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Production of biomaterials and biochemicals from lignocellulosic biomass through sustainable approaches: current scenario and future perspectives

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Abstract

Lignocellulosic biomass which is mainly composed of cellulose, hemicellulose, and lignin, is an abundant and renewable resource of biomass with great potential for producing valuable biomaterials. However, its complex structure and the inefficiencies of traditional processing methods present challenges in its sustainable conversion. Recent advances in nanotechnology have introduced new avenues to transform lignocellulosic biomass into useful products such as nanomaterials, biofuels, nanocellulose, biochar, and nanofertilizers. For instance, nanocellulose derived from lignocellulosic feedstocks exhibits tensile strength exceeding that of steel at comparable densities, while biochar production has shown to sequester up to 50% of the initial carbon content of biomass, enhancing soil fertility. These innovations improve biomass processing efficiency and offer more sustainable alternatives. This review explores the latest techniques for converting lignocellulosic biomass into novel biomaterials, their applications in various sectors such as agriculture, energy, and environmental management. Quantitative analysis from the reviewed literature reveals that incorporating metal oxide nanoparticles, such as Fe_3O_4, can enhance enzymatic hydrolysis rates by up to 40%, and biofuel yields can be increased by approximately 30% when nanotechnological interventions are applied during fermentation processes. Moreover, different challenges involved in scaling these technologies for industrial use have also been discussed. Sustainable utilization of lignocellulosic biomass can contribute to the development of a circular economy, reducing waste and dependence on fossil fuels while supporting global sustainability efforts.

Keywords Lignocellulosic biomass, Biomaterials, Biochar, Biofertilizer, Biofuel, Nanocellulose

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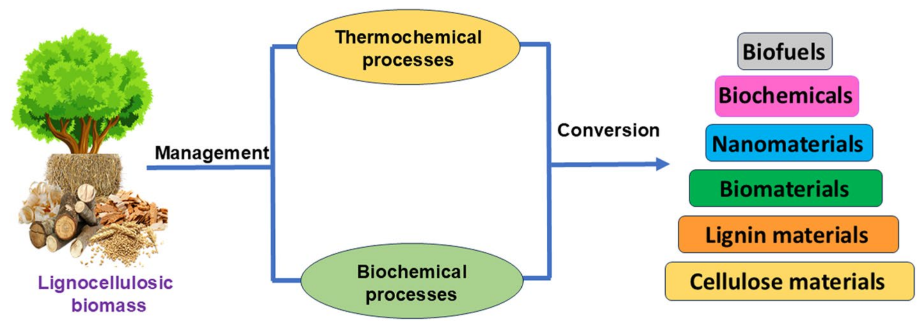
Graphical Abstract



Introduction

Global population growth and industrialization have intensely increased the demand for various products like energy and biomaterials and it poses significant challenges to environmental sustainability and resource availability [1]. To meet these growing demands, renewable resources have gained considerable attention as sustainable alternatives to fossil-based raw materials [2]. Among these, solar energy, wind energy, algae-based resources, and bio-based feedstocks such as starch, oils, and lignocellulosic biomass have emerged as key players in the pursuit of a circular economy [3]. Solar and wind energy offer clean and abundant sources for generating power, while algae-based resources provide a versatile platform for producing biofuels, nutraceuticals, and biopolymers. Also, bio-based feedstocks such as starch and vegetable oils have been widely used in the production of bioplastics, biofuels, and other value-added materials [4–6]. However, these resources often compete with food crops for agricultural land, posing socio-economic and ethical concerns regarding food security [7]. In this context, lignocellulosic biomass, which is primarily composed of cellulose, hemicellulose, and lignin, has emerged as a promising renewable resource. Lignocellulosic biomass encompasses agricultural residues, energy crops, grasses, wood by-products, forest residues, and municipal paper waste. Typically, its composition consists of 35–55% cellulose, 20–40% hemicellulose, and 10–25% lignin. The composition of lignocellulosic biomass can vary depending on the source [8]. Unlike starch and oil-based feedstocks, lignocellulosic biomass is derived from non-food sources such as agricultural residues, forestry waste, and dedicated energy crops, making it an environmentally and ethically viable alternative [9]. It offers immense potential for producing biofuels, bioplastics, nanomaterials, and other high-value products, aligning with the principles of sustainability and resource efficiency. However, the efficient utilization of lignocellulosic biomass remains hindered by its recalcitrant structure and the limitations of conventional processing technologies [10].

Conventional methods for managing lignocellulosic waste are available but they often rely on landfilling, incineration, or simplistic reuse, leading to environmental concerns such as greenhouse gas emissions, soil degradation, and energy inefficiencies [11]. These approaches not only fail to harness the full potential of biomass but also contribute to ecological imbalance and resource depletion [12, 13]. Traditional biomass conversion methods to fermentable sugars, such as thermochemical, biochemical, and chemical processes, are available but they are often hindered by high energy consumption, limited efficiency, and environmental issues like the generation of toxic by-products and residual waste. These challenges highlight the pressing need for innovative solutions to enhance the sustainability and effectiveness of lignocellulosic biomass transformation.

In this context, nanotechnology has emerged as a transformative approach, offering unparalleled capabilities for enhancing biomass conversion [14]. For instance, nanomaterials like magnetic nanoparticles have been used for enzyme immobilization, enhancing enzyme stability and reusability during hydrolysis processes [15, 16]. Similarly, nanocellulose derived from lignocellulosic biomass has been successfully utilized in the development of high-strength composites and bioplastics. Metal oxide nanoparticles, such as zinc oxide and titanium dioxide, have shown potential in enhancing fermentation efficiency by reducing microbial contamination and improving product recovery [17]. These advancements underscore the pivotal role of nanomaterials, including carbon nanotubes and mesoporous silica, in overcoming the technical barriers of biomass conversion and enabling the production of value-added biomaterials [18]. The unique physicochemical properties of nanomaterials such as their high surface area, tunable reactivity, and multifunctionality make them ideal catalysts, adsorbents, and structural enhancers in biomass valorization [19–22]. By integrating nanotechnological tools into biomass conversion, it is possible to overcome the challenges associated with lignocellulosic biomass processing, such as complex enzymatic hydrolysis, inefficient fermentation, and low product yields [23].

This review uniquely highlights the synergy between lignocellulosic biomass and nanotechnology, focusing on their role in promoting sustainability and supporting a circular economy. Unlike previous reviews, which primarily emphasize either biomass processing or nanotechnology independently, this work bridges the gap by offering a comprehensive analysis of how nanotechnological advancements address specific challenges in biomass conversion, such as enzymatic hydrolysis and fermentation inefficiencies. Additionally, the review provides an in-depth discussion on cutting-edge developments like nanocellulose, biochar, biofuels, and xylitol, emphasizing their real-world applications and potential to create sustainable materials. It also examines the social and environmental implications of integrating nanotechnology, including nanoparticle toxicity and regulatory concerns, while advocating for innovative research and policy frameworks to unlock the full potential of this transformative approach.

Lignocellulosic biomass: A global concern or opportunity?

The utilization of lignocellulosic biomass via biorefinery and its economic potential has received more attention in recent years. The bioconversion of various components of lignocellulosic biomass (i.e. cellulose, hemicellulose, and lignin) into value-added products such as biofuels and biomolecules, represents an important opportunity for a sustainable bioeconomy [24]. However, the challenges such as the irregular supply chain, logistic of collection, storage and transportation, the variability of composition, difficulty in scaling up, and economic aspects (financial support and capital), are some of the main concerns associated with the biomass and its utilization [25]. Despite the considerable potential of these materials, challenges related to biomass supply chain and technology may substantially reduce the implementation of industrial processes for their transformation.

Economic challenges

The cost of the feedstock is a significant factor influencing the profitability of the industry and it also depends on its transportation costs. In order to reduce costs, it is essential that the processing industry must be situated in close proximity to the source of biomass [25]. Probably, one of the most important challenges for investors is the significant fluctuations in capital and the scarcity of financial resources for biomass processing initiatives, having detrimental impact on biorefinery growth. Several countries of the European Union subsidy the utilization of biomass (wood, pellets and agriculture residues) as part of their biomass energy strategies. This supports the aim of reducing the emissions of GHGs and incentivise investments in biomass energy generation. However, these economical supports are under risk since a discussion is going on to stop subsidies to energy from biomass, particularly wood, is advancing in Europe Commission [26]. Also, there is limited financing for the acquisition of new technologies, usually associated with the considerable economic risk. In this sense, the adoption of mature technology can facilitate the reduction of the inherent risks and financing [27]. Moreover, the acquisition of technologies for biomass pretreatment and conversion is often financially inaccessible to farmers and small farmers. The implementation of such technologies in biofuels may restrict the potential for expansion of the biorefineries, limiting their availability to a relatively limited number of investors. For instance, the second-generation bioethanol from lignocellulosic feedstock is not yet available at the same scale as first-generation biofuels, therefore, advanced approaches are highly required for the effective conversion of biomass at low operational cost [28].

Operational and technological challenges

The impediments to the expansion of the biomass industry can be attributed mainly to two principal factors, such as, the inefficient management of resources and the government's policy of non-intervention [29]. Some factors, including the regional and seasonal availability of feedstock, and climate changes can affect also the biomass supply and prices. Depending on the distance, volume, and moisture of the biomass, the transportation cost can negatively affect the rentability for a future processing plant installation. Furthermore, a latent problem exists in obtaining long-term contracts for the constant supply of raw materials at a reasonable price. Moreover, technical obstacles persist that require resolution. Most of these obstacles are linked to the absence of suitable pretreatment techniques and equipment for an extensive range of biomass, which can prevent biomass degradation and facilitate rapid processing. Another challenge associated is the complexity of technology. For example, the 1G fuels, such as bioethanol is relatively simple and already established for decades in the industry, while the 2G ethanol is still under development and requires several and complex step for availability of sugar for fermentation [30]. These operational challenges directly impact the future economic sustainability of the biomass-transforming industries, reducing the interest of potential new investors [31]. Besides operational concerns, several challenges associated with technologies usually play a crucial role in biomass conversion. Moreover, current conversion technologies such as thermochemical and enzymatic hydrolysis, or simultaneous saccharification are considered to be energy and cost-intensive which limits their commercial scalability. Considering these facts, many efforts have been made to modify and optimize the existing approaches to make the process efficient and cost-effective.

Environmental and social challenges

The major factor determining the increase in agriculture products demand, and consequently, the biomass generated from this sector, is population growth. Biomass from agricultural production and those derived from agro-industry are frequently accumulated in the field or industrial areas. Poor management or disposal results in environmental pollution. For example, widely expanded in developing countries, the practice of open burning of residual biomass contributes to air pollution and climate change, by increasing the greenhouse gases (GHGs). Similarly, residues in decomposition produce lixiviates that leach into waterways, affecting superficial and groundwater quality.

Regarding social implications, biomass uses concerns and the acceptance of the implantation of industry facilities in a determined region can be avoided or minimized by an effective communication and legislative framework [32]. The legislation should demand strategies of environmental care, consideration on the area of affectation and respect of the original population where is planned the plant location. As mentioned, poor communication related to the technologies to be utilized, environment risk and the economic advantages for the surrounding community, could increase the opposition to promote biomass conversion for obtaining energy or bioproducts [33]. It is important communicate that the construction and operation of new industrial facilities in a determined region can increase land cultivation that may compete with food, raising ethical concerns about food security, and potentially impacting the biodiversity, and consequently, the overall quality of life [34].

Similarly, social acceptance could be influenced by inadequate technology. Some methods for lignocellulose conversion require high energy inputs, which may still depend on fossil fuels, negating the environmental benefits of biomass use. If not managed correctly, the biomass and bioenergy systems can generate GHG emissions, exceeding those of conventional fossil fuels, especially if the feedstock transportation and residue management. However, any potential social impacts must be compensated with others benefits, such as the generation of permanent employment and economic well-being.

Policy and regulatory challenges

Few countries are working on policy and regulatory issues for the management and utilization of biomass. Most of these policies are oriented towards the promotion and development of alternative and renewable energy sources for electricity generation and forest biomass regulations [35]. In many countries the government subsidizes prices for petroleum-derived fuels and first-generation biofuels, such as biodiesel and bioethanol. Also, the electricity generated from conventional fuels poses a lower price than those obtained from the combustion of renewable resources due to subsidies. Recently, the Netherlands announced the end of wood biomass subsidies for electricity, claiming that its utilization is not reducing emissions, promoting climate and biodiversity crises. Other European countries also discuss that possibility. The Biomass Crop Assistance Program (BCAP) is a US Program to provides financial assistance to farmers and non-industrial private forest land who wish to establish, produce, and deliver biomass (forest and agriculture residues) feedstock [36]. Other US initiatives include the Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program that will provide up to $250 million to assist in the development, construction, and retrofitting of new and emerging technologies for advanced biofuels, renewable chemicals and biobased products [37]. Also, the European Commission for Biobased Products and Processes are working in sustainable biomass sourcing, logistics and production systems, with focus on high-value applications and uses and overall resource efficiency [38]. There is no specific and definitive regulatory framework for the utilization of these resources in many countries. It is therefore necessary to establish policies that promote the utilization of biomass.

In other hand, the biomass utilization offers many opportunities, Private and public sectors are working to reduce these uncertainties by improving infrastructure, innovation technologies, and financial support. The effective management and conversion of biomass offer environmental benefits, as they mitigate the issues associated with inadequate disposal, thereby reducing soil, water, and air pollution. In this regard, the conversion of biomass into biofuels contributes to the reduction of greenhouse gases (GHGs), preventing the climate change and dependence of petroleum-based fuels [39]. Certainly, the future biorefinery should be integrated with the existing industrial facilities to reduce the challenges of industrialization and reduce in part the cost of implantation.

Despite these concerns, lignocellulosic biomass presents huge opportunity to solve problems related to the global sustainability and employment. The conversion of biomass into biofuels such as ethanol, butanol, bio-oil, biohydrogen, biogas and biochar can stimulate the expansion of renewable energy markets. For example, undervalued agriculture biomass (leaf and straw) has enormous potential to produce biogas in anaerobic digestion [40]. Advanced thermochemical technologies, such as pyrolysis, gasification, and fermentation, have been developed to explore the potential of lignocellulosic biomass for obtaining value-added products [41]. The use of biomass presents considerable economic potential that can be used to improve well-being in low-income and developed countries. In addition to biofuels innovative approaches can transform biomass into products that can expand the frontiers of the nanotechnology (e.g. functionalized nanocellulose and nano-lignin) [42]. Lignocellulosic biomass has become a pivotal point of global concern and opportunity. While its improper utilization can result in environmental risks, its appropriate utilization offers sustainable and economic opportunities. Investing in advanced technologies and promoting policies that encourage the sustainable use of biomass.

Conventional approaches for lignocellulosic biomass management and their implications

Lignocellulosic biomass constitutes an important byproduct of agricultural and forestry activities in the world. According to Kumar et al. [43], the total agricultural biomass produced per year amounts to 140 billion metric tons. Despite its potential as a renewable resource, the abundance of the resource represents a problem since conventional management are frequently inefficient to avoid environmental impacts [44]. The traditional methods of managing these residues include open burning, landfilling, composting, and fertilizer. Open burning is the most utilized strategy to manage biomass in regions with extensive agricultural production and is employed to clear fields for the next plantation cycle. However, this activity affects the air directly, resulting in the emission of significant quantities of greenhouse gases (GHGs), including carbon dioxide (CO_2), carbon monoxide (CO), nitrous oxide (N_2O) and methane (CH_4), as well as carbon and other particulates. In addition to damaging air quality, these emissions cause a significant health risk to surrounding communities. Furthermore, soil and groundwater contamination, usually associated with hydrocarbons and ash produced during burning, represents another adverse consequence of this activity.

Landfilling is another widely implemented biomass management strategy. Nevertheless, landfilling requires considerable land, which is not a viable alternative in highly urbanized regions [45]. The anaerobic digestion of landfills containing agricultural biomass to produce biogas could be economically beneficial. Raw biogas is composed predominantly of methane (45%–65%) and carbon dioxide (39%–42%), nitrogen, oxygen, sulfide, and other components [46]. After purification, the biogas achieves a minimum CH_4 content of 90%. At the point of injection into natural gas pipelines, concentrations can reach 98%. In addition, anaerobic digestion yields a solid, which is highly rich in nutrients called digestate, which can be utilized as a fertilizer. In this sense, the utilization of biomass as feedstock to obtain natural fertilizer represents an opportunity for the fertilizer industry, since it could reduce the dependency on non-renewable feedstock, and at that time, avoid biomass accumulation [47]. Another method to manage biomass accumulation consists of direct incorporation into the soil, a widely accepted practice in sustainable agriculture. This improves soil structure, fertility, and water retention in degraded soil. The degradation of biomass depends on the composition of vegetal materials, the abundance of microorganisms, and the climate and soil characteristics. However, it is not suitable for large amount of biomass waste, and improper incorporation can result in localized accumulation of recalcitrant vanillyl and other lignin-derived monomers, such as syringyl and cinnamyl, as well as gas formation by anaerobic degradation of cellulose and hemicellulose [48].

The direct combustion of lignocellulosic biomass in boilers for generating heat and energy (electricity) represents another conventional method of biomass management. Although this method is more environmentally friendly than open burning, the efficiency of the conversion of the furnace utilized, as well as, the logistics of transport and storage, and localized air pollution, impose limits on biomass utilization in several countries [49]. The mentioned practices of biomass management usually fail to harness the total value of lignocellulosic biomass, discharging opportunities of valorisation. Innovative strategies such as thermochemical processes for obtaining fuels (e.g., pyrolysis, gasification, hydrothermal carbonization) and biochemical conversion (e.g. fermentation and enzymatic production of ethanol and bio-based chemicals), are fundamental for biomass utilization [50–52]. These technologies not only minimize environmental impacts but also create opportunities for a circular economy.

Conversion of lignocellulosic biomass in novel biomaterials

Although the recalcitrant structure of lignocellulosic biomass and the inefficiencies of traditional processing methods pose significant challenges, but advancements in green chemistry and nanotechnology are unlocking new possibilities for its transformation. These innovations are driving the development of high-value

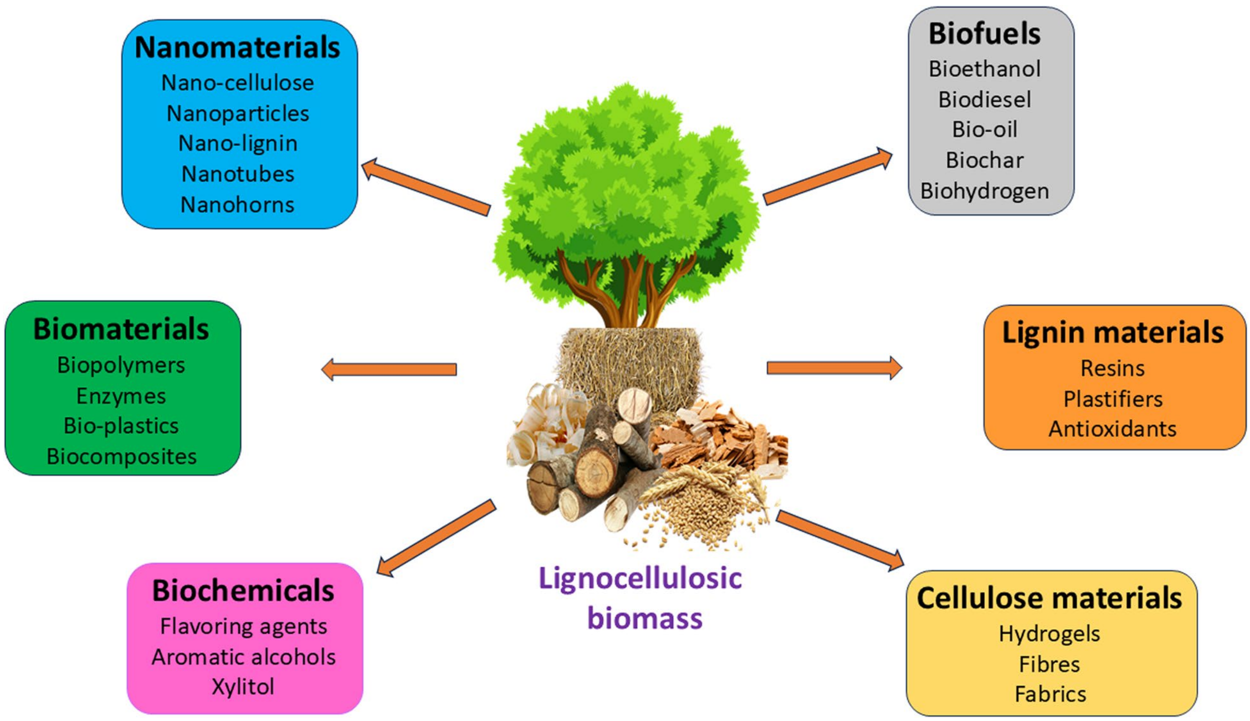


Fig. 1 Production of different value-added products from lignocellulosic biomass

biomaterials, offering sustainable alternatives to conventional materials, and facilitating progress towards a circular economy.

Lignocellulosic biomass, composed of cellulose, hemicellulose, and lignin, is a renewable and sustainable resource with immense potential for producing diverse biomaterials. Its abundant availability and unique structural composition make it ideal for value-added applications. Recent innovations in nanotechnology and green chemistry have enabled the conversion of lignocellulosic biomass into high-value products such as nanomaterials, biofuels, and functional biochemicals. Additionally, innovations in the production of nanocellulose, biochar, and nanofertilizers have demonstrated its transformative potential across industries, from agriculture to energy. Production of different value-added products from lignocellulosic biomass is depicted in Fig. 1. This section examines the various pathways and technologies employed to harness lignocellulosic biomass, highlighting their applications and exploring future prospects.

Nanomaterials from lignocellulosic biomass

Nanomaterials are materials with structural features at the nanoscale, typically ranging from 1 to 100 nm [53]. They exhibit unique physicochemical properties such as high surface area, enhanced reactivity, and tunable optical, thermal, and mechanical characteristics, making them indispensable in diverse fields including medicine, energy, agriculture, and environmental remediation [54, 55]. However, synthesizing nanomaterials poses significant challenges due to high production costs, environmental concerns, and scalability issues. To date, various approaches such as chemical, physical, and biological methods have been employed for the synthesis of nanomaterials. Among these, chemical methods, though precise, are often resource-intensive and generate toxic by-products [56]. Physical methods usually involve the use of radiation, high temperature, and pressures. On the other hand, bioinspired methods, utilizing plant extracts or microorganisms, offer an eco-friendly alternative but face limitations in scalability [57]. Industrial by-products such as fly ash provide opportunities for waste valorization but suffer from inconsistency and limited availability [58]. In contrast, lignocellulosic biomass a renewable, abundant, and cost-effective feedstock derived from agricultural and forestry residues offers a promising pathway for sustainable nanomaterial production [59–61].

Recent studies have leveraged agro-waste as a viable source for synthesizing nanomaterials. Santhanam et al. [62] utilized *Citrus limon* peel extract to synthesize aluminium oxide nanoparticles (Al_2O_3 NPs) through a green chemistry approach. By digesting aluminium foil under varying temperatures (60–90 °C) and peel extract concentrations (10–40%), they achieved optimal conditions at 80 °C with 20% extract. The resulting nanoparticles, with a crystalline spherical structure (284 ± 58 nm), were characterized by UV–Vis spectroscopy (λmax at 225 nm) and FTIR analysis. These Al_2O_3 NPs demonstrated remarkable anti-inflammatory, antioxidative, and antibacterial properties, showcasing the potential of agricultural residues in nanotechnology. Similarly, Amor et al. [63] converted orange peel waste into carbon nanoparticles (CNPs) of approximately 70 nm using thermal treatment, chemical activation, and ultrasonication. Surface modification with chitosan produced a chitosan@CNPs nanocomposite with enhanced properties, such as higher carbon content, distinct crystalline peaks, and altered optical properties with a higher band gap energy (3.92 eV). The composite showed superior anti-hemolytic activity (74.4%) but slightly lower antioxidant activity (59.97%) compared to CNPs (89.52%). Both materials exhibited excellent biocompatibility, reinforcing the potential of agro-waste-derived nanomaterials for applications in drug delivery, biosensing, and environmental remediation.

Also, Ramimoghadam et al. [64] demonstrated an innovative approach to synthesize titanium dioxide nanoparticles (TiO_2-NPs) using rice straw, a widely available lignocellulosic biomass, as a soft biotemplate via the sol–gel method. This strategy not only valorizes agricultural waste but also enables the production of ultrasmall TiO_2-NPs, with sizes as small as 13.0 ± 3.3 nm, as confirmed by various characterization techniques. The study further revealed that increasing rice straw concentration enhanced the surface area and porosity of the nanoparticles, significantly improving their photocatalytic potential. These findings underscore the importance of lignocellulosic biomass in creating nanomaterials with customizable properties, paving the way for sustainable advancements in nanotechnology. Also, Arcentales et al. [65] utilized rose biomass waste to develop lignocellulosic-based nanoparticles with an average size of 156 nm, exhibiting strong photoluminescence in the near-infrared (NIR) region (800 nm) upon excitation at 500 nm. These naturally luminescent nanoparticles eliminate the need for encapsulation or functionalization for imaging applications. In vitro studies revealed an IC50 of 3 mg/mL, and in vivo tests showed no toxicity up to 57 mg/kg, confirming their biocompatibility. With the ability to circulate in blood and be excreted in urine, these nanoparticles demonstrate significant promise as eco-friendly and efficient bioimaging agents. Parveen et al. [66] synthesized photoluminescent carbon dots (sc-CDs) from sugarcane bagasse (SCB), an abundant agro-industrial residue, using an eco-friendly one-pot hydrothermal method. The sc-CDs exhibited green fluorescence with an excitation wavelength range of 340–420 nm and a quantum yield of 12.31%. Characterization techniques, including FTIR, SEM, and XRD, confirmed the presence of functional groups, spherical morphology, and crystallinity. The sc-CDs demonstrated significant antioxidant activity and enhanced catalytic degradation of methylene blue dye. This study highlights the potential of SCB as a renewable precursor for high-value nanomaterials with applications in environmental and biomedical fields.

Despite these advancements, challenges remain in scaling up lignocellulose-based nanomaterial production. Energy-intensive processes such as pyrolysis and hydrothermal carbonization, coupled with variability in biomass composition, can impact yield and purity. Addressing these drawbacks through process optimization and integration of renewable energy sources is crucial for the commercial viability of these technologies.

Biofuels from lignocellulosic biomass

The lignocellulosic biomass comprising cellulose (35–50%), hemicellulose (15–35%), lignin (15–20%), and other components (15–20%) can be converted in liquid, solid and gaseous fuels. The thermochemical conversion of biomass by pyrolysis, torrefaction, hydrothermal carbonization, and gasification are the most important process to energetically densify the lignocellulosic material [67]. Pyrolysis, the most extended process, typically results in high energy density solid fuel called biochar with HHV in the range of 20—30.27 MJ/kg, a fuel gas (Syngas), composed by 25–50% carbon monoxide (CO), 25–30% hydrogen (H_2), 5–15% carbon dioxide (CO_2) and 1–6% methane (CH4), whit a heating value of 11.61 MJ m^{-3} [68] and bio-oil which HHV in the range of 30–30 MJ/kg [69]. Liquid biofuels such bioethanol and biodiesel obtained by first-generation (1G) fuels are produced from vegetable biomass, such as sugarcane and soybean [70]. Although 1G biofuels offer higher yields and lower production costs, their cultivation requires the use of arable land, which can have a negative impact on global food supplies. However, second-generation (2G) biofuels do not compete with the food supply because these biofuels are derived from non-food crop biomass, such as residual crops material (husk, leaf, straw, etc.), forest biomass and agro-industrial biomass [71].

This material exhibits a complex structural and three-dimensional configuration than constitute a challenge for its utilization. Lignin composed majority of aromatic compounds forming a complex structure strongly adheres to cellulose and hemicellulose microfibrils. This adhesion is achieved by means of covalent bonds, resulting in a widely branched amorphous structure [72]. The denaturation of lignocellulosic into fermentable sugars (mono and disaccharides) from cellulose and hemicellulose for obtaining bioethanol via fermentation requires

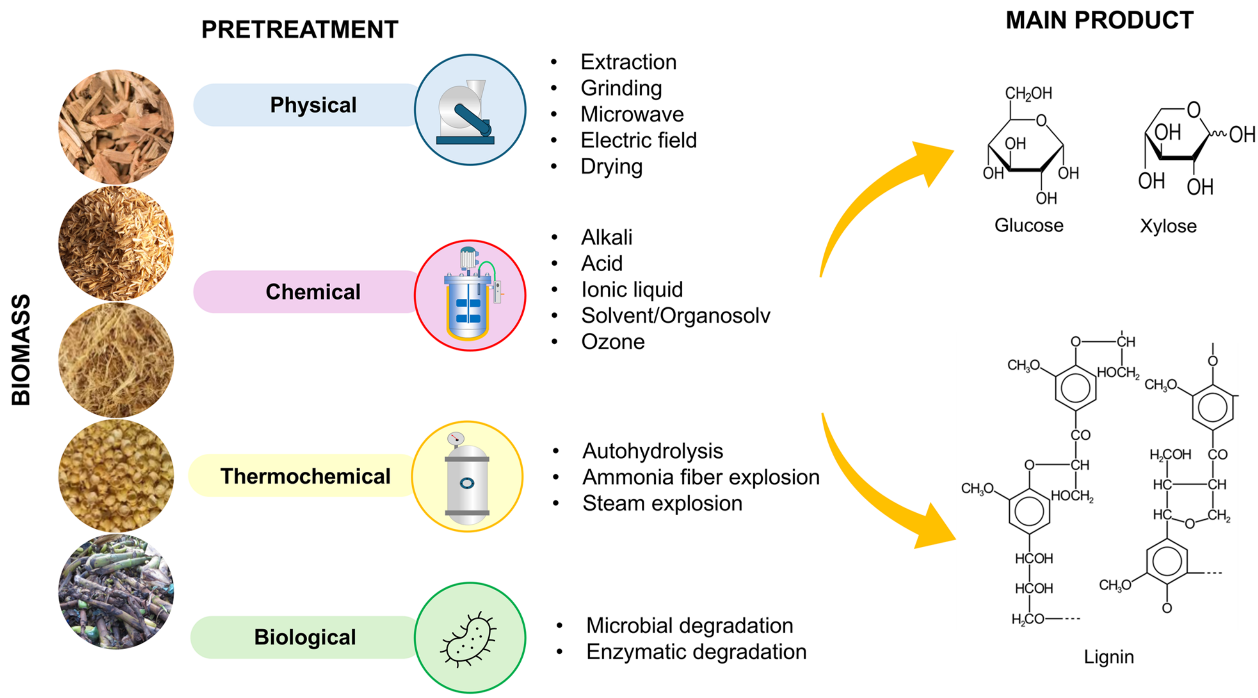


Fig. 2 Important approaches commonly used in the pretreatment of lignocellulosic biomass

pretreatments, including, physicochemical, thermochemical, chemical, enzymatic or a combination of pretreatments [73]. In the laboratory, pilot and industrial scale, chemical and thermochemical technologies of pretreatments consist of acid hydrolysis, hydrothermal hydrolysis (autohydrolysis), alkali treatment, ammonia fiber explosion, steam explosion, weak acid hydrolysis and a combination of these processes. These technological approaches are employed mainly for accessing the monomers (glucose and xylose) from cellulose and hemicellulose. Figure 2 shows the approaches which are commonly used in the pretreatment of lignocellulosic biomass.

Acid hydrolysis (diluted acid, 1–5% sulfuric acid) and autohydrolysis at high temperature are strategies usually used for a wide variety of biomass. However, these conditions also yield different quantities of undesirable compounds derived from lignin (phenolic compounds) and those from sugar degradation (furfural and hydroxymethyl furfural), and acetic acid, which could inhibit the microbial conversion of the compounds in biofuels (e.g. ethanol or butanol) [74]. Typically, these treatment yields low concentration of sugars (< 20 g/L), being required an ulterior water evaporation to achieved necessary concentration for the fermentation process. Another method of biomass pretreatment consists of the combination of autohydrolysis and water vapor/sulphur dioxide as preparative for enzymatic treatment. Cellulose saccharification via acid hydrolysis and enzymatic hydrolysis are the main pretreatment used to denature this biopolymer into fermentable sugars. Currently, enzymatic and microbial step are combined simultaneously for saccharification-fermentation for obtaining biofuels [75].

Furthermore, the use of ozone, deep eutectic solvent based on choline-chloride, ionic liquid (BHEM-Mesy-glycol/EMIN OAc), hydrogen peroxide and organosolv (ethanol as solvent) combined with enzymatic hydrolysis (cellulase/ xylanase) as biomass pretreatment strategies, are efficient methods for enhancing biomass saccharification [76–79]. Many initiatives are being carried out to increase the utilization of lignocellulosic material at industrial scale, especially for the production of 2G bioethanol. For instance, the Oil Marketing Companies (OMCs), a group of public sector oil marketing companies in India, projects to establish twelve 2G bio-refineries in India with an investment of $1.68 billion, expanding the ethanol production in this country. These bio-refineries will employ lignocellulosic biomass and other renewable feedstocks for ethanol production [37]. In the United States, despite the potential of cellulosic bioethanol, the production remains uneconomically advantageous, and no commercial 2G ethanol production has been reported at the end of 2023. In Brazil, Raizen (an energy company of the São Paulo State) has recently inaugurated the largest second-generation ethanol plant with an annual production capacity of 82 million liters, which has been constructed with the use of proprietary technology and an investment of R$ 1.2 billion [80]. This company employs steam explosion which yield high C5 sugars concentration during pretreatment and C6 sugars recovery during enzyme hydrolysis [39]. GranBio, in the state of Alagoas has two proprietary technology platforms to produce 2G ethanol (AVAP® Biomass Fractionation and BioFlex®), which use Novozyme's customized enzyme for saccharification [81]. This industrial plant has processing capacity of 200,000 tons of sugar cane straw per year. Despite the abundance and availability of agriculture and forestry biomass for cellulosic ethanol in Brasil, some initiatives have paused the scaling up production. In China, the EcoCeres produce cellulosic ethanol in Hebei Province, which completed its first shipment of cellulosic ethanol from China to Europe in 2023 [82]. The adoption of second-generation (2G) ethanol is a crucial step in meeting the growing demand for ethanol while assisting the global community in achieving net zero carbon emissions. Table 1 shows the details about the production of different biofuels using various approaches from a variety of biomass [70, 75–79, 83–95].

The recalcitrance of lignocellulosic biomass to hydrolysis of its components typically requires high energy consumption, chemical or enzyme catalysts, and multiple operating steps, including those for product purification. Scaling up traditional processes is costly and, in some cases, time-consuming, so new solutions are needed to make biomass conversion cost-effective, highly productive and environmentally sustainable. Nanotechnology, specifically the use of nanomaterials for lignocellulosic conversion, is being intensively investigated as a feasible and scalable technique [96]. The use of nanoparticles as support for enzymes, acids, and metals (functionalized nanoparticles) catalytic activity to promote partial or total hydrolysis of lignocellulosic materials to previous fermentation for fuels production (hydrogen, biogas, bioethanol, and butanol) has gained significant interest in recent years [83]. Typically, magnetic nanoparticles covered with natural polymers such as chitosan are being employed for immobilization of pure and blends of enzymes aiming to use in pretreatments and saccharification of lignocellulose biomass. Figure 3 shows a schematic representation of magnetic nanoparticle coated with chitosan for saccharification of pretreated biomass for bioethanol production. Table 2 presents the latest reports on the utilization of nanomaterials for lignocellulose conversion [97–110]. Many strategies are being developed to increase the selectivity of catalysts to facilitate denaturation of lignocellulosic polymers. For instance, the use of metal anchored on magnetic nanoparticles and sulphonation enhances the specific attack the β−1, 4-glycosidic bonds between the monomeric units of carbohydrates and the hydrogen bonds formed with the hydroxyl groups of the cellulose of the lignocellulosic materials [97].

Xylitol from lignocellulosic biomass

Among the myriads of products derived from lignocellulosic materials, xylitol stands out for its high market value. Xylitol is a polyol that has been gaining attention in the food, dental, pharmaceutical, and medical fields, and it also shows significant potential for application in other industrial sectors. Among its properties, its sweetening power—similar to sucrose—its anticariogenic effects, and its suitability for consumption by diabetics, obese individuals, and patients with glucose-6-phosphate dehydrogenase deficiency are particularly noteworthy [111, 112]. Currently, xylitol is produced on an industrial scale through a chemical process that involves pure xylose extracted from hemicellulosic hydrolysates, under high pressure and temperature conditions [112, 113]. This process requires the use of a nickel catalyst, which complicates the later stages of production due to the need to remove residual catalysts. Besides, this process requires high energy costs, and it is quite a complex production system (e.g., low selectivity and formation of L-Arabinitol or other by-products) driving the search for alternative routes that are more environmentally friendly [113, 114].

An alternative method for producing xylitol is through biotechnology, and significant efforts are underway to develop a fermentation-based technology for its production, it is worth noting that these routes are more environmentally friendly [112, 113]. Given the enormous amount of agricultural waste generated worldwide and the environmental problems associated with the accumulation of these residues, xylitol production through biotechnology is an excellent alternative for utilizing these second-generation residues, such as sugarcane bagasse, corn cobs, wood chips, grains, and others [112]. Table 3 shows some lignocellulosic residues used for xylitol production and the different process conditions used [114–119]. In general, all types of biomass-derived residues can be used, including agro-industrial, food industry, and wood residues, among others [111].

Xylitol obtained from lignocellulosic materials undergoes several processing steps. Initially, the material needs to be fractionated to extract soluble monomeric sugars (glucose, xylose, arabinose, galactose, mannose and others), from the insoluble portion that is predominantly composed of lignin and cellulose. This extraction is traditionally carried out via a chemical route using acids such as sulfuric, hydrochloric, nitric, phosphoric and others.

Table 1 Recent advances in biofuel production from lignocellulosic biomass

Biomass/carbon source	Pretreatment/process	Conditions	Products	Quantity	Reference
Softwood sawdust	Formic acid organosolv and steam gasification	-	Hydrogen	56.3 vol% and a yield of 40 $g_{h2}/kg_{cellulose}$	[83]
Wheat straw	-	Lipopeptide biosurfactants facilitating the microbial Degradation of lignocellulose and inducing enzymatic hydrolysis, anaerobic dark fermentation	Biohydrogen	4.50 mmol H_2/g	[84]
Lignin, cellulose, hemicellulose	-	Ni_2P/CdS for simultaneously heightening photocatalytic	Hydrogen	From lignin (322.8 µmol/h/g), cellulose (534.3 µmol/h/g), hemicellulose (382.2 µmol/h/g)	[85, 86]
Coffee and pineapple skins	Alkaline H_2O_2 pre-treatment	Dark fermentation	Hydrogen	47.99 ml/gvs (coffee skin) 91.80 ml/gvs (pineapple skin)	[86]
Corn stover	80 ºC pre-incubation	Simultaneus saccharification fermentation (Cellulase, xylanase, and pectinase, *Thermotoga maritima*/ Dark fermentation	Hydrogen	60 ml H_2/g bimass	[75]
Agave bagasse	Ozonolysis/Enzymatic hydrolysis (independent and combined processes)	Anaerobic digestion	Biohydrogen, methane	9 – 81 L H_2/kg dry bagasse 73–163 CH_4/kg dry bagasse	[78]
Cacao pod husk	Acid hydrolysis	Dark fermentation	Biohydrogen	257.05 ml H_2/L	[87]
Sorghum leaves	Green liquor-inorganic salt /microwave	Simultaneous saccharification and fermentation	Bioethanol Biohydrogen	12.16 g ethanol /l, 78.44 ml H_2/g sugar (from effluent of ethanol production)	[88]
Rice straw	Organosolv-NaOH and sulfuric acid-NaOH/Nano-silica particles	Dark fermentation	Biohydrogen	63.8 ml H_2 /g rice straw	[79]
Psidium guajava leaves	Hydrothermal treatment/ diluted sulfuric acid	ABE fermentation	Biobutanol	5.5 g/L	[89]
Corn stover	Diluted sulfuric acid/enzymatic hydrolysis	Non-detoxified hydrolyzed co-fermentation	Ethanol/butanol	24.0 g/L ABE (20.8 g/L ethanol and 2.4 g/L butanol)	[90]
Sugarcane bagasse, corncob and pine supplemented with wheat bran	Enzymatic hydrolysis	ABE fermentation	Butanol	14.51 g butanol/L	[70, 85]
Bamboo	Sodium hydroxide	Abe fermentation process/co-fermentation	Ethanol/butanol	0.5 g/l butanol, 1.3 g/l butyric acid, and 0.3 g/l ethanol	[91]
Wheat straw	Diluted sulfuric acid/Enzymatic hydrolysis	ABE Fermentation of detoxified hydrolysate	Butanol Ethanol	7.42 g/L butanol, 12.97 g/L acetone–butanol–ethanol	[92]
Rice husk	Deep eutectic solvents (choline chloride and urea)	ABE fermentation	Butanol	4.7 g/L	[93]
Rice straw	Sodium hydroxide/NPs CuS/Cu_2S/semiconductor nanoparticles	Butyrate-butanol fermentation	Butanol	14.6 g/L	[94]
Rice husk and wheat husk	Ionic liquid (1-Ethyl-3-methylimidazolium acetate—EMIM oac)/Enzymatic hydrolysis	Yeast fermentation	Ethanol	24.28 g/L	[95]
Giant reed	Alkaline (Sodium hydroxide)/Enzymatic hydrolysis	Yeast fermentation	Ethanol	8.63 g/L	[92]
Corn-stalk	Ionic liquid ([BHEM]mesy- glycol system)/Enzymatic hydrolysis	Fed-batch fermentation	Ethanol	93 g/L	[77]
Sugarcane trash (dry leaves, green leaves, and tops)/ jatropha (shell and seed cake)	Hydrogen peroxide / sodium hydroxide/Enzymatic saccharification	Yeast fermentation	Ethnaol	325.4 mg/g dry biomass	[76]

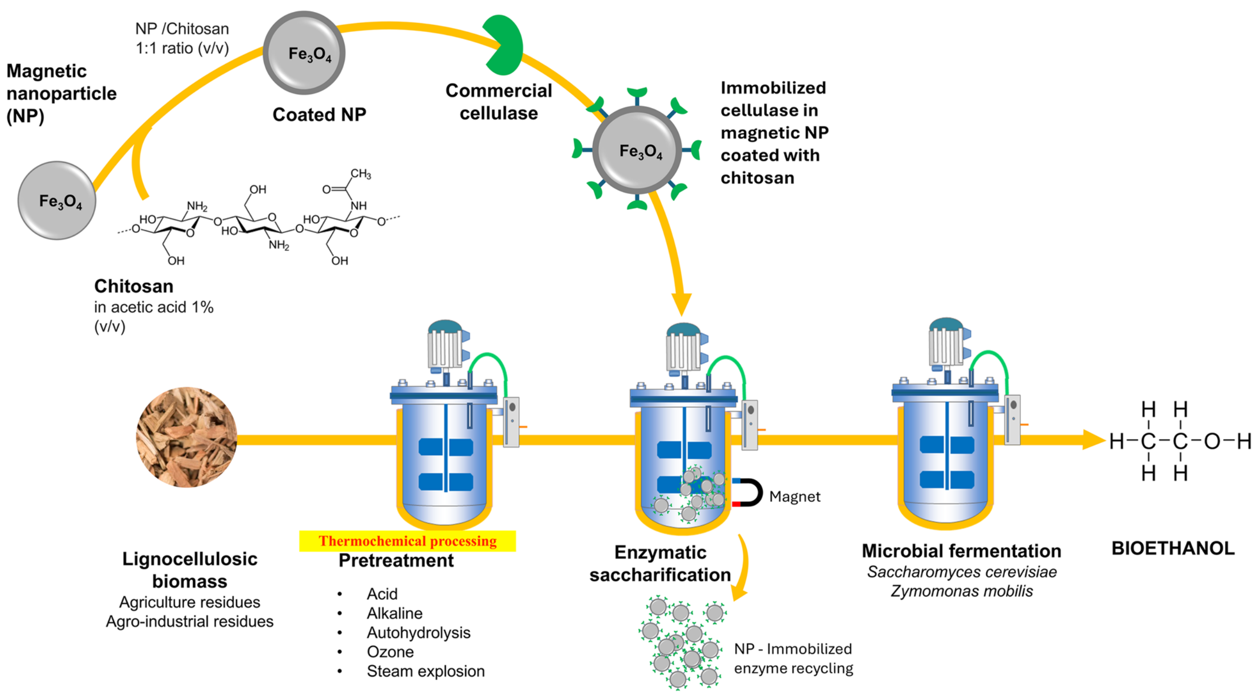


Fig. 3 Schematic representation of magnetic nanoparticles coated with chitosan used for saccharification of pretreated biomass for bioethanol production

Acid hydrolysis primarily solubilizes hemicellulose, which is subsequently catalytically converted into xylitol [112, 115].

It is important to note that acid pretreatments have the disadvantage of causing sugar degradation into compounds such as furfural, hydroxymethylfurfural and acetic acid as well as the breakdown of phenolic compounds derived from lignin. These compounds are known as inhibitors, and they decrease the ability of microorganisms to utilize the carbon source for xylitol production, resulting in a decrease in fermentation yield [111, 115].

During the process, a purification stage (the second stage) is carried out to reduce or eliminate undesirable by-products, phenolics, and volatile compounds, ensuring a high fermentation yield in the subsequent stage. The mechanisms involved in this process, which uses ion-exchange chromatography and activated carbon, include the removal of diluted salts, degradation of by-products, and discoloration of the hydrolysate [111].

The biotechnological route offers several advantages, such as the use of milder conditions of pressure and temperature and specific enzymes and microorganisms can be used, which act exclusively in the conversion of xylose into xylitol, leading to higher yield and facilitating separation [120], and it does not require high-purity xylose, as microorganisms can directly convert xylose into xylitol from hemicellulosic hydrolysates [112]. Furthermore, the biological route does not result in the formation of toxic residues that would need to be removed during the purification process [111, 112]. Furthermore, considering the environmental context, it has characteristics that minimize environmental impact, such as reduced toxicity of effluents and the use of renewable resources, like plant biomass. It also offers a higher conversion yield to xylitol and lower production costs compared to the chemical route [114]. There is a diversity of microorganisms capable of metabolizing pentoses to produce bioproducts. Specifically, about the ability to reduce xylose to xylitol, certain bacteria, yeasts, and fungi have shown potential for use in fermentation pathways to produce this product [111]. In general, among microorganisms, yeasts are considered the best producers of xylitol, with those from the *Candida* genus standing out, allowing for the best result [121]. Currently, the use of genetically modified microorganisms is a promising strategy for increasing the yield of xylitol production through biotechnology [112].

Nanofertilizers from lignocellulosic biomass

Nanofertilizers, engineered at the nanoscale, are designed to enhance nutrient efficiency, reduce nutrient loss, and promote sustainable agricultural practices [117]. They provide controlled nutrient release directly to plants, improving uptake efficiency and minimizing environmental impact compared to traditional fertilizers [122,

Table 2 Recent developments in pretreatment and saccharification of cellulose and lignocellulosic biomass using nanoparticles

Biomass/substrate	Nanoparticles	Catalyst	Characteristic	Reference
Carboxymethylcellulose	Magnetic nickel nanoparticles	Cellulase	Immobilized NiNPs maintained 99.1% of the free enzyme's cellulase activity	[98]
Corn cob pretreated by autohydrolysis	Fe_3O_4 magnetic nanoparticles coated with chitosan	Cellulase blend (Cellic CTec2)	Yield 21.84 g/L glucose—64.45% substrate conversion	[99]
Sorghum residue	Fe_3O_4 nanoparticles were coated with chitosan	Cellulase	Yield 5.42 g/L glucose	[100]
Agave atrovirens leaves	Chitosan-coated magnetic nanoparticles	Cellulose	Re-used up to four cycles with 50% of activity decrease	[101]
Carboxymethylcellulose	Silicacoated-aminefunctionalized iron oxide nanoparticle	Cellulase blend (Cellic CTec2)	retained~80% activity even after repeated 6 cycles	[102]
Sugarcane bagasse (pretreated with NaOH)	Silicacoated-aminefunctionalized iron oxide nanoparticle	Cellulase blend (Cellic CTec2)	Retained activity up to 6 cycles	[103]
Potato peel waste	Fe_3o_4 magnetic nanoparticles	-	Improvement of reducing sugar recovery from potato peel waste without enzyme inclusion	[104]
Paddy straw	chitosan functionalized magnetic nanoparticles	Cellulase	Saccharification efficiency of 35.78%, retained up to 5 recycles	[105]
Algal biomass	Mg-Zn Fe_2O_4 nanoparticles	Cellulase	Nanoparticles increased bioethanol production up to 4.2-fold over thermo-acidic pretreatment	[106]
Rice straw (pretreated with ionic liquid tris (2-hydroxyethyl) methylammonium methyl sulphate ([TMA][$MeSO_4$]) and microwave irradiation	Silica-coated magnetic nanoparticles Fe_3O_4@SiO_2-NH_2	Cellulase/Xylanase	Reusability potential for five consecutive cycles	[107]
Corn cob	Sulfonated magnetic nanoparticle (Fe_3O_4/C–SiO_2-–SO_3H	-	Hydrolysis rate increased with reaction time and temperature. Sulfonated Fe_3O_4/C–SiO_2 showed sustained activity after being reused four times	[108]
Corn cob, palmyra fruit peel	Sulfonated magnetic nanoparticle (Fe_3O_4–@C–SO_3H)	-	Best hydrolysis conditions yield 97.6% and 90% for corn cob and palmyra fruit peel, respectively	[109]
Wheat straw (pretreated with NaOH)	Magnetic nanoparticle CC-Fe_3O_4@SiO_2	β-Xylanase	Maximum saccharification was 20.61%. Immobilized MNPs could be reused for 11th time for saccharification process	[110]
Fruit and vegetable waste (Ultrasound-assisted acid pretreatment)	Sulphonated MnO_2 nanoparticle	-	Concentration of 0.1192 g/L reducing sugar	[97]

Table 3 Xylitol production by different techniques and operational conditions using lignocellulosic raw material

Residual waste	Route used for xylitol production	Conditions	Xylitol productivity (g/g)	Microorganism used	Reference
Sugarcane straw	Biotechnological	NS (Aerobic condition, initial OD 0.5)	0.91	*S. cerevisiae* FMYX	[115]
Sugarcane bagasse	Biotechnological	Acid pretreatment (H_2SO_4, 121 °C, 20 min) 1.50)	1.50	*Candida tropicalis*	[116]
Brewer's spent grain (BSG) and grape stalks 70,877	Biotechnological	Acid pretreatment [3% (w/w) H_2SO_4, 121 °C, 1 bar]	BSG hydrolysate = 0.56 Grape stalks = 0.25	*Komagataella pastoris* DSM 70877	[117]
Olive stones	Biotechnological	Aqueous extraction (to extract solids) (130 °C, 90 min)	0.38	*Candida boidinii*	[114]
Banana leave	Biotechnological	H_2SO_4 2.5%; 121 °C; 30minpH adjustment; Activated carbon; 200 rpm; 55 °C; 60 min *Candida tropicalis*; 30 °C; 200 rpm; 60 h	0.186	*Candida tropicalis*	[118]
Corn biomass (corn bran)	Chemical	Acid pretreatment (72% H_2SO_4, 30 °C, 1.5 h) 0.79 –	0.79	--	[119]

123]. Lignocellulosic biomass, such as wheat straw, rice husks, corn stover, and sugarcane bagasse, has emerged as a sustainable feedstock for producing nanofertilizers [124]. These materials are used to synthesize nanostructures like nanohydroxyapatite, silica nanoparticles, and cellulose nanocrystals, which serve as carriers or sources of essential nutrients in fertilizers [125, 126].

Elsabagh et al. [127] demonstrated the potential of date palm pits, a lignocellulosic biomass, for producing eco-friendly and cost-effective nanofertilizers. Using a planetary ball milling process, they synthesized nano-enabled fertilizers (nDPF1 and nDPF2) by impregnating nanostructured date palm pits with KH_2PO_4 and MgO. These nanofertilizers significantly enhanced soil water retention, with nDPF2 showing a 5.6-fold increase compared to conventional fertilizers. Additionally, they provided controlled nutrient release, improving nutrient uptake and biomass production in maize plants, showcasing the role of lignocellulosic biomass in sustainable agriculture. Also, Latha et al. [128] explored the use of coconut coir-derived lignin to develop a nanofertilizer aimed at improving nitrogen use efficiency. Lignin was extracted using the organosolv process, then converted into spherical lignin nanoparticles (LNPs) via solvent displacement. These LNPs were combined with chitosan and a cross-linker to create a stable and effective nanocomposite (lignorea) that gradually released nitrogen over 15 days, demonstrating the potential of lignin-based nanocomposites for enhancing fertilizer efficiency and minimizing environmental impact. Salam et al. [129] studied the use of agricultural waste-derived biochar from citrus tree trimmings for synthesizing carbon nanoparticles (CNPs) for nanofertilizer production. Pyrolysis at 650 °C in the absence of air produced biochar, which was then used to synthesize CNPs. These CNPs were impregnated with potassium nitrate (KNO_3) to create a CNPs/NK nanocomposite, which significantly enhanced the growth, yield, and quality of common bean (*Phaseolus vulgaris L.*). The study demonstrated the potential of using lignocellulosic biomass to create sustainable nanofertilizers. In recent research by Tang et al. [130], lignocellulosic biomass was used to green-synthesize hydroxyapatite (HAP) nanoparticles through a one-pot hydrothermal process. This method transformed refractory calcium phosphates into nanoenabled HAP, improving phosphorus uptake in crops. Soybean cultivation experiments showed that HAP derived from lignocellulose increased phosphorus accumulation by 14.11–36.61%, particularly in the fruit, compared to traditional fertilizers. This study highlighted the crucial role of nanoparticle properties, such as surface hydrophilicity and particle size, as well as interactions with rhizobacteria, in enhancing phosphorus uptake and promoting plant growth.

These studies collectively highlight the growing potential of lignocellulosic biomass in producing sustainable nanofertilizers, offering environmentally friendly alternatives to conventional fertilizers while improving nutrient use efficiency and supporting sustainable agricultural practices. Future research can explore the scalability of these approaches, the impact of nanofertilizers on diverse soil types, and their long-term effects on plant–microbe interactions. The full potential of lignocellulosic biomass in nanofertilizer development remains to be explored, particularly in optimizing production methods and enhancing nutrient-release control for a wider range of crops.

Nano-cellulose from lignocellulosic biomass

Nano-cellulose, derived from the lignocellulosic matrix of plant biomass, has emerged as a highly versatile nanomaterial, characterized by exceptional mechanical strength, high surface area, and tunable physicochemical properties [131]. Its renewable nature and biodegradability make it an ideal, sustainable alternative for a wide range of applications, including biomedicine, packaging, composites, and environmental remediation [132]. The production of nano-cellulose typically involves breaking down lignocellulosic biomass into nanoscale cellulose fibrils or crystals through mechanical, chemical, or enzymatic processes. This not only adds value to agricultural and forestry residues but also aligns with the principles of a green and circular economy [133].

Recent research has underscored the potential of agricultural residues, such as pruning residues, for producing nano-cellulose with multifunctional applications. Morcillo-Martín et al. [134] explored raspberry pruning residues for producing lignocellulose nanofibers (LCNF) and cellulose nanofibers (CNF) using TEMPO-mediated oxidation. Incorporating these nanofibers into chitosan-based edible films improved tensile strength, reaching 40.98 MPa at 0.03 g/g LCNF-TO5. Residual lignin in LCNF enhanced UV-blocking, achieving 84.56% at 0.15 g/g. Coatings with up to 0.1 g/g LCNF improved firmness and reduced bacterial counts after 7 days, showcasing the potential of lignocellulosic biomass for sustainable food packaging. Also, in a study by Suman et al. [135] it demonstrated the use of nanocellulose derived from rice straw, blended with polyacrylonitrile (PAN), to produce cost-effective carbon nanofibers. They stabilized nanocellulose/PAN (NC/PAN) films at 280 °C and carbonized them at 700 °C, finding an 18% reduction in activation energy compared to pure PAN. Their TEM analysis revealed an amorphous carbon nanofiber structure comparable to PAN films carbonized at 1000–1200 °C. Raman spectroscopy showed a lower ID/IG ratio (0.87 vs. 1.02), indicating higher carbonization efficiency. They attributed this to the chiral properties of nanocellulose, which facilitated graphene plane orientation. This study highlights the potential of agro-waste-derived nanocellulose in reducing costs and energy demands for carbon nanomaterial production. The conversion of agro-waste into valuable nanomaterials presents a sustainable solution to mitigate environmental challenges posed by their disposal.

Some of the reports highlights the potential of using different pretreatment methods for efficient and sustainable nanocellulose production from agricultural waste, offering a promising approach for large-scale biorefining. Pradhan et al. [136] investigated a sustainable method for producing cellulose nanofibers (CNF) from barley straw using ultrasound-assisted choline chloride-formic acid (ChCl-FA) deep eutectic solvent (DES) pretreatment. The DES treatment, combined with high-intensity ultrasound (HIUS), effectively solubilized 84.68% lignin and 82.96% hemicellulose, yielding cellulose with over 90% purity. Further processing via wet grinding and HIUS achieved more than 80% nanofibrillation efficiency, producing CNFs with diameters below 100 nm and a Type I cellulose structure. This study demonstrates the viability of using agricultural waste for sustainable nanocellulose production. Building on the promising results of using ionic liquids (ILs) for nanocellulose (LNC) extraction from lignocellulosic biomass, Raza et al. [137] explored the use of ILs for isolating lignocellulosic nanocellulose (LNC) from date palm waste. Their study demonstrated that ILs, specifically 1-ethyl-3-methylimidazolium chloride ([Emim]Cl), efficiently hydrolyzed partially delignified lignocellulose, yielding rod-shaped LNC fibers with nanoscale diameters and high aspect ratios. The synthesized LNC exhibited excellent thermal stability, crystallinity, and a narrow particle size distribution. This work highlights the potential of ILs as a sustainable and effective approach for producing high-quality nanocellulose from lignocellulosic biomass for various industrial applications.

The use of lignocellulosic biomass for nanocellulose production presents a sustainable solution to valorize agricultural waste and create high-value materials with diverse applications in various industries. Advances in pretreatment methods, including chemical, mechanical, and enzymatic approaches, have proven effective in isolating nanocellulose with enhanced properties. Future research should focus on improving process efficiency, exploring alternative biomass sources, and enhancing the functionalization of nanocellulose to expand its potential applications in fields such as biomedicine, packaging, and environmental sustainability.

Biochar from lignocellulosic biomass

Lignocellulosic biomass has certain inherent limitations that restrict its use for energy production. These include high moisture and volatile content, elevated oxygen levels, low density, low calorific value, variable particle size, and hardness [138]. Besides, the variability of sources of biomass feedstock, physical and chemical properties vary considerably with the composition, affecting the storage, transportation, conversion and other aspects of processing. Different thermochemical processes usually used for the conversion of biomass into solid fuel as biochar

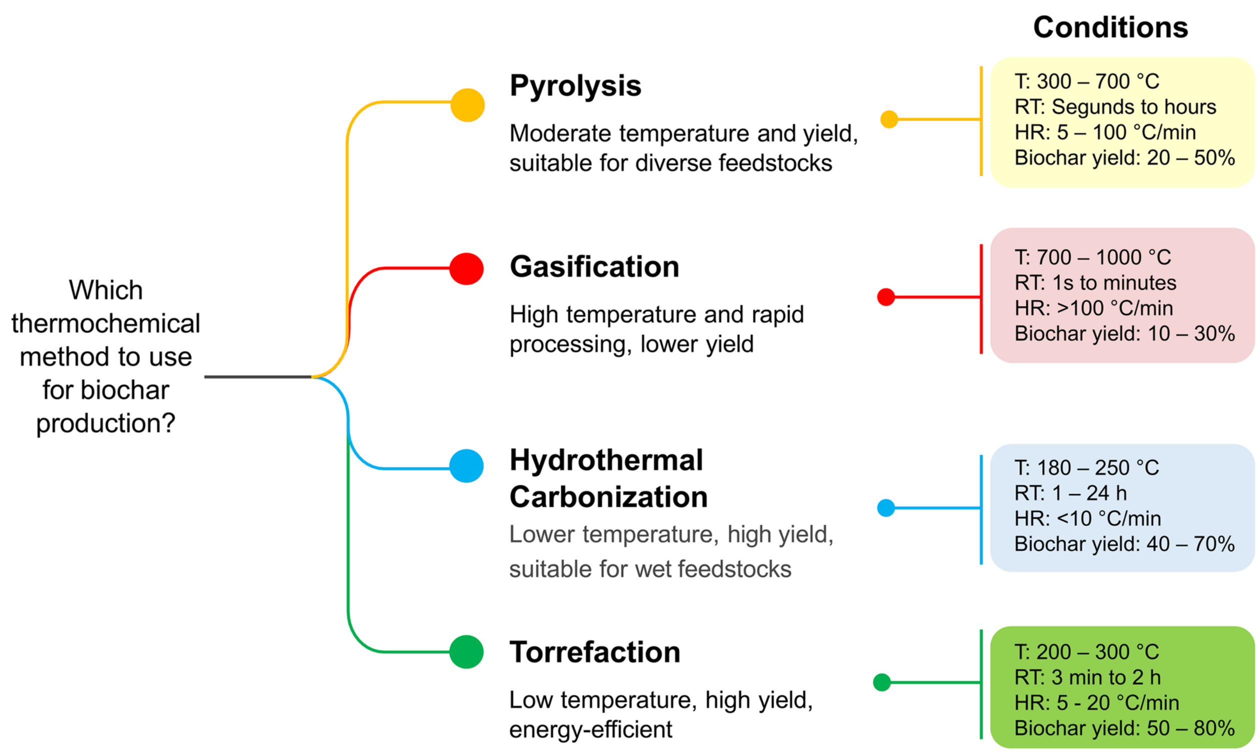


Fig. 4 Different thermochemical processes commonly used for biochar production

these mainly include pyrolysis, torrefaction, hydrothermal carbonization, and gasification. The details regarding the operational conditions for all these methods have been presented in Fig. 4. However, in the present review, we have briefly discussed only two approaches i.e. hydrothermal carbonization, and gasification. Biochar is a carbonaceous solid, with high porosity and low density resulting from the thermal degradation or volatilization of biomass, with higher energy density than that of the original feedstock [139]. This material is considered eco-friendly and has demonstrated excellent performance in several applications, including wastewater treatment, gas adsorption (CO_2 capture), air purification, and as a silage additive [140]. Lignocellulosic materials, including sugarcane bagasse, rice husk, corn stover, wood wastes, manure, and sludge from anaerobic wastewater treatment, as well as a variety of residual agriculture materials, are viable feedstock for biochar production.

Hydrothermal carbonization

A higher moisture content in biomass may result in a greater yield of bio-oil production, which may have an adverse impact on biochar production [141]. Alternatively, the hydrothermal carbonization (HTC), also known as wet pyrolysis has been shown an effective method for biochar production. This method consists of thermal degradation of the biomass in an aqueous medium in the absence of oxygen at relatively low temperature (180–300 °C) and retention time between 1 and 12 h. The main product of HTC is called hydrochar, representing between 50 and 60% of the products, with carbon content lower than the biochar obtained via dry pyrolysis (70–95%) [142]. In general, it is observed a decrease in biochar and hydrochars mass yields when increase the temperature of pyrolysis [143, 144]. Characterizing biochar and hydrochar is essential, as it is crucial for understanding their significance and potential applications in industry and the environment.

Gasification

Gasification involves the partial combustion of biomass at very high temperatures (600–1200 °C) for a short time (10–20 s). The main product is a gas mixture of carbon monoxide, hydrogen and carbon dioxide known as Syngas with a net calorific value of 11 MJ. m^{-3} [68]. This process yields lower amount of biochar (8–10%) and high content of polycyclic aromatic hydrocarbons (PAHs) in solid, that fate limit its applications as soil amendment since the toxicity of hydrocarbons.

Applications of biochar

Biochar is a highly porous structure with large specific surface area, cost-effectiveness and high stability, with great advantages as a promising material for removal of water contaminants, such as recalcitrant dye from textile, heavy metals and pharmaceuticals compounds, present industrial wastewater. Several works showed the effectiveness of biochar nanoadsorbent for the removal of chemicals, antibiotics, pesticides, hormones, microplastics [162–165]. This material is also effective as adsorbent of mycotoxins, being useful for obtaining biosensors to detect pathogenic organisms and other contaminants. Furthermore, biochar can be used as filler material in food packaging materials to extend shelf life through gas barrier formation and inhibition of microbial growth. Also, this material can promote higher mechanical resistance and electrical conductivity, with potential applications for smart packaging [166]. However, its utilization is still limited to laboratory or pilot scale process due to some impediment, such as heterogeneity of the composition of the biomass used for its production. The utilization of lignocellulosic biomass for biochar production can be an alternative to non-biodegradable polymers and ceramics traditionally used as adsorbent in wastewater treatment, which represent an opportunity for reduce the environment concert on residual biomass disposal and conversion [167]. Recent studies on the production of biochar are presented in Table 4 [143, 145–161]. Most of the reports are focused on slow pyrolysis method for biochar production, which application are focused on contaminant removal production.

Nano-biochar is obtained by mechanical treatment of biochar synthesized by pyrolysis of residual biomass to obtain particles with size less than 100 nm. This material has a large surface area, high porosity, high adsorption capacity and thermal stability. These materials are insoluble in organic solvents and mostly insoluble in water (may contain soluble components, e.g.: potassium, calcium and other elements), which is an advantage for recycling and reuse in catalytic processes [105, 168]. These soluble elements in biochar are particularly important for agriculture. Biochar and carbon nanoparticles improve plant growth by increasing root biomass, fine root length, stem diameter, and aboveground biomass in plants [169]. In addition, biochar is a non-toxic material that can potentially be used to inhibit microorganisms and adsorb gases, improving food and packaging properties and extending shelf life [166]. For example, silver nanoparticles are antibacterial agents that are widely used in food preservation against *Escherichia coli*, *Staphylococcus aureus*, and other foodborne microbial pathogens. However, their use requires stabilization by a solid carrier such as biochar, which is generally inexpensive, non-toxic, and compatible for food contact. However, biochar has irregular morphology and porosity due to the different methods used for its preparation. This can be addressed by preparing composites with polymers such as polyvinyl alcohol (PVA) and chitosan (CS), which are biocompatible and biodegradable [170].

Moreover, biochar nanoparticles are usually used as adsorbent of recalcitrant contaminants in water, including organic and inorganic compounds, pesticides, fertilizers, heavy metals, and pharmaceutical-derived products [171]. In addition, biochar nanoparticles are used as soil amendment since it is mostly alkaline, hydrogen peroxide activator, support for catalysts in chemical reactions, gas adsorption and other applications [171–177]. Since it is produced from residual biomass or recycled lignocellulosic materials, biochar nanoparticles are a green, versatile, biocompatible and relatively inexpensive material whose surface contains functional chemical groups (carbonyl, hydroxyl and carboxylic acid) that can form bonds and support biological (e.g.: cellulolytic enzymes) and inorganic catalysts (e.g.: palladium, nickel and copper) and organic compounds [168, 178, 179].

For obtaining biochar nanoparticles there are three factors affecting its characteristic including biomass type, pyrolysis temperatures and physical methods for achieving nanosized particles. Production at high temperature pyrolysis usually results in biochar with higher specific surface area with lower yield and oxygen-to-carbon ratio than those obtained at lower temperature [180]. Three methods are widely used to achieve nanoparticle size, including ball milling, microwave treatment, centrifugation, manual grinding, and ultrasound [173]. Ball milling is the most widely used method because it improves the surface area by reducing the particle size and increases the adsorption and catalytic efficiency by exposing oxygen-containing functional groups. High efficiency of size reduction with this method depends on rotational speed, ball to solid ratio and time [181]. In addition, this method is relatively economical and sustainable compared to ultrasound and centrifugation treatment, which are energy intensive. However, reports of its use are limited to laboratory scale. Table 5 shows progress in the production and use of nanobiochar [70, 164, 165, 169, 170, 176–188].

Nano-biochar is a promising alternative to traditional carbon-based nanomaterials due to its low cost, relatively simple production, high surface area, and easy structural modification to increase its functionality for various applications. The nano-biochar shows effectiveness in environmental remediation, reducing toxic organic and inorganic pollutants with higher efficiency than the raw biochar. Moreover, this material is easily combined with metals and several functional molecules to prepare composites with antimicrobial and antioxidant properties. It

Table 4 Recent advances in biochar production

Biomass	Process	Temperature (°C)	RT	HR (℃. min^{-1})	Specific surface ($m^2.g^{-1}$)	Application	Reference
Eucalyptus (*Eucalyptus globulus*)	Biochar coated with Fe3O4	-	-	-	234.46	Magnetic biochar for methylene blue adsorption	[145]
Softwood pellet, Oak, Oilseed rape straw, Miscanthus straw pellet, and Wheat straw pellets		700	12–15 min	79–103	451–1061	Supercapacitor electrode	[146]
Wheat straw	Pretreatment with cellulase	-	-	-	-	Adsorption of bisphenol A	[147]
Coconut shell	Slow pyrolysis	350, 500, 700	30, 90 min	-	-	Methylene blue adsorption	[148]
Residue of corn stover from ethanol production	Slow pyrolysis	500	2 h	5	3.0–8.0	Methylene blue adsorption	[149]
Corn stalk	Pretreatment and enzymatic hydrolysis	-	-	-	1697.3	Dye and chemical removal	[150]
Apple pruning	KOK as activator. Slow pyrolysis	900	2 h	20	1176.5 (1 step) 1297.2 (2 steps)	Methylene blue adsorption	[151]
Wood and waste wook of oak and larch	Pretreated with NaOH, low pyrolysis	600	1 h	-	403.18 (oak) 481.18 (larch)	Ibuprofen adsorption	[152]
Oil palm trunks	Pretreated with NaOH and sodium chlorite. Slow pyrolysis	500	3 h	28.8	3.27	Methylene blue adsorption	[153]
Almond, walnut, and peanut shells	Slow pyrolysis	500	2 h	20	-	Magnetic solid-phase extraction of naproxen	[154]
Sugarcane bagasse	Pretreated with KOH	800	2 h	5	1061.7	Cu (II) removal	[155]
Raw olive pomace (Impregned with Olive mill wastewater)	Hydrothermal carbonization (HTC) and slow pyrolysis (PY)	180,200,220 (HTC) 400,500,600 (PY)	24 h (HTC)1 h (PY)	10 (HTC) 5 (PY)	-	Biofertilizer and for removal of anionic contaminants such orthophosphates,	[156]
Hornbeam wood chips	Hydrothermal carbonization (HTC), pyrolysis (PY) and torrefaction (TO)	225—575	-	-	-		[143]
Cellulose, hemicellulose, lignin and Pinewood	-	350 – 650	60	20	-	Capacitor	[157, 158]
Empty Fruit Bunch	Torrefaction	225–300	20–60	-	-	Solid fuel (HHV: 20 MJ/kg, EY: 89%)	[158]
Walnut shell and pearl mile	Torrefaction. Nitrogen atmosphere	230–300	30 – 90 min	-	-	Solid fuel (HHV: 27 MJ/kg). Adsorbent, biocomposite, soil and plant conditioner	[159]
Spent coffee ground	Torrefaction	250, 300	10,20,30 min	-	-	Solid fuel with increased HHV	[160]
Sesame stalks (SS) and Bean husk (BH) and	Torrefaction	200, 225, 250, 275, and 300	30, 60	-	-	Solid fuel SS (20.5 MJ/kg), BH (16.2 MJ/k)	[161]

HHV High Heating Value, *EY* Energy Yield

Table 5 Recent development on biochar nanoparticles and biochar-based nanocomposite and its applications

Biomass	Biochar production	Characteristics/performance	Applications	Reference
Chicken manure (with high straw content)		Nanocatalyst functionalized with Cu and di(pyridin-2-yl) methanone) (Cu-DPMI@biochar). Recovered and reused for 6 runs without metal leaching or reducing in its activity,	Synthesis of 5-substituted 1H-tetrazoles as antimicrobial agent	[171]
Rice husk	Pyrolysis at 500 oC for 2 h	Biochar with silicon NPs (nSi), and iron NPs (nFe) modifications	Reducion of Cadmium bioavailability in soil and its toxicity in maize	[175]
Limonia acidissima shell	Pyrolysis at 700 °C for 4 h	TiO_2 nanoparticles were synthesized via sol–gel process	Photo catalytic process for leachate water degradation. Removal of COD and color	[176]
Melia azedarach fruit biomass	Pyrolysis at 450 °C for 20 min	Al_2O_3 nanoparticle previously synthetized and the biomass the pyrolysis reactor results in Biochar@Al_2O_3 Nanocomposite	Photocatalytic methylene blue dye degradation	[182]
Banana peels	Hydrothermal carbonization at 180 °C for 12 h	ZnO/biochar nanocomposites	Photocatalytic degradation of methylene blue	[183]
Wheat straw	Pyrolysis at 500 °C	MnO_2/biochar nanocomposite ZnO/biochar nanocomposite	mmobilization and bioavailability of Pb, Cd, Zn, and Ni in soil	[81]
Barley distillers' grains shell	Biochar obtained by Calcination at 300 °C for 2 h, followed by calcination with $AgNO_3$ at 200 C for 2 h (for Ag fixation)	Silver-loaded biochar was introduced into polyvinyl alcohol-chitosan (C–Ag-loaded PVA/CS) to form composite film	Good thermal stability, hydrophobicity, high antioxidant and antibacterial activity	[170]
Rice husk	Pyrolysis at 700 °C for 1 h	Biochar impregnated with $AgNO_3$ and avocado seed extract and irradiated with blue LED light for 4 h under continuous stirring	Dye reduction process and antibacterial activity	[184]
Pine sawdust	Ion hydrothermal treatment and microwave activation	Hydrothermal char-supported metal (Fe, Ni and Co) nanoparticle composites	Production of bio-oil rich in phenol	[185]
Pine wood	Hydrothermal carbonization at 200 °C for 6 h followed by microwave activation at 800 °C for 1 h	Bimetallic hydrothermal char catalysts Co–Ni/MHC, Fe-Co/MHC, Fe–Ni/MHC)	Production of bio-oil up to 42.7% styrene	[186]
Hazelnut shells	Hydrothermal carbonization at 240 °C for 4 h	Hydrochar impregned with SnO_2 nanoparticles	Nanosensor for cathecol detection	[187]
holocellulose extracted from açai seeds (Euterpe oleracea)	Hydrothermal carbonization with and without citric acid	sulfonated carbon sphere catalysts	Esterification reaction for biofuel production	[188]
Banana peel	Hydrothermal carbonization at 180 C for 3 h	Hydrochar / Chitosan nanparticle	Adsorption of trihalomethanes	[189]
Tea waste	Hydrotermal carbonization at 220 °C, 55 min	Fluorescent carbon dots and green coal-like hydrochar	Antibacterial activity against *B. subtilis* and *E. coli*	[190]
Peanut shell	Solvothermal coupled with calcination, followed by Pyrolysis at 700 °C	ZnO/N—O-contained biochar nanocomposites	Dyes and antibiotic removal	[191]
Peanut shell	Pyrolysis at 400 – 700 °C for 2 h	ZnO/biochar nanocomposites	Removal of methylene blue dye	[192]
Corn residues and *Conocarpus erectus* L. Wood waste	Pyrolysis temperatures (400 °C and 700 °C). Hydrothermal treatment of biochar using H_2SO_4/HNO_3	Woody biochar nanoparticles contained higher surface area, pore volumes, stability, polarity, and acidic functional groups than corn-based biochar nanoparticles	pH regulation in soils	[193]
Rice and corn straw	Pyrolysis at 350 °C	-	Soil amendment to alleviate salt stress/ rice straw biochar nps inhibited the transfer of na from roots to shoots	[194]

is also an effective carrier for enzymes and catalysts for biofuel production, as a nutrient retention and growth promoter in agriculture, and as a support for biosensors to detect toxic pollutants. Key challenges for the expansion of nanobiochar include studies to improve synthesis methods and scale-up.

Nano lignin from lignocellulose biomass

Lignin is an abundant aromatic polymer found in lignocellulosic biomass which can be isolated using various pretreatment methods such as alkaline, organosolv, or acid hydrolysis processes [195]. Nanolignin, derived from lignin is a also a major component of lignocellulosic biomass. It has gained significant attention as a versatile nanomaterial due to its unique properties and sustainable nature [196]. Lignin once extracted from lignocellulosic biomass, can be converted into nanolignin through a variety of methods. These include top-down approaches, such as high-energy ball milling, ultrasonication, or high-pressure homogenization, which break down lignin into nanoparticles. Alternatively, bottom-up methods, including chemical self-assembly and precipitation, synthesize lignin nanoparticles by carefully controlling factors like pH and solvent type [197, 198]. Emerging green synthesis techniques, such as the use of ionic liquids or biological agents, are also being explored for eco-friendly nanolignin production. These processes yield nanolignin particles with a high surface area, tunable size, and enhanced functional properties [199, 200].

Nanolignin's unique characteristics, such as its antioxidant, antimicrobial, and UV-blocking properties, make it highly valuable for a range of applications [196]. In bioplastics, nanolignin acts as a reinforcing agent, significantly improving the mechanical strength and thermal stability of polymer composites [201]. Polylactic acid (PLA) films reinforced with lignin nanoparticles (LNPs) demonstrate significant potential as advanced bioplastics, as reported by Cavallo et al. [202]. The inclusion of pristine (LNP), citric acid-modified (caLNP), and acetylated (aLNP) lignin nanoparticles improved the mechanical strength and thermal stability of PLA, highlighting nanolignin's role as an effective reinforcing agent. Additionally, the films exhibited UV-blocking, antioxidant, and antibacterial properties, enhancing their functionality for food packaging applications. Chemical modification of LNPs further improved nanoparticle dispersion and ductility while maintaining biodegradability comparable to neat PLA, making nanolignin a valuable addition to sustainable polymer composites. Its antioxidant properties are particularly beneficial in food packaging, where it can extend the shelf life of perishable items [203]. As demonstrated by Rani et al. [204], biomass-derived nanoparticles such as nanolignin (NL), nanocellulose (NC), and nanohemicellulose (NHC) were incorporated into chitosan films to create higher-barrier active packaging materials. The addition of 1.5% NL and NHC enhanced the mechanical, water, and UV barrier properties while significantly improving antioxidant and antimicrobial activity. In practical application, fresh meat packed in chitosan films with 1.5% NL retained its quality for up to 18 days when stored at 4 °C, compared to complete spoilage by the sixth day in commercial LDPE packaging. This study underscores nanolignin's potential as a reinforcement in biopolymer films, offering a sustainable solution for extending the shelf life of highly perishable foods. In the agricultural sector, nanolignin-based formulations are being developed as slow-release carriers for fertilizers and pesticides, offering a sustainable approach to farming [205]. Furthermore, nanolignin has been utilized in cosmetics, pharmaceuticals, and coatings due to its bioactive and eco-friendly nature [206, 207]. These multifunctional applications demonstrate the potential of nanolignin to drive innovation in green technologies while contributing to the circular economy.

The development of cost-effective, scalable methods for nanolignin production remains a critical area of research, ensuring that the vast lignocellulosic biomass resources can be efficiently transformed into high-value nanomaterials for widespread industrial and environmental benefits.

Socio-economic and environmental impacts of nanotechnology in biomass conversion

The integration of nanotechnology in biomass conversion has become a focal point for advancing sustainable practices in both socio-economic and environmental domains [208, 209]. In this review, we explore the multifaceted impacts of nanotechnology, specifically its potential to reduce costs, enhance efficiency, and promote sustainability. The discussion centres around how nanotechnological advancements can revolutionize biomass processing by contributing to economic growth, resource efficiency, and environmental preservation. Below, we examine these impacts in two main categories: socio-economic and environmental.

Socio-economic impacts of nanotechnology in biomass conversion

Economic benefits

The application of nanotechnology in biomass conversion offers promising economic advantages. Nanomaterials enable the improvement of process efficiency, leading to reduced conversion costs, lower energy consumption, and enhanced product quality [210]. These advances not only make biomass-based products more affordable but also pave the way for new industries and job opportunities. Emerging sectors such as nanomaterials production, bioenergy, and sustainable agriculture stand to benefit, fostering job creation in research, manufacturing, and technical fields [211]. Furthermore, the ability to create high-value products like biofuels, bioplastics, and nanomaterials from biomass waste can stimulate market expansion, offering new economic opportunities and enhancing the viability of biomass-based industries [212].

Value addition and efficiency

Nanotechnology also drives significant improvements in biomass-to-energy conversion efficiency. By utilizing nanomaterials as catalysts or additives, the conversion processes can be optimized, yielding higher biofuel outputs with better resource utilization [213]. This not only increases the productivity of bioenergy systems but also supports the circular economy by converting biomass waste into valuable products, such as nanocellulose, biochar, and biofertilizers [214]. This capacity for value addition presents further economic opportunities, enhancing both the sustainability and profitability of biomass-based industries.

Societal impact

For nanotechnology to gain widespread adoption, societal acceptance and trust are critical. Public concerns surrounding safety, health risks, and environmental impact must be carefully addressed to foster confidence in nanotechnology applications [215, 216]. Additionally, the potential risks of exposure to nanomaterials need thorough evaluation, and the development of safe handling protocols is essential to protect workers and consumers alike. Clear communication of the benefits and risks of nanotechnology is supreme in alleviating public fears. Initiatives such as public engagement programs, education campaigns, and transparent reporting on the safety and efficacy of nanotechnology-based products can play a crucial role in building trust.

Moreover, regulatory frameworks need to be established and standardized globally to govern the production, use, and disposal of nanomaterials, ensuring that their applications are aligned with public health and environmental safety goals. International collaborations between governments, industries, and academia can facilitate the development of robust guidelines for the ethical and sustainable use of nanotechnology. For instance, the implementation of lifecycle assessments (LCAs) can help evaluate the environmental footprint of nanomaterial production and applications, fostering a balance between innovation and sustainability [217].

The societal benefits of nanotechnology in biomass conversion will be fully realized when these challenges are mitigated, ensuring that its implementation is both safe and effective [218]. For example, advancements in nanotechnology can lead to cost-effective and efficient biomass conversion processes, reducing dependency on fossil fuels and promoting rural development through the utilization of agricultural residues. By creating job opportunities in nanomaterial production and application, nanotechnology can contribute to economic growth in underserved regions. Additionally, nanotechnology-enabled products such as biochar and nanofertilizers can significantly enhance agricultural productivity, addressing global food security concerns.

Ultimately, the integration of nanotechnology into biomass conversion holds the potential to revolutionize waste management, energy production, and material science. However, achieving societal acceptance requires a proactive approach to address safety, ethical considerations, and equitable access to the benefits of these innovations.

Environmental impacts of nanotechnology in biomass conversion

Sustainable biomass valorization

Nanotechnology has the potential to significantly enhance sustainability in biomass conversion processes. It plays a key role in improving biomass conversion efficiency by reducing waste and maximizing the utilization of biomass residues. Nanomaterials enable the transformation of diverse agricultural wastes, such as straw, husks, corn stover, and lignocellulosic residues, into high-value products including biofuels, bioplastics, and biochemicals which ultimately promote the circular economy [219]. For instance, nano-enhanced catalysts facilitate the depolymerization of complex polymers in biomass, improving the recovery of fermentable sugars and subsequently boosting bioethanol yields. These processes not only increase product output but also contribute to waste minimization by converting non-utilized residues into usable forms [220].

Additionally, the application of nanotechnology addresses challenges in energy consumption by improving the energy efficiency of biomass conversion. Nano catalysts and nano-enhanced enzymes reduce activation energy requirements in reactions, leading to lower energy inputs during critical processes like hydrolysis, pyrolysis, and gasification. This reduces the overall carbon footprint of the conversion process, aligning it with sustainability goals. Moreover, nanotechnology-driven innovations, such as nanofiltration membranes, assist in separating and purifying conversion by-products, ensuring efficient resource recovery while reducing process waste [221]. These advancements make biomass conversion more sustainable and environmentally friendly.

Reduction in greenhouse gas emissions

One of the most significant environmental benefits of nanotechnology in biomass conversion is the reduction in greenhouse gas emissions. By improving process efficiency, nanotechnology helps lower the release of CO_2 and other pollutants typically associated with biomass conversion. This makes biomass energy production a more sustainable and eco-friendlier alternative to traditional fossil fuel-based energy sources [222].

Furthermore, nanomaterials such as biochar have been demonstrated to significantly enhance soil carbon sequestration capabilities. Biochar, when integrated into soil, not only improves fertility but also acts as a stable carbon sink, effectively mitigating climate change by offsetting GHG emissions [223]. Additionally, nano-catalyzed processes produce lower emissions by minimizing by-product formation and ensuring complete conversion of biomass feedstocks. For example, the integration of nanocatalysts in biomass gasification systems has shown a marked reduction in methane and NOx emissions, further contributing to a cleaner energy profile [224, 225].

Enhanced soil and water quality

Nanotechnology also contributes to the improvement of soil and water quality, a crucial aspect of sustainable biomass conversion. The development of nano-enabled fertilizers, such as nano-encapsulated nutrients, has revolutionized nutrient delivery systems by enhancing nutrient-use efficiency. These fertilizers provide controlled-release mechanisms, ensuring optimal nutrient availability while reducing nutrient leaching and runoff [122]. This approach not only improves soil fertility but also mitigates contamination in surrounding water bodies caused by conventional fertilizers [226].

In addition to fertilizers, nanotechnology enables advanced pollutant remediation during biomass processing. Nanomaterials like nano-Fe3O4 and carbon nanotubes are employed to absorb, degrade, or neutralize pollutants, thereby reducing contamination in wastewater streams generated during biomass conversion [227, 228]. For instance, nano-adsorbents have shown remarkable efficiency in removing heavy metals and organic pollutants from biomass-derived effluents, ensuring safer disposal and reuse of water [229, 230]. These applications not only enhance the sustainability of biomass conversion but also have broader environmental implications for preserving ecosystem health.

The integration of nanotechnology in biomass conversion holds significant socio-economic and environmental promise, offering the potential to revolutionize both the biomass industry and agricultural practices [1]. Nanotechnology can reduce conversion costs, enhance product value, and optimize resource efficiency, while also minimizing environmental impacts. As a result, it presents a compelling pathway toward sustainable development. However, the broader adoption of these technologies is contingent upon addressing societal concerns, establishing rigorous safety standards, and refining conversion processes to maximize their environmental and economic contributions. As research and technological advancements continue, nanotechnology's role in biomass conversion is controlled for further expansion, driving a more sustainable and economically viable future for biomass-based industries.

Toxicological concerns of nanotechnology in biomass transformation

The application of nanotechnology in biomass transformation introduces several toxicological concerns that require careful evaluation for safe implementation [231]. Nanoparticles (NPs), due to their unique properties such as high surface area and small size, may enter biological systems through various routes, potentially causing harmful effects on human health and the environment [232, 233].

Nanoparticles can enter living organisms via inhalation, ingestion, and dermal absorption. Inhalation of airborne NPs may pose risks to the respiratory system, leading to inflammation, lung injury, or even carcinogenesis [234]. Ingestion of contaminated water or food could affect the gastrointestinal system, while dermal exposure may lead to skin irritation or penetration of NPs into deeper tissues, potentially causing systemic toxicity [235]. Once inside the body, NPs may accumulate in tissues, leading to long-term effects on organs such as the liver, kidneys, and brain. Additionally, these particles can disrupt cellular processes by inducing oxidative stress, inflammation, and immune responses [236].

Examples of nanomaterials and their toxicity include nanocellulose, silver nanoparticles (AgNPs), and zinc oxide nanoparticles (ZnO NPs). Nanocellulose, derived from lignocellulosic biomass, is considered biocompatible but poses risks of bioaccumulation, potentially affecting food safety and ecosystem health. Studies suggest that excessive exposure to nanocellulose could interfere with plant growth and soil microbiota, impacting agricultural productivity [234]. Silver nanoparticles (AgNPs), widely used as antimicrobial agents in biomass transformation, pose environmental risks due to their potential to leach into soils and water bodies. Studies have shown that AgNPs can bioaccumulate in soil organisms, such as earthworms (*Pheretima guillemi*), with significantly higher silver concentrations in their digestive systems compared to controls. Although low-level AgNPs exposure does not affect survival or growth, it induces intestinal damage, metabolic interference, and lipid peroxidation in earthworms, disrupting

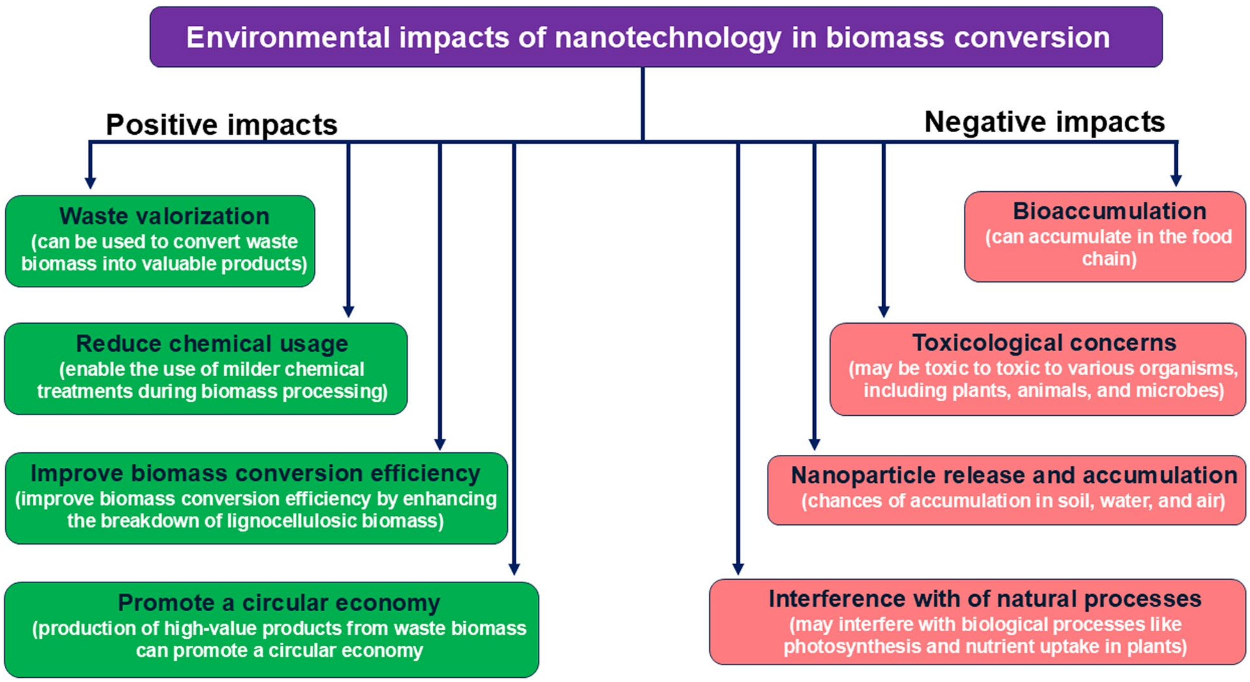


Fig. 5 Schematic representation of various environmental impacts of nanotechnology in biomass conversion

glycerophospholipid, glutathione, and energy metabolism. Additionally, AgNPs toxicity extends to aquatic organisms, including algae and fish, raising concerns about water quality and ecosystem health [235, 237]. Zinc oxide nanoparticles (ZnO NPs), extensively utilized in biomass conversion, present alarming risks to soil health and aquatic ecosystems. Research on *Salvia miltiorrhiza* shows that exposure to 100–700 mg kg^{-1} ZnO NPs significantly increases zinc accumulation in plant roots while depleting essential iron, potentially disrupting plant growth and nutrient balance. At higher concentrations (700 mg kg^{-1}), ZnO NPs drastically alter rhizosphere microbial communities, promoting zinc-tolerant species like *Humicola* and *Thiobacillus* at the expense of microbial diversity vital for soil fertility. Even more concerning is their bioaccumulation in aquatic organisms, threatening biodiversity and ecosystem stability. These findings highlight the urgent need for stricter assessment and mitigation strategies to manage the ecological risks of ZnO NPs [236, 238].

To ensure the safe use of nanotechnology in biomass transformation, it is crucial to implement strategies that minimize the potential toxicity of nanomaterials [239]. One approach is developing environmentally safe synthesis methods for nanomaterials, avoiding the use of toxic chemicals. Surface modification of nanoparticles can reduce their toxicity, making them more stable and less likely to release harmful substances into the environment [232, 240]. The use of biodegradable or bio-based nanomaterials can help minimize long-term environmental impacts [234]. Comprehensive risk assessments, including evaluating nanoparticle fate, interactions with living organisms, and potential for bioaccumulation, must be carried out to ensure the responsible deployment of nanotechnology in biomass conversion [235] Fig. 5 represents the schematic presentation of various environmental impacts of nanotechnology in biomass conversion.

Biotechnology companies driving sustainable bioproducts development from renewable feedstocks

Many biotechnology companies are actively engaged in producing biofuels, biochar, biopigments, biofertilizers, and biopesticides using fermentation of renewable feedstocks. In the biofuels sector, notable companies include Amyris, Inc., which uses advanced fermentation techniques to produce sustainable biofuels, and Terragia, specializing in converting lignocellulosic biomass into ethanol. Terragia is a U.S.-based company, specializes in carbon-negative ethanol production using thermophilic microorganisms. Their innovative C-CBP process eliminates thermochemical pretreatment, reducing costs, steps, and carbon intensity while enhancing efficiency in lignocellulose conversion. [241, 242]. ICODOS focuses on transforming industrial off-gases into methanol, while Esylys develops portable biogas plants for organic waste utilization. Esylys, an India-based company, offers the HiPrBio system, a portable biogas plant converting food waste into high-methane biogas and hydrogen. Utilizing digital twin technology, it optimizes energy systems and supports waste management efficiently [241]. Polski Biogaz and Green2x are also key players, leveraging agricultural residues such as straw to produce bioenergy. Polski Biogaz (Poland, founded 2022) develops modular, AI-driven biogas plants that convert organic waste, including farm and industrial residues, into renewable energy. The mobile units are scalable and minimize downtime, ensuring uninterrupted operations during maintenance. Green2x (Denmark, founded 2020) specializes in converting straw into bioenergy. Using advanced fermentation, the company produces high-energy biogas, biomethane, and bio-methanol, offering sustainable alternatives to natural gas for manufacturing and transport while reducing CO_2 emissions [241]. Votion Biorefineries (Sweden, founded 2022) produces advanced biofuels, sustainable aviation fuel (SAF), and specialty biochemicals. Leveraging technologies from pulp mills, oil refineries, and petrochemical plants, it utilizes diverse sustainable lignocellulosic biomass as feedstocks to drive innovation in renewable energy [241].

In the biochar segment, companies like Avello Bioenergy and MASH Makes A/S lead the way by employing pyrolysis technologies to convert agricultural residues into carbon-negative biofuels and biochar [243, 244]. The biofertilizer and biopesticide sectors feature companies like Bioceres S.A., a pioneer in agricultural biotechnology, and Bills Biotech Pvt. Ltd., which manufactures biofertilizers and biopesticides through fermentation processes. Genexis Biotech Pvt. Ltd. focuses on precision fermentation to develop sustainable proteins and biofertilizer components, while several other companies worldwide are advancing biopesticide production using innovative fermentation technologies [245, 246]. These organizations demonstrate the immense potential of biotechnology in transforming renewable feedstocks into high-value, sustainable bioproducts.

Given that, approximately 181.5 billion tons of lignocellulosic biomass is produced annually globally. Out of which, only 8.2 million tons of lignocellulosic biomass is used in various application sectors [247, 248] showing the enormous scope of converting the biomass in low carbon chemicals and fuels meeting the net zero carbon emissions goal set by many countries. The judicious application of biomass can reduce GHG emissions effectively via converting into biofuels, biochemicals, biochar, among others. However, composting of biomass can lead to the generation of GHG emissions [249].

Conclusion and future perspectives

This review highlights the immense potential of lignocellulosic biomass as a renewable and sustainable resource for the production of high-value biomaterials. While traditional methods for managing and processing lignocellulosic biomass are limited by inefficiencies and environmental concerns, advancements in green chemistry and nanotechnology have revolutionized its utilization. Innovative approaches, such as the synthesis of nanomaterials, biofuels, nanocellulose, biochar, and nanofertilizers, have demonstrated the ability to transform this abundant resource into products with applications across agriculture, energy, and environmental remediation. The incorporation of nanotechnology has proven to be a key advancement, addressing challenges associated with biomass recalcitrance and enabling scalable and cost-effective solutions. For instance, the development of nanocellulose and biochar offers sustainable alternatives to conventional materials, while nanofertilizers provide eco-friendly agricultural inputs. Moreover, the integration of these technologies aligns with the principles of a circular economy, reducing waste and promoting resource efficiency. Despite these advancements, challenges such as economic feasibility, scalability, and potential environmental risks of nanomaterials remain. Future research must focus on optimizing processing techniques, minimizing costs, and evaluating the long-term impacts of these technologies. Policymaking and industry collaboration will also play a critical role in advancing the sustainable conversion of lignocellulosic biomass at a global scale. By addressing these challenges, lignocellulosic biomass can serve as a foundation for achieving sustainability goals, mitigating climate change, and reducing reliance on fossil-based resources. The convergence of technological innovation and strategic policy support holds the key to unlocking the full potential of this resource, transforming it into a driver of environmental and economic progress.

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Authors' contributions
A.P. Ingle: conceptualization, writing the original draft review, and editing, S. Saxena: manuscript writing, and editing, M. P. Moharil: manuscript writing, draft review, J. D. Rivaldi: manuscript writing, draft review, and editing, L. Ramos: manuscript writing, and editing, A. K. Chandel: conceptualization, writing the original draft review, and editing All authors reviewed the manuscript.

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Competing interests
The authors declare no competing interests.

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