value to available agro-industrial residues (Yaashikaa et al., 2022).

Thermochemical biomass conversions such as combustion, liquefaction, torrefaction, pyrolysis, and gasification involve the heating at specific temperature ranges to produce biochar, bio-oil, syngas, and heat for energy and transport applications (Figure 3) (Wang & Wu, 2023). When used as a pretreatment, torrefaction reduces moisture, partially decomposes biomass, and increases carbon content and hydrophobicity, producing a solid with enhanced combustion performance, suitable as coal substitute (Wang & Wu, 2023). Liquefaction occurs under high pressure and relatively low temperatures allowing biomass decomposition into small molecular fragments in water and other solvents. These fragments are light, unstable, and reactive, and can repolymerize into oily compounds of a wide range of molecular weights. In lignocellulosic biomass, the abundance of hydroxyl groups can be converted through liquefaction into intermediates, for the production of biopolymers, polyurethane foams, plywood adhesives, and other products (Zhang et al., 2010). Pyrolysis can be conducted in slow, fast, or flash modes, depending on the heating rate, resulting in biochar, bio-oil, or gas. The specific composition of pyrolysis products depends on the original biomass (Hu & Gholizaden, 2019). Hemicellulose is converted mainly into volatile products, cellulose into char and volatile compounds (acetol, furfural, and formaldehyde), and lignin into gaseous, liquid, and solid products (formaldehyde, acetaldehyde, phenolic

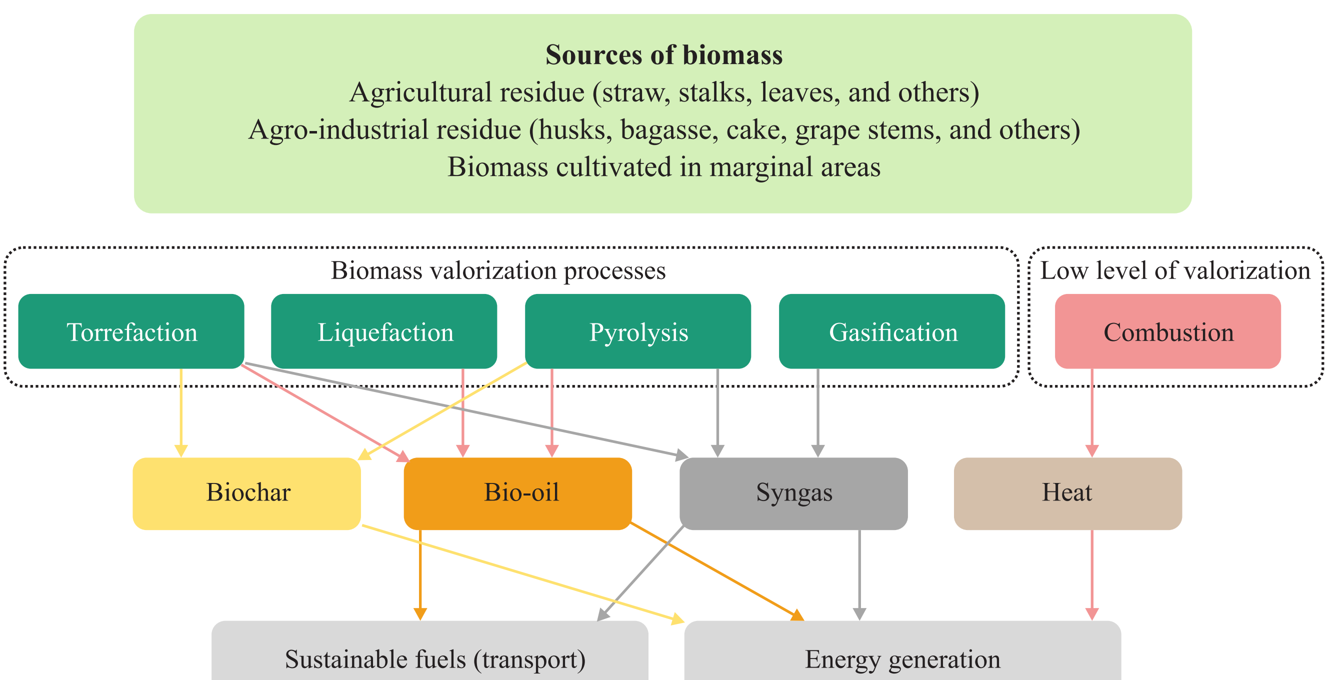

Figure 3. Thermochemical conversion of biomass: principal route 1. Source: adapted from Wang & Wu (2023).

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compounds, guaiacol, and charcoal). Gasification encompasses heating, devolatilization, and oxidation processes. Heating removes moisture; devolatilization releases gases, tar, and char; and oxidation provides heat necessary to drive, following endothermic reduction reactions, resulting in gaseous products from conversion of volatiles (homogeneous oxidation) and char (heterogeneous oxidation). The resulting gases primarily include hydrogen, carbon monoxide, carbon dioxide, water vapor, methane, and hydrocarbons, with composition influenced by the characteristics of the biomass feedstock (Segurado et al., 2019).

The biochemical conversion of biomass refers to a process in which microorganisms degrade organic matter and transform it into products, such as alcohols, fatty acids, gases, biofuels, bioproducts, and biofertilizers. Anaerobic digestion and fermentation are the main technologies used (Ciliberti et al., 2020; Awasthi et al., 2023). These processes are particularly beneficial for materials with high-moisture content, as they allow of conversion without the need for removing large volumes of water, making them an efficient and environmentally sustainable solution (Ciliberti et al., 2020). According to Awasthi et al. (2023), this method shows a great potential for converting lignocellulosic biomass into high value-added products, due to its ability to break down efficiently the structural components of biomass, including cellulose, hemicellulose, and lignin, into commercially valuable compounds (Figure 4). Among the most explored biochemical routes is fermentation, a biological process in which microorganisms, such as yeasts and bacteria, convert organic matter into industrially relevant products such as ethanol and organic acids. Alcoholic fermentation, for example, occurs in two main steps: initially, pyruvate is decarboxylated into acetaldehyde by the enzyme pyruvate decarboxylase; then, acetaldehyde is converted into ethanol by the enzyme alcohol dehydrogenase (Zamel et al., 2024). These fermentative processes are present in industries that produce ethanol, wine, and beer. Because of fermentation, a large amount of carbon dioxide (CO_2) gas is released into the atmosphere. New studies have shown the application of carbon dioxide (CO_2) for obtaining valuable products. One factor encouraging this approach is that the CO_2 produced by fermentation units is nearly pure and easy to capture. Currently, only a portion of these fermentation units carries out carbon capture, primarily for the food industry, for beverage carbonation and food preservation (Zhang et al., 2017).

Solutions for harnessing forest

Over the past decades, studies have intensified efforts to transform industrial residues into high value-added inputs, focusing on sustainable solutions (Nizzy & Kannan, 2022). At the Universidade Federal do Paraná (UFPR) and Embrapa Forestry, professors and researchers have spearheaded innovative studies aimed at developing new methods for forest residues valorization, as shown below.

In 2025, approaches for the sustainable valorization of lignocellulosic residues were proposed, which can be organized according to the processes and products (Figure 5). The figure shows how different tree components such as leaves, wood, and residual biomass can be used across various value chains including thermochemical, biochemical, and kraft processes.

Within thermochemical processes, Aparicio et al. (2025) developed a simple and cost-effective method,

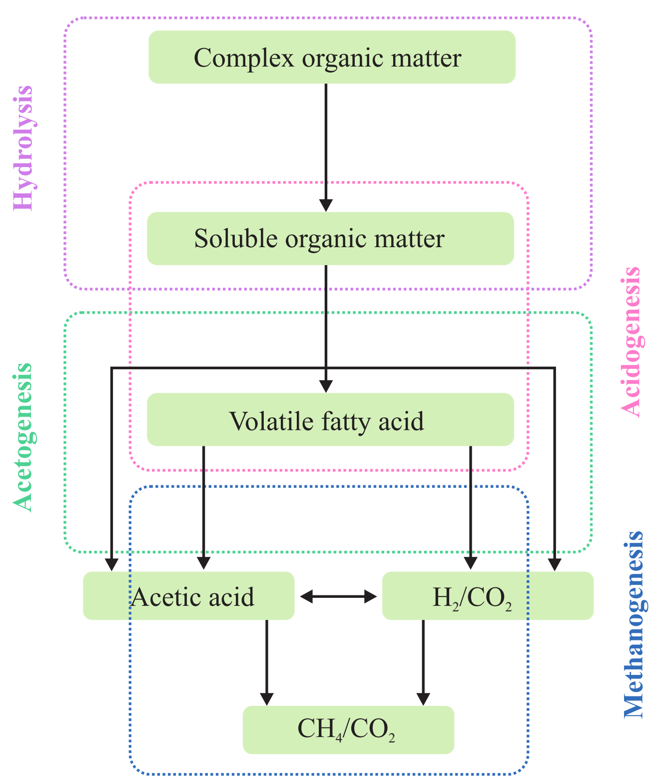

Figure 4. Stages of the anaerobic digestion process. Source: adapted from Yadav et al. (2022).

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to produce fluorescent carbon dots from pyrolytic lignin through controlled thermal pyrolysis in water. This approach utilizes lignin as a by-product of woody biomass, contributing to industrial modernization through environmentally friendly processes (Sustainable Development Goals 9.4 - SDG 9.4), promoting waste reduction via recycling and reuse (SDG 12.5), and integrating sustainable practices into climate policy (SDG 13.2). Similarly, Sanson et al. (2022) explored water-soluble fractions of pyrolytic lignin combined with bentonite nanostructures, to protect wood from physical and biological damage, enhancing water repellency and resistance to fungi.

Matos et al. (2020) demonstrated a pilot-scale fast pyrolysis of eucalyptus wood fines, generating bio-oil, charcoal, and lignin-derived compounds with high calorific value, thereby contributing to renewable energy development (SDG 7.2), waste reduction (SDG 12.5), and climate impact mitigation (SDG 13.2).

Biochemical processes offer complementary pathways for residue valorization. Arantes et al. (2025) developed cellulose-based biosorbents from peach palm residues, to remove copper from *cachaça*, highlighting the potential of cellulose for clean industrial applications and advancing SDG 9.4 and 12.5. Lima et al. (2025) reviewed strategies to enhance nanocellulose films for packaging, improving barrier and antioxidant properties through additives such as tannins and lignin, fostering innovation in biomaterials, and supporting environmentally sound chemical and waste management (SDG 9.5 and 12.4).

Oliveira et al. (2025) assessed the ecotoxicity of nanofibrillated cellulose from bleached kraft pulp, confirming its industrial safety and contributing to water pollution control (SDG 6.3), environmentally sound technology development (SDG 9.4), chemical impact reduction (SDG 12.4), and climate change mitigation capacity-building (SDG 13.3). Additionally, Leal et al. (2024) explored the use of *pinhão* (*Araucaria angustifolia*) seed coat nanosuspension in cosmetics, transforming agro-industrial waste into value-added products (SDG 12.5, 12.6, and 13.2). Quelé et al. (2025) functionalized residual curcumin with silica nanoparticles, and applied photodegradation to enhance antimicrobial and antioxidant properties, offering a sustainable solution for spice industry waste (SDG 9.4, 12.4, and 3.9).

Leaf-derived compounds, although less explored, present further opportunities. Soares et al. (2025) optimized hydrodistillation of *Corymbia citriodora*

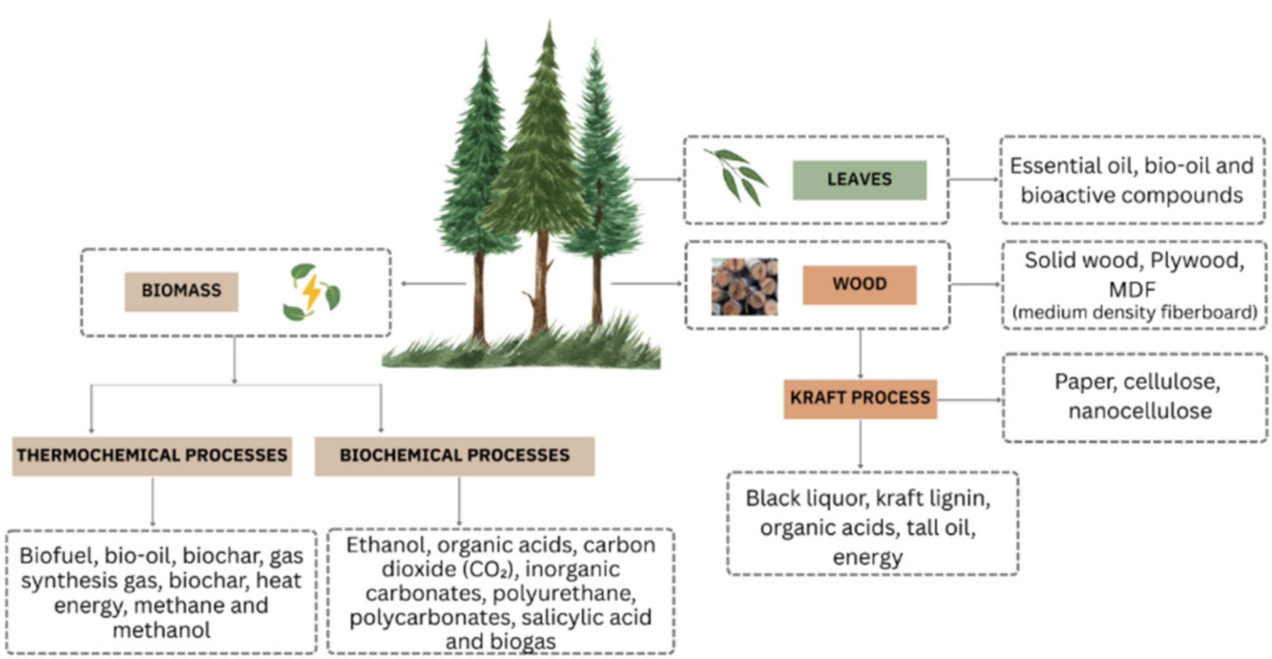

Figure 5. Overview of the valorization routes for biomass from forest resources.

leaves, showing that effluents can be reused multiple times to concentrate bioactive compounds. This method supports water quality improvement (SDG 6.3), advances scientific and technological research (SDG 9.5), and promotes the efficient use of natural resources (SDG 12.2). Despite these promising results, products derived from leaves such as essential oils and bioactive compounds remain underexplored, representing a clear opportunity for future research.

Integration of biomass research

Scientific contributions of researchers from Brazil and abroad working on the Brazilian lignocellulosic biomass have brought technical solutions aligned with the SDG of the 2030 Agenda.

Approaches for the valorization of lignocellulosic residues have focused on the extraction of bioactive compounds for wood treatment and on the development of functional materials. Leaf, bark, and other biomass by-products are recognized as promising sources of phenolic compounds with antimicrobial, antioxidant, and biocidal-substitution potential. These strategies are directly aligned with the SDG 12.5, which aims to reduce waste generation substantially through recycling and reuse, as well as with the SDG 3.9, by reducing reliance on toxic products traditionally used in the preservation of lignocellulosic materials (Mattos et al., 2023).

At the national level, Missio et al. (2018) explored the application of nanocellulose extracted from plant residues, in the development of biodegradable films and active packaging with antimicrobial and tunable barrier properties. The synthesis of materials from tannins, combined with nanocellulose, shows technical feasibility in replacing conventional plastic packaging, providing a comparable performance for specific applications. These approaches are directly aligned with the SDG 9.4, which encourages the modernization of industrial infrastructure, focusing on resource efficiency and adoption of clean technologies. Additionally, the research has investigated thermochemical and acidic pathways to convert *Eucalyptus urograndis* wood into cellulosic ethanol, expanding the potential to replace fossil fuels with renewable sources and contributing to the SDG 7.2, which aims to increase the share of renewable energy in the global energy mix (Missio et al., 2018).

Beyond chemical valorization, Cademartori et al. (2017) focused on the surface modification of lignocellulosic materials, using clean technologies such as cold plasma. The study reported the effectiveness of atmospheric plasma treatment in depositing fluorocarbon films, resulting in wood surfaces with enhanced hydrophobic properties, reducing the need for conventional chemical treatments, and contributing to the SDG 9.4 and SDG 12.4, which promote the environmentally sound management of chemicals and all wastes throughout their life cycle (Cademartori et al., 2017).

Magalhães (2019) highlighted the full utilization of forest biomass, particularly lignin, as a source of macromolecules capable of replacing petrochemical inputs in industrial formulations. In addition to investigating the antioxidant and emulsifying properties of lignin, the study promoted the concept of decentralized biorefineries focused on converting lignocellulosic residues into value-added products. These approaches are directly aligned with the SDGs 12, 13, and 15 (Magalhães, 2019).

Opportunities and challenges for Brazil to lead the global bioeconomy

The world is marked by the urgent need for sustainable practices and climate change mitigation, placing Brazil in a strategic position to lead the transition to a forest-biomass-based bioeconomy. This position derives from the country’s extensive forest resources, its high biodiversity, and the strength of consolidated sectors such as pulp and paper, timber, and forest plantations, which generate large volumes of lignocellulosic residues with potential for high-value applications (Machado et al., 2021; Bastos Lima, 2022; Freitas et al., 2024). Unlike agricultural biomass, forest biomass provides not only energy inputs, but also structural and chemical components, such as cellulose, hemicellulose, and lignin, which are essential for the development of advanced bioproducts (Machado et al., 2021).

A robust forest bioeconomy offers Brazil significant opportunities to foster sustainable socioeconomic development and technological leadership. The valorization of residues such as sawdust, bark, lignin, black liquor, and kraft pulp by-products can create new value chains within the forestry sector. For

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instance, lignin can be transformed into resins and adhesives, as well as into carbon fibers and green chemicals (Claro et al., 2025). Nanocellulose obtained through mechanical or chemical processes enables the production of films, coatings, and packaging with superior barrier and mechanical properties, in addition to serving as reinforcement in biocomposites and pharmaceutical carriers (Missio et al., 2018; Lima et al., 2025).

Pyrolysis of eucalyptus residues and industrial chips generate bio-oil, which can be used as renewable fuel and as a chemical precursor, and biochar which improves soil fertility, increases water retention, and contributes to long-term carbon sequestration (Hu et al., 2019; Matos et al., 2020).

Black liquor from kraft pulp mills, already used for energy generation, can also be refined for the recovery of lignin and other high-value compounds (Kumar & Verma, 2024).

Biocomposites based on cellulose fibers are replacing fossil-based plastics in automotive parts, construction materials, and food packaging, reducing the dependency on petroleum derivatives (Mattos et al., 2023).

Some studies indicate that these value chains can positively affect the gross domestic product, diversify income sources in forest-dependent regions, and generate green jobs in rural areas and forestry frontiers (Machado et al., 2021). In addition, the expansion of biocomposites and second-generation biofuels derived from forest biomass strengthens Brazil's position in international markets aiming at decarbonization (Bastos Lima, 2022; Freitas et al., 2024).

However, several challenges must be addressed for Brazil to fully realize these opportunities. One major issue is the need to ensure social justice and equity in forest bioeconomy initiatives (Bastos Lima, 2022). Large pulp and paper groups concentrate most of the financial gains, while traditional communities, small farms, and extractivist populations often face marginalization or limited access to technological and financial resources. Without inclusive governance, the forest bioeconomy risks reproducing existing asymmetries, rather than contributing to sustainable development (Bastos Lima, 2022).

Another critical challenge concerns the sustainable use of land and residues. Expanding forest plantations for energy or bioproduct purposes must not compromise food security, biodiversity, or hydrological cycles (Bastos Lima, 2022; Freitas et al., 2024). The conversion of native forests for industrial plantations continues to generate pressure on ecosystems, and inadequate residue management may cause soil and water contamination (Machado et al., 2021). In this context, policies for sustainable intensification, ecological restoration, and valorization of underutilized residues are essential. By promoting the reuse of by products such as black liquor from kraft pulp mills or sawmill residues, Brazil can increase efficiency without expanding the forest frontier (Freitas et al., 2024).

Technological development and the scaling up of innovations are also decisive factors. While the production of nanocellulose, lignin derivatives, and bio-oil from forest residues is advancing in research centers, most processes remain at laboratory or pilot scale, lacking proven economic feasibility at industrial levels (Hu & Gholizaden, 2019; Matos et al., 2020; Claro et al., 2025). Moving from pilot to industrial scale requires large investments in infrastructure, process integration with existing pulp and paper facilities, and optimization of logistics chains, particularly in remote regions such as the Amazon, where transportation and energy costs are limiting factors (Bastos Lima, 2022). The creation of decentralized biorefineries based on forest residues could mitigate some of these challenges, but this requires robust technological capacity building and supportive regulatory frameworks (Freitas et al., 2024).

Finally, coherent and long-term public policies are indispensable for consolidating the forest bioeconomy. Stable regulations, legal security in land use, and financial incentives, such as tax credits or green bonds, are necessary to reduce investment risks and stimulate private sector participation (Machado et al., 2021). In addition, state support must encourage diversification of the forestry sector, moving beyond traditional exports of pulp and sawn wood toward a portfolio of high value bioproducts aligned with global decarbonization goals, including advanced biomaterials, green chemicals, and bioenergy (Machado et al., 2021; Bastos Lima, 2022; Freitas et al., 2024). Without such measures, Brazil risks remaining a supplier of commodities rather than consolidating itself as a global leader in forest based technological innovation (Machado et al., 2021; Bastos Lima, 2022).

Conclusions

1. Biorefineries play a strategic role in the transition to a low-carbon economy.

2. Brazil has a broad biomass base and a consolidated scientific infrastructure.

3. National universities and institutions generate high-value-added technologies aligned with the SDGs.

4. Logistical, political, and technological barriers persist, limiting the consolidation of the bioeconomy.

5. COP30 represents an opportunity for Brazil to assert climate and technological leadership.

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Declaration of use of AI technologies

During the preparation of this work, the author(s) used ChatGPT in order to translate specific sections of the manuscript and improve the overall language quality and flow. After this use, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the contents of the publication.

Conflict of interest statement

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