

Review

Exploring Recent Advances in Lignocellulosic Biomass Waste Delignification Through the Combined Use of Eutectic Solvents and Intensification Techniques

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Abstract: Growing awareness of resource sustainability and waste management has driven the search for circular-economy solutions. Lignocellulosic biomass waste, the most abundant renewable carbon resource, offers green potential as an alternative to declining non-renewable fuels. However, due to its recalcitrant nature, it requires pre-processing to convert it into valuable products like energy and chemicals. Biorefineries play a key role in this process by promoting the integral use of biomass, by finding ways to utilize lignin, previously treated as waste. Common pretreatment methods are unsustainable, prompting research into eco-friendly solvents and advanced techniques like ultrasound- and microwave-assisted methods. Recent approaches have also explored the use of eutectic solvents, which, when combined with these intensification techniques, offer promising results. These green technologies improve delignification efficiency, which in turn improves the saccharification process, reduces solvent use, and minimizes environmental impact. Despite progress, challenges remain in making these methods economically viable and adaptable to diverse biomass types. This review article highlights recent advances in sustainable treatment technologies, including the combined use of eutectic solvents and process-intensification techniques, and the potential of the obtained lignin in various industrial applications. It also discusses future prospects for more environmentally friendly processes in biomass utilization.

Keywords: lignocellulosic biomass; lignin; eutectic solvents; green solvents; microwave-assisted treatment; ultrasound-assisted treatment; delignification; sustainable process; biorefinery



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1. Introduction

The decreasing availability of non-renewable fuels and environmental degradation have prompted the search for sustainable alternatives, with lignocellulosic biomass waste emerging as a promising and eco-friendly option for the production of biofuels, biochemicals, and other value-added products, intensifying the interest in renewable feedstocks [1,2]. Lignocellulosic biomass, recognized as the most abundant carbon renewable resource worldwide, is harnessed in lignocellulosic biorefineries to maximize the utilization of agricultural by-products, in harmony with the principles of sustainability, environmental responsibility, and the bio-based circular economy [3,4]. Lignocellulosic biomass, consisting mostly of cellulose, hemicellulose, and lignin, is structured by complex covalent and non-covalent interactions that generate a rigid matrix resistant to physical, climatic, and microbial stresses. Such natural structural recalcitrance requires pretreatment prior to

chemical or biological processing to break down its compact composition. This deconstruction process facilitates the conversion of biomass into a wide range of products, including energy, chemicals and materials, within the context of biorefining [3,5,6].

While cellulose and hemicellulose are used commercially, lignin is often underutilized or considered a waste product. Traditionally discarded and burned in the pulp industry to generate heat and steam, lignin is being explored for more efficient and economically competitive uses [7]. Recognizing lignin and its components, which have similarities to petrochemicals and potential as substitutes in various applications, is crucial for improving biorefinery efficiency and reducing waste. Numerous opportunities have recently emerged in different applications, ranging from feedstock for platform chemicals to biomedical materials, pyrolytic oil production, or adhesive manufacturing, among others [1,4].

A pretreatment step is essential, depending on the ultimate goal of biomass processing, to improve the yield and efficiency of bioconversion of lignocellulosic biomass [6]. Traditional methods (such as steam explosion, acid hydrolysis, and alkaline treatment) can be costly and inefficient for industrial adaptation, driving ongoing research into more selective and efficient techniques [5,8,9]. Efforts dedicated to lignin valorization have prompted the development of new pretreatment methods using a new class of solvents [1]. Green solvent-based biorefineries have emerged as a promising solution, using alternative solvents, such as eutectic solvents, instead of conventional solvents, offering economic benefits and minimal environmental impact [1,7,10]. In addition, the combined use of intensification techniques is gaining attention for its alignment with green-chemistry principles [2,11]. In recent years, researchers have reported good performance of lignocellulosic treatment using ultrasound- or microwave-assisted treatment, which can also be combined with the use of green solvents [12,13]. These technologies stand out for their sustainability, lower energy consumption, reduced processing times, and minimization of negative environmental impacts [2,11]. In addition, the energy applied helps the dissolution or solvation of lignin in the extractive solvents, favoring the delignification process, which subsequently improves carbohydrate hydrolysis yields and the overall efficiency of the process [14,15].

These methods address the limitations of traditional pretreatment processes and improve the overall efficiency and sustainability of biomass utilization [2,6,9]. However, the main challenge is the high capital cost and lack of a comparative analysis of these sustainable techniques on various lignocellulosic biomass, as well as studies on how they can be advantageously utilized in future biorefineries [9,14]. Therefore, thorough investigations and feasibility studies are needed to identify the most efficient and applicable emerging technologies [9]. Although there is a wide collection of reviews on the use of either eutectic solvents or intensification techniques as pretreatment agents for the delignification of lignocellulosic biomass, reviews focusing on the combined use of both aspects are lacking. Therefore, this review aims to address this gap. This exploratory review starts by outlining the current status and types of lignocellulosic biomass derived from agricultural and forestry practices, detailing their lignin content, and summarizing different treatment methods for delignification. Subsequently, this article focuses on recent advances in delignification over the past five years, with particular attention paid to the beneficial use of alternative solvents in combination with intensified techniques. Additionally, the characteristics and potential applications of the recovered lignin are evaluated. Finally, the challenges and prospects related to the use of alternative solvents in lignocellulosic processing are highlighted.

2. Biomass Waste and Lignin Content

Agricultural and forestry practices provide large volumes of lignocellulosic biomass waste, and plants' dry matter can serve as a sustainable resource to produce biofuels and high-added-value products. The main structural components of these biomasses are cellulose, hemicellulose, and lignin. As is well known, cellulose and hemicellulose are carbohydrates, and they are well-known precursors in the bioconversion process for producing biofuels and biochemicals. Lignin plays a role in the recalcitrance factors, which

have an inhibitory effect on the biological conversion of biomass. Several factors have been evaluated as responsible for the recalcitrance of lignocellulose, including the crystallinity and degree of polymerization of cellulose, the hydrophobicity of lignin, and the difficult cellulose accessibility due to the matrix lignin–hemicellulose strongly associated with covalent and hydrogen bonds [16]. In Table 1 are listed several representative types of lignocellulosic biomass waste from agricultural and forestry practices, together with their composition in terms of main components: cellulose, hemicellulose and lignin. It can be observed that the lignin content can reaches values between 10 and 30% in these types of biomasses.

Table 1. Types of biomass waste from agricultural and forestry by-products, as well as food waste, along with their chemical composition (cellulose (%), hemicellulose (%), and lignin (%) on a dry-weight basis).

Lignocellulosic Biomass Waste		Composition			Ref.
Biomass Type	Biomass Name	Cellulose (%)	Hemicellulose (%)	Lignin (%)	
Agroresidues food crops	Rice straw	37.8	17.9	20.8	[17]
Agroresidues non-food crops	Cotton stalk	67.0	16.0	13.0	[18]
Food waste	Raquis from banana waste	26.1	11.2	10.8	[19]
Hardwoods forest residue	Eucalyptus wood	48.1	18.4	28.2	[20]
Softwood forest residue	Pine	45.6	24.0	26.8	[21]
Forest residue	Bamboo powder	45.5	22.0	29.3	[22]
Industrial/municipal wastes	Brewery by-products	27.6	35.0	38.7	[23]

Lignin is a complex aromatic polymer formed by three units of phenylpropane monomers: p-coumaryl, coniferyl, and sinapyl alcohols, which are precursors of p-hydroxyphenyl (H), guaiacyl (G), and syringyl (S). Their representative structures are shown in Figure 1. The monolignols basic units are connected via carbon–carbon linkages (e.g., β - β , β -5, 5–5, and β -1) and ether bonds (e.g., α -O-4 and β -O-4) [24]. The ratio of different monomer units depends on the biomass source, which can include lignocellulosic materials from forestry waste, energy crops, and agricultural residues, as well as industrial or municipal waste. Lignin in hardwood plants is generally composed of S as the main component, followed by G units. In contrast, in softwood plants, lignin is mainly composed of G, followed by a small amount of H unit. Finally, herbaceous residues are characterized by a lignin mainly composed of G, followed by H and S units [25]. The relationship between the lignin S/G ratio and biomass recalcitrance is complex, as the presence of these lignin units can either facilitate or hinder biomass conversion. One study in the literature has identified a positive correlation between the S/G ratio and enzymatic hydrolysis. This correlation is attributed to the higher binding capacity of guaiacyl, which has a branched structure, compared to syringyl, which has a linear structure and a lower degree of polymerization, for cellulose [26].

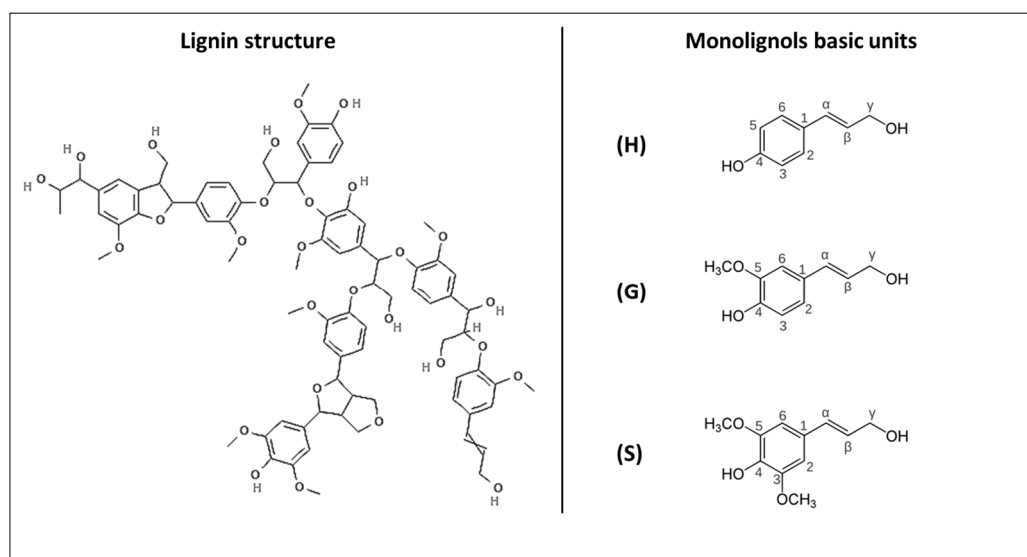


Figure 1. Simplified structure of a representative lignin (organosolv type) and of the basic monolignol units in lignin: (H) p-hydroxyphenyl, (G) guaiacyl, and (S) syringyl. The chemical formula for organosolv lignin was obtained from the PubChem database (<https://pubchem.ncbi.nlm.nih.gov/>, accessed on 28 October 2024).

3. Common Methods for Delignification of Lignocellulosic Biomass

The separation of lignin from carbohydrates can be difficult due to the complex linkages and interaction between components that make lignocellulosic biomass highly recalcitrant. There are two possible approaches to this problem: the traditional, industrially well-established methods, which focus on obtaining high-purity cellulose; or the more recent “lignin-first” processes, which seek to efficiently separate lignin without greatly affecting its properties and reactivity [27]. Cellulose-oriented methods usually employ harsh conditions to achieve their objective, resulting in modified lignin products that are difficult to valorize [28]. However, in the “lignin-first” approach, fractionation processes consisting of two or more steps are commonly used, and operation conditions tend to be milder, thus minimizing hemicellulose degradation and avoiding lignin-condensation problems. Depending on the method utilized, the properties of the extracted lignin may vary, and so do its possible applications [27]. According to their action mode, the delignification technologies can be divided into chemical, physical (or chemo-physical), and biological methods.

Chemical delignification processes are usually well known and quite well-established in the industry, i.e., Kraft and sulfite processes; however, some innovations have been developed in the last years. For instance, Liu et al. [29] proposed a novel application method to delignify large chips of Chinese fir (20 × 20 × 30 mm) using a chemical reagent. They employed a solution of 1 wt% NaClO₂ and applied consecutive positive–negative pressure cycles to impregnate the biomass. Using this method, they achieved a uniform removal of lignin, reducing the time needed for the treatment and preserving the cellulose skeleton shape for posterior functional applications of Chinese fir. In addition, acid hydrotropes have shown a good capacity of lignin solubilization under mild conditions. Thus, Yang et al. [30] applied benzenesulfonic acid and p-toluene sulfonic acid at a low temperature (80 °C) and in a short time (20 min) to remove lignin from eucalyptus wood and achieved delignification yields around 80%, obtaining high-purity homogeneous lignin with medium molecular weights (4390–5440 g/mol).

Also, within chemical methods, the conventional organosolv process is based on the solubilization of lignin using organic solvents like ethanol, methanol, acetone, or ethylene glycol, either alone or in combination with catalysts [2]. The temperature is usually high (150–200 °C), and the treatment time is about 1–3 h [7]. Modifications of this process have been commercialized under different names, but none of them has been able to replace the

Kraft method successfully. Several developments have been incorporated into traditional organosolv pretreatment, such as the enhancement of delignification using oxygen under mild-temperature conditions (90 °C) [31]. Moreover, Zhang et al. [20] recently employed a ternary solvent system composed of 50% volume of 1,1,3,3-tetramethyl guanidine, 20% morpholine, and 30% water to remove lignin from eucalyptus. The wood chips were cooked for 6 h at 160 °C with the objective of producing high-purity cellulose, and the treatment resulted in the removal of almost 90% of lignin and 81% of hemicellulose. Notably, the authors were able to quantitatively recover the solvents via vacuum distillation.

Recyclable biphasic systems are another interesting alternative to fractionate lignocellulose and recover their components separately. Choosing the adequate combination of solvents results in the selective separation of lignin, solubilized in the organic phase; hemicellulose, found in the aqueous phase; and cellulose, left in solid form. This partition makes the recovery of each of the components easier with regard to downstream processes [32]. A recent study by Xie et al. [28] evaluated the performance of three biphasic systems (ρ -toluene sulfonic acid/pentanol, H₂SO₄/butanol, and AlCl₃/5-methyltetrahydrofuran), using experimental and computational methods, with the aim to advance in the comprehension of the mechanisms of lignin and xylan solubilization. In another study, a biphasic 2-phenoxyethanol/water system was employed, reaching more than 80% lignin removal from rice straw at 80 °C and testing the recyclability of the organic phase three times, with similar delignification yields [33]. In addition, bio-based solvents have recently attracted a lot of attention [2,10,34]. Lately, the potential of biomass derived solvents such as γ -valerolactone or ϵ -caprolactone for the fractionation of lignocellulosic biomass is starting to be explored. For example, González et al. [10] mixed γ -valerolactone with water and a small amount of sulfuric acid to pretreat sugarcane bagasse and pine sawdust. The authors achieved a considerable removal of lignin from sugarcane bagasse (95%) at 166 °C and 96 min, with results comparable to other feedstocks treated with the same solvent. Additionally, Chen et al. [35] used the system ϵ -caprolactone and water to fractionate various agricultural and forestry residues, achieving almost complete delignification for some of them.

Within the category of physical delignification methods, the use of non-thermal plasma, a solvent-free and low-temperature process to remove lignin, is an innovative solution. Non-thermal plasma consists of a partial electrical discharge that causes the formation of reactive species, inducing chemical and physical processes that are finally able to break down lignin [36]. An application of this technology was described by Pereira et al. [23], who were able to extract 50% of lignin contained in a brewery bagasse by treating the biomass with air plasma and at a solid consistency of 12.5% for only 5 min. Other physical methods, such as ultrasounds, high-voltage electrical discharges, and microwaves, have also shown a great potential, especially in combination with green solvents as eutectic solvents (ESs), as will be further discussed in Section 5 below.

Multi-step fractionation is another common strategy to selectively separate the components of lignocellulosic biomass. Usually, the targets of the first stage are hemicelluloses, which are easier to remove, while the objective of the second treatment is delignification. One recent example of this strategy is presented in the paper by Zhang et al. [22], who carried out a first mechanical activation step (pulverization in a ball mill), followed by a hydrothermal extraction of hemicelluloses and removal of the lignin from the remaining solid using an ES based on choline chloride (ChCl)/lactic acid (LA). They obtained over 78% lignin removal with the ES. A similar approach using hydrothermal pretreatment plus delignification with ES (in this particular case, assisted by microwave) was chosen by Guo et al. [37] to fractionate bamboo-processing residue. In this work, the authors obtained a xylooligosaccharides yield of 34% and a delignification rate of 84%.

Biological methods for delignification include the use of fungus, bacteria, and their purified ligninolytic enzymes. In the field of enzymes, Muniraj et al. [38] have recently developed a new Enzolv process for the simultaneous delignification of wood and depolymerization of the obtained lignin to high-value derived products, such as isothiazole, vainillin, and triazine derivatives. This process combines hydrothermal treatment in an

autoclave, followed by an incubation with a laccase produced by the authors for 17 h at 40 °C. A small amount of ethanol was added to stimulate the optimal activity of the enzyme. The maximum lignin removal obtained using this process was 48%, but the authors highlight the mild operation conditions employed and the use of simple and, therefore, less expensive laccase and mediator. The Enzolv process has been further optimized in following works, using different biomasses, such as banana fiber, or cotton spinning-mill waste [39,40]. New enzymes are continuously identified and isolated from lignin-degrading microorganisms, with promising results [41]. Among fungus, white-rot fungi has been identified as the most effective to degrade lignin due to their ligninolytic enzymes (lignin peroxidase, manganese peroxidase, laccase, and versatile peroxidases) [42]. Species such as *Ceriporiopsis subvermispora*, *Pleurotus eryngii*, and *Lentinula edodes* have been recently used to delignify wheat straw and study the mechanisms behind this process [43]. Working with the white-bottom mushroom *Agaricus bisporus*, Duran et al. [44] were able to remove 42% lignin from pre-composted wheat straw from an industrial setting. Studies on lignin-degrading bacteria are less common, but there are nonetheless some promising results in the literature. For instance, Tsegaye et al. [17] were able to identify and isolate from a termite gut a bacterium capable of degrading lignin, which removed more than half of the lignin contained in rice straw. Biological processes have the advantages of being more environmentally benign than chemical and harsh physical methods, as they are carried out under mild conditions and produce fewer pollutants. Nevertheless, longer reaction times, the high cost of purified enzymes, and the low efficiency, are some of the problems that still limit their industrial application [2].

4. Eutectic Solvents for Delignification

Effective fractionation of biomass prior to conversion is crucial, and although various traditional methods have been employed, environmentally friendly and efficient approaches are increasingly needed to comply with new regulations and to follow green-chemistry guidelines. Chemical delignification, for instance, often involves hazardous chemicals that produce toxic emissions and pollution, and physical methods are energy-intensive, and their environmental impact may depend in part on the use of non-renewable energy sources [45–47]. Biological methods are generally more environmentally friendly, generating fewer pollutants and consuming less energy, but their slower processing rates and lower efficiency can increase resource demands [48]. These facts have led to the option of developing pretreatments using alternative solvents and techniques, which can overcome the problems faced by conventional pretreatments. Recently, there has been growing interest in the use of eutectic solvents for fractionation due to their remarkable ability to solubilize lignin from lignocellulosic biomass [1,34]. Since they were first introduced in 2004, ESs have gained much attention as alternative and more environmentally friendly solvents in multiple applications [1,49].

ESs are generally formed by mixing a hydrogen-bond acceptor (HBA) and a hydrogen-bond donor (HBD) in specific ratios, under mild conditions and for periods ranging from minutes to hours, resulting in a homogeneous liquid around the eutectic of the mixture [1,3,49]. The interaction between HBAs and HBDs via hydrogen bonds leads to charge delocalization, which significantly reduces the melting point compared to the individual components [1,8]. As a general rule, a higher hydrogen-bonding capacity correlates with a more pronounced reduction in the melting temperature. Herein, it has been decided to exclude the term “deep” from the common designation of these types of solvents, due to the existing controversy; otherwise, the nomenclature would not be correct, because, by this type of solvent, we mean mixtures that have the lowest possible solidification temperature and therefore form at the eutectic point, and also stable liquid mixtures that form with other HBA:HBD ratios without reaching the eutectic temperature [50,51]. ESs can be generally classified into five main types depending on the HBA compounding agents used. Type I ESs are those formed using quaternary ammonium salts and metal halides. Type II ESs incorporate hydrated metal halides. Type III ESs combine quaternary ammonium salts with various HBDs. Type IV ESs include

inorganic transition metals and HBDs. Finally, type V ESs consist only of non-ionic molecular substances and are difficult to characterize due to their hydrophobic nature, although they offer the advantage of possible recovery by evaporation [1]. ESs can also be classified according to their pH and water miscibility [1]. In addition, ESs that are strictly made up of natural components (amino acids, organic acids, sugars, or choline derivatives) are often referred to as natural eutectic solvents (NAESs) or natural deep eutectic solvents (NADESs) [52]. The ESs are aligned with the 12 principles of green chemistry, playing a pivotal role in diminishing conventional harmful solvents by serving as environmentally benign substitutes. In terms of their main characteristics, they possess advantageous attributes, such as easy availability of their raw materials; simple preparation, without purification steps; tunable properties; biodegradability; and potential for efficient recyclability. Moreover, they offer numerous advantages over conventional solvents, as they generate minimal waste under mild conditions and are renewable, cost-effective, and biocompatible [1,8,53].

The ESs, with their intramolecular hydrogen bonds, enhance biomass dissolution and conversion rates by forming hydrogen bonds with compounds like lignin, thereby improving their solvation properties [3,8]. The interaction between ESs and biomass may be explained as an acid–base catalysis mechanism [54]. In ESs, the HBD interacts with the hydroxyl groups of cellulose and hemicellulose, while the HBA targets the phenolic and aliphatic hydroxyl groups of lignin. These interactions disrupt the intermolecular forces that bind the biomass, leading to structural alterations [3,47]. ESs are able to dissolve and extract lignin from biomass, minimizing carbohydrate (cellulose and hemicellulose) losses to a minimum [8,54]. Delignification is achieved, thereby improving cellulose accessibility in biomass and, consequently, enzymatic digestibility [55]. To date, type III ESs, which have the advantages of a simple and low-cost preparation, are the most frequently studied category for lignocellulosic biomass fractionation [1,3]. Figure 2 shows several HBAs and HBDs that have been used in ES formation for biomass-fractionation and -delignification studies.

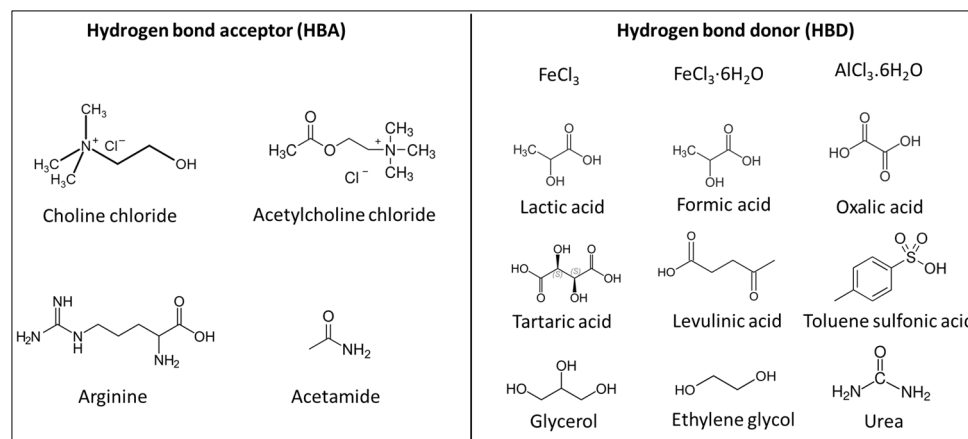


Figure 2. Some hydrogen-bond acceptors (HBAs) and hydrogen-bond donors (HBDs) commonly used for ES synthesis used in biomass-delignification treatments.

The delignification and treatment efficiency of ESs are highly dependent on several factors, including ES composition and operational conditions, such as the eutectic composition, ability to form hydrogen bonds, viscosity, acidity/basicity, reaction temperature, reaction time, solvent/biomass ratio, addition of water to the ES mixture, and recalcitrant nature of the biomass [3,47,56]. It has been observed that ESs with strong hydrogen-bonding interactions and lower viscosity can be more effective in dissolving biomass components. The specific choice of hydrogen-bond donor and acceptor can influence the selectivity of ES towards different biomass components. Increasing the molar ratio of hydrogen acceptors has been found to lead to an increase in lignin solubility [3,47]. Temperature also plays a key role in relation to lignin: increasing the temperature tends to improve lignin purity, influences the deconstruction of the cellulose structure, reduces polydispersity, and can

enable higher biomass loadings by lowering viscosity and improving mass transfer rates. Although a high temperature normally leads to higher lignin extraction yields, excessively high temperatures can lead to the degradation of ESs and, consequently, lower lignin extraction yields. Additionally, they can cause the degradation and condensation of lignin, decreasing its molecular weight and forming polydisperse lignins or pseudo-lignins, thus reducing its solubility and reactivity. They may also promote the generation of inhibitory compounds that negatively impact the functionality of recovered lignin [47,56]. As for reaction times, longer times and an optimal ratio between ESs and biomass lead to better penetration of the solvent into the biomass, more efficient bond breaking in the cellulosic cell wall, and more efficient interactions [3,56]. It was found that the addition of a low amount of water can significantly impact the lignin solubility in ESs without adversely affecting their microstructure [53,57]. Water can be mixed with the solvent to decrease the viscosity and increase mass transfer, which is beneficial in the lignin recovery process and thus improves delignification. However, this can introduce new characteristics into the aqueous mixed solvent. Depending on how the water interacts with the components of the ES, the effect can be either positive or negative, as it may enhance or reduce the potential for hydrogen bonding with lignin. Generally, lignin solubility could remain stable or even improve when using hydrated ESs [57,58]. For instance, Kumar et al. [58] reported that adding 5.0% (*v/v*) water during biomass fractionation significantly increased total lignin extraction, releasing approximately $22 \pm 3\%$ more lignin from the residual biomass into the ES extract. However, excessive water can destabilize the nanostructure of the eutectic solvent [59,60]. In general, the use of ESs in biomass fractionation offers several advantages compared to other methods. ES treatment does not require extremely high temperatures (typically between 50 and 200 °C) or pressures (ranging from 1 to 10 MPa), reducing energy consumption and the risk of biomass degradation. Moreover, it generates fewer inhibitory compounds and increases conversion rates [3]. The benefits of using eutectic solvents for lignin recovery include improved solute solubility and higher lignin-extraction efficiency. ESs offer a green and sustainable alternative for lignin valorization due to their environmentally friendly properties and potential for industrial-scale applications [61]. Additionally, ESs can be recycled, reducing operating expenses, and are compatible with various types of biomasses [3]. The volume of publications on ESs in the field of lignocellulosic biomass processing has seen an exponential growth in recent years. However, challenges remain, mainly affecting process design, costs, and industrial scalability [3].

After the treatment, the extracted or dissolved lignin in the ES can be recovered or regenerated by precipitation and purification via adding antisolvents such as water (neutral or acidified), ethanol, or mixtures of ethanol/water and acetone/water, crucially affecting the lignin recovery efficiency [1,56]. Antisolvents disrupt hydrogen bonds between HBA and HBD, changing the medium's polarity and causing precipitation of solubilized components [57]. In addition, this washing step in turn neutralizes the pH and removes possible residual pretreatment agents that may affect enzymatic hydrolysis or subsequent treatment [62].

Apart from the type of antisolvent used, the recovery procedure also influences the efficiency of the process; generally, a vacuum-filtration-and-washing process is used, followed by removal of the antisolvent via vacuum evaporation, or recovery via distillation, and subsequent collection of lignin precipitated via centrifugation and washing to remove as much of the remaining ES as possible [1,56]. Although ESs exhibit high selectivity for lignin, the purity of the fractionated lignin may be minimally affected by the ES configuration and treatment severity. Impurities in the fractionated ES–lignin typically consist of residual ES from the washing step or polysaccharide residues resulting from increased dissolution, for instance, due to the addition of water to the ES to reduce viscosity, enhancing efficiency and operability [1]. Typically, ES–lignin contains a higher concentration of phenolic OH groups than native lignin, mainly due to β -O-4 bond cleavage. This increase, along with its thermal stability and volatility, directly influences its potential for further processing. These characteristics enhance its suitability for aromatic monomer production through

lignin depolymerization or subsequent valorization. Compared to native lignin, ES–lignin decomposes at higher temperatures and yields fewer total aromatic monomers [1]. ESs can modify the structure of lignin and, thus, its properties, making it more soluble and easier to recover, which can further increase its applicability in different industries. Fractionated ES–lignin also exhibits various beneficial biological attributes, such as UV blocking, free radical scavenging, and antimicrobial effects, like other technical lignins. Therefore, this lignin can find applications across a broad spectrum of fields, from energy production to the creation of value-added products, common chemicals, or smart materials [1,8].

5. Enhanced Delignification Using ES Combined with Intensification Techniques

In recent years, ESs have been integrated with other environmentally friendly treatment strategies to improve the efficiency of biomass fractionation. This section will discuss the incorporation of process-intensification techniques, such as ultrasound- or microwave-assisted technologies, along with the use of eutectic solvents for treatment of lignocellulosic biomass. It is sought to develop treatments with low operating costs, applicability to various lignocellulosic materials, easy product recovery, low energy consumption, robustness for continuous high-load operations, and that meet the requirements of green chemistry [11]. Therefore, the main objective of this section, its motivation, is to review novel studies using intensification techniques combined with eutectic solvents for delignification, compiling the results obtained and proposing directions for future research. All the mentioned studies, along with additional ones listed below in Tables 2 and 3, demonstrate that the combination of these intensified strategies with ESs achieves efficient biomass fractionation and lignin recovery, aiming for the full utilization of lignocellulosic biomass. Furthermore, the combined use of ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) processes brings benefits to biomass conversion, thus reducing reaction times and energy consumption and promoting the use of less toxic and hazardous solvents, in compliance with the basic principles of green chemistry [2,3,63]. Figure 3 illustrates the processes involved (to be discussed in more detail below), highlighting the effects that facilitate biomass fractionation and lignin extraction in each case.

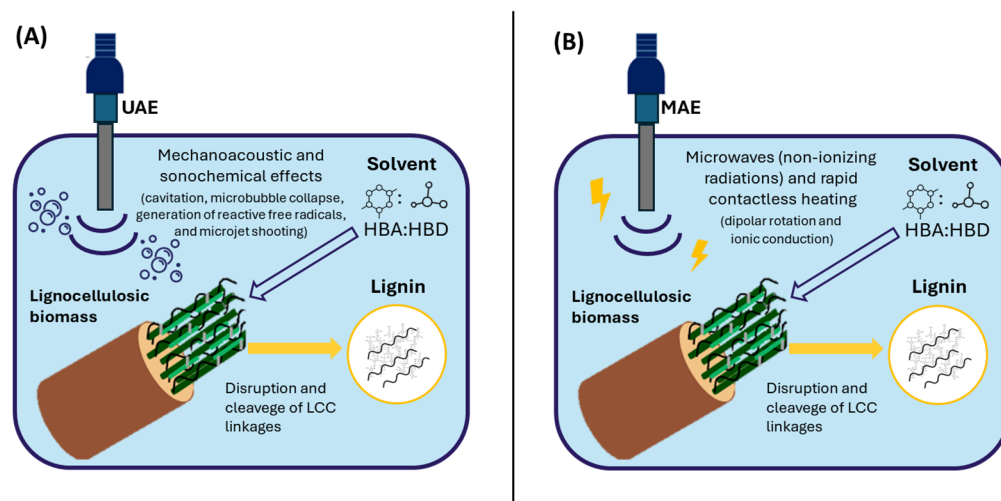


Figure 3. Schematic representation of the process combining the use of eutectic solvents with intensification techniques, (A) ultrasound-assisted extraction (UAE) and (B) microwave-assisted extraction (MAE), for biomass fractionation and lignin extraction. Abbreviations: HBA, hydrogen-bond acceptor; HBD, hydrogen-bond donor.

5.1. Enhanced Delignification Using ES Combined with Ultrasound-Assisted Extraction (UAE)

Ultrasound-assisted extraction or treatment can optimize lignocellulosic biomass fractionation. Ultrasonic energy provides a unique physicochemical environment that disrupts the lignin barrier [1]. This process improves the efficiency of lignin solubilization

compared to conventional methods, requiring less time and lower temperatures, while helping to break down cell walls and increasing cellulose yield [2,12,47]. The effects of ultrasound on lignocellulosic biomass are diverse and complex but can be subdivided into physical or mechanoacoustic effects and chemical or sonochemical effects [3]. Regarding the physical effect, acoustic cavitation occurs when a sound wave propagates in a liquid medium, generating bubbles that grow and collapse violently in successive cycles of compression and rarefaction. A mechanical acoustic wave with frequencies between 10 kHz and 20 MHz transmits high energy to the reaction medium through cavitation and other associated effects [14]. This process breaks down the cell wall, reduces particle size, and enhances mass and heat transfer, intensifying the contact and separation of reactants, thus accelerating the reaction or altering its kinetics [3,14]. Regarding the chemical effect, derived from the effect of acoustic cavitation, reactive free radicals are generated that promote the decomposition of biomass macromolecules under the influence of ultrasound; this causes rapid changes in temperature and pressure, together with turbulence and intense shear forces, producing morphological alterations. Furthermore, shear forces and high-speed microjet formation cause the breaking of chemical bonds in lignocellulosic biomass, such as the breaking of the α -O-4 and β -O-4 bonds of lignin, as well as the breaking of the ether bonds between hemicellulose and lignin [3,12]. Therefore, the application of ultrasound, combining both its physical and chemical effects, improves the efficiency of delignification. This approach works effectively under mild conditions, reducing energy consumption and promoting environmental sustainability. Furthermore, ultrasound conditions can be tailored to specific biomass components [2,12].

Moreover, the use of ultrasound can enhance the delignification efficiency of thermal and chemical reactions when combined with suitable solvents [3,63]. The lignin present in the outermost part of the lignocellulosic material is generally the fraction that comes into direct contact with the solvent [12]. Ultrasound waves enhance solvent penetration and material swelling by creating and collapsing gas bubbles within the solvent. This process enlarges the matrix pores and can disrupt cellular tissue, making it easier to release the target compounds [3,63]. Significant synergistic effects have been observed between ultrasound and various ESs in lignin fractionation from biomass. This synergy improves the effectiveness of breaking down lignin structures, enhances reactivity, facilitates more efficient lignin degradation, and can lead to localized heating during the process [1,64]. Although the application of ultrasound increases lignin extraction yields and can improve lignin purity, the treatment can have variable effects on the molecular weight of the extracted lignin due to competing reactions of separation, degradation, and recondensation, which can occur depending on the nature of the treatment solution [15]. Acoustic cavitation in lignocellulosic biomass is a complex phenomenon influenced by solvent properties such as viscosity, surface tension, and volatility. In particular, cavitation occurs preferentially in liquids with low volatility, medium viscosity, and high surface tension [3]. As shown in Table 2, different combinations of ultrasound-assisted eutectic solvent treatment have been studied for lignin extraction from biomass, as well as the influence of different conditions on the extraction yields, including biomass type, ES ratio and concentration, solid/liquid ratio, reaction time, temperature, and ultrasonic power [2,3,63]. Significant synergistic effects have been observed between ultrasound and certain ESs on the fractionation of various biomasses. For instance, it was found that ultrasound-assisted pretreatment using ChCl/lactic acid 1:5 in a single-step extraction yielded 40.5% of lignin from oil palm empty fruit bunch [65]. The use of NaOH aqueous as a cosolvent with ChCl/urea 1:2 in a two-step extraction process was also able to enhance the delignification in oil palm fronds up to 47.0% of lignin removal [66]. Likewise, it has been proved that the delignification of grape stalks using a single-step ultrasound-assisted extraction with ChCl/levulinic acid 1:2 yielded 73.9% of extracted lignin [67]. Moreover, it has been reported that a two-step extraction, including an ultrasound-assisted pretreatment and a conventional delignification, using ES based on ChCl/glycerol, and lactic acid yielded the highest lignin removal of 87.5% from corncob [67]. Additionally, by treating sugarcane bagasse treated with a eutectic solvent

mixture of ChCl/glycerol/FeCl₃·6H₂O in a 1:1:0.3 ratio and using the UAE process for 60 min at a solid-to-liquid ratio of 1:10, an extraction yield of up to 86.4% was achieved [68].

Table 2. Delignification methods and results of studies testing ESs combined with UAE technique on different biomasses. Abbreviations: ES, eutectic solvent; UAE, ultrasound-assisted extraction; S:L, solid/liquid; ChCl, choline chloride.

Delignification with UAE + ESs					
Biomass	Eutectic Solvent	Molar Ratio	Delignification Method Conditions	Lignin Removal	Ref.
Oil palm empty fruit bunch	ChCl/lactic acid	1:5	UAE at 50 °C, 210 W for 30 min and 1:10 S:L ratio.	40.5%	[65]
Oil palm fronds	ChCl/urea	1:2	UAE at room temperature for 30 min and 1:4 S:L ratio using NaOH 2.5% (<i>w/v</i>) as cosolvent. Then, conventional extraction at 120 °C for 240 min and 1:4 S:L ratio with the same solvent.	47.0%	[66]
Grape stalks	ChCl/levulinic acid	1:2	UAE at 50 °C, 200 W for 60 min and 1:50 S:L ratio.	74.0%	[67]
Corn cob	ChCl/glycerol/lactic acid	1:1:2	UAE at room temperature and 40 + 60 kHz, 300 W for 60 min and 1:10 S:L ratio. Then, conventional extraction at 120 °C for 180 min and 1:10 S:L ratio with the same solvent.	87.5%	[69]
Sugarcane bagasse	ChCl/glycerol/FeCl ₃ ·6H ₂ O	1:1:0.3	UAE at 20 + 28 + 40 kHz, 240 W, 60 min, and 1:10 S:L ratio.	86.4%	[68]

5.2. Enhanced Delignification Using ES Combined with Microwave-Assisted Extraction (MAE)

Another method used to intensify the extraction process is the microwave-assisted extraction (MAE) or a treatment that uses microwave energy to heat solvents and biomass tissues, accelerating the kinetics of the process via ionic conduction and dipolar rotation [70]. This technique is widely recognized for its effectiveness in sample extraction, offering rapid heat transfer that, when combined with pressure, maximizes the yield of target compounds from biological matrices [63]. The microwaves generated are non-ionizing radiations situated between radio waves and infrared waves on the electromagnetic spectrum. This non-ionizing radiation raises temperature by increasing the kinetic energy of molecules or atoms without removing electrons. Microwave heating is a contactless energy-transfer process that is achievable through two distinct mechanisms: dipolar rotation and ionic conduction [1,3]. In lignocellulosic biomass, microwaves interact with polar molecules, leading to the rapid heating and decomposition of the lignocellulosic structure and a more effective disruption of the H-bond microfibril network [70,71]. Microwave-assisted solvolysis at mild temperatures (<200 °C) depolymerizes biomass to produce value-added chemicals [12]. Microwave energy can directly heat and partially degrade lignin, enhancing cellulose accessibility for enzymatic or chemical hydrolysis in subsequent steps [2]. The microwave irradiation enhances the dissolution, since the depolymerization of cross-linked phenylpropanoid units of lignin and hydrogen-bonding interactions between the biomass matrix and the ES is intensified [1,2]. Microwave heating accelerates biomass fractionation by increasing the heating rate, while also facilitating selective bond cleavage during lignin depolymerization. Specific bonds, such as the Cβ–O in the β–O–4 linkage, are stretched under the electric field generated by microwave irradiation [1]. The combination with eutectic solvents facilitates direct volumetric heating, as their molecules tend to align with the microwave electric field, enhancing bond breaking. This synergy between ES and microwave irradiation significantly improves the cleavage of lignin–carbohydrate complexes; stretches certain lignin bonds (e.g., β–O–4), increasing the probability of breakage; and allows for the rapid fractionation of biomass compared to conventional methods [1,13,72].

The effectiveness of microwave-assisted treatment depends on factors such as biomass type, moisture content, particle size, solvent, microwave power, and duration [2]. As summarized in Table 3, various studies have demonstrated the effectiveness of microwave treatment combined with ES for the fractionation of different biomass types. Wang et al. [73] and Chen et al. [74] investigated delignification in different biomass types, such as corn stover, switchgrass, or miscanthus, using an ES based on ChCl and lactic acid. Delignification of rice straw and pinewood sawdust was performed with microwave-assisted extraction, using ChCl/formic acid 1:2, obtaining 36.1% and 89.6% of lignin removal, respectively [13,75]. Some researchers have suggested introducing a third constituent to form a ternary ES system to improve the delignification efficiency. For instance, authors have proposed the addition of $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$ to the ChCl/oxalic acid ES system for lignin extraction from sugarcane bagasse, obtaining a lignin removal of 83.3% [76], or to the ChCl/glycerol ES system to remove up to 92.5% lignin from CSE down-regulated poplar [77]. The addition of $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ to a glycerol and guanidine hydrochloride ES to extract 81.17% of lignin from moso bamboo powder [78] and the formation of toluene sulfonic acid/ChCl/glycerol ES for lignin removal from cocoa bean, with a 95.5% yield [79], were also some of the ternary ES systems proposed in recent years. Meanwhile, a quaternary ES systems can also be used to remove lignin from biomass, as studied by Xu et al. [80], who used ChCl/ethylene glycol/toluene sulfonic acid/ FeCl_3 to extract 40.8% of lignin from dried rose hips. Furthermore, poplar achieved a lignin extraction yield of 90.9% using a mixture of acetamide/tartaric acid, while Moso bamboo reached yields ranging from 84.8% to 90.0% by employing either arginine or acetylcholine chloride combined with lactic acid [81–83].

The combination of microwaves with ultrasound for biomass pretreatment has also shown significant improvements in lignin removal and enzymatic hydrolysis [12]. When using sequential multimode-ultrasound- and microwave-assisted ternary eutectic solvent pretreatment, the delignification efficiency increased to 61.50% (under intense conditions of 120 °C and 1 min) and 57.39% (under mild conditions of 60 °C and 60 min). It was observed that the combined use of ultrasound and microwave technologies improved the ability of ES to solubilize lignin, and also the purity of the fractionated lignin [84].

Table 3. Delignification methods and results of studies testing ESs combined with MAE technique on different biomasses. Abbreviations: ES, eutectic solvent; MAE, microwave-assisted extraction; S:L, solid/liquid; ChCl, choline chloride.

Delignification with MAE + ESs					
Biomass	Eutectic Solvent	Molar Ratio	Delignification Method Conditions	Lignin Removal	Ref.
Oil palm empty fruit bunch	ChCl/lactic acid	1:2	MAE at 120 °C, for 30 min and 1:10 S:L ratio	57.1%	[85]
Corn stover	ChCl/lactic acid	1:2	MAE at 160 °C for 30 min and 1:20 S:L ratio	89.8%	[73]
Switchgrass	ChCl/lactic acid	1:2	MAE at 152 °C, 800 W for 45 s and 1:10 S:L ratio	72.2%	[74]
Miscanthus	ChCl/lactic acid	1:2	MAE at 152 °C, 800 W for 45 s and 1:10 S:L ratio	65.2%	[74]
Corn stover	ChCl/lactic acid	1:2	MAE at 152 °C, 800 W for 45 s and 1:10 S:L ratio	79.6%	[74]
Pinewood sawdust	ChCl/formic acid	1:2	MAE at 150 °C for 15 min and 1:6 S:L ratio	89.6%	[13]
Rice straw	ChCl/formic acid	1:2	MAE at 155 °C for 30 min and 1:10 S:L ratio	36.1%	[75]

Table 3. Cont.

Delignification with MAE + ESs					
Biomass	Eutectic Solvent	Molar Ratio	Delignification Method Conditions	Lignin Removal	Ref.
Sugarcane bagasse	ChCl/oxalic acid/ $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$	1:1:0.2	MAE at 100 °C, 280 W for 30 min and 1:10 S:L ratio	83.3%	[76]
CSE down-regulated poplar	ChCl/glycerol/ AlCl_3	1:2:0.1	MAE at 110 °C, 400 W for 10 min and 1:15 S:L ratio	92.5%	[77]
Moso bamboo powder	Glycerol/guanidine hydrochloride/ $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$	2:1:0.1	MAE at 120 °C, at 350 W for 2 min and 150 W for 10 min, 1:20 S:L ratio	81.2%	[78]
Cocoa bean shell	Toluene sulfonic acid/ChCl/glycerol	2:1:1	MAE at 130 °C, 850 W, 30 min and 1:20 S:L ratio	95.5%	[79]
Dried rose hips	ChCl/ethylene glycol/toluene sulfonic acid/ FeCl_3	1:2:0.3:0.3	MAE at 80 °C, for 30 min, 1:10 S:L ratio	40.8%	[80]
Poplar	Acetamide/tartaric acid	1:1	MAE at 120 °C, 400 W for 20 min and 1:10 S:L ratio	90.9%	[81]
Moso bamboo	Acetylcholine chloride/lactic acid	1:2	MAE at 120 °C, 600 W for 10 min	90.0%	[82]
Moso bamboo	Arginine/lactic acid	1:7	MAE at 120 °C, 600 W, 30 min and 1:20 S:L ratio	84.8%	[83]

6. Characteristics and Applications of Recovered Lignin

Once the biomass is fractionated using the above methods, the separated ES–lignin obtained has unique characteristics and applications due to its modified structure and enhanced solubility properties. The fractionation treatments alter the lignin structure by breaking the β -O-4 bonds, which can facilitate the disruption of the cell wall matrix and improve the solubility of lignin into the solvents. However, this process can also lead to undesirable condensation, reducing the value of the recovered lignin. The physical and chemical properties of both the treated solid residue and the dissolved lignin are significantly altered, resulting in a decrease in lignin and hemicellulose content, an increase in specific surface area, and a high phenolic hydroxyl content, improving the antioxidant capacity. In most single-step treatment methods, contamination of the lignin stream with other components, mainly hemicellulose, as well as other extracts, ash, and even partially decomposed cellulose, cannot be completely avoided [7,86]. To improve lignin utilization, lignin quality has to be prioritized, along with productivity, so further purification steps are sometimes necessary, e.g., solvent extraction, membrane filtration, or precipitation techniques [7]. The valorization of recovered lignin is crucial to improve the economic and environmental profitability of the overall lignocellulosic biomass-conversion process [7,86].

Then, recovered lignin, whether in polymer, monomer, or degraded form, has significant commercial value as a precursor for various industrial applications, such as biofuel and biochemical production, the preparation of lignin nanoparticles, and the fabrication of spherical lignin nanoparticles for versatile hybrid and functional nanomaterials [1]. Figure 4 shows the most relevant current applications. At present, two main approaches are distinguished for lignin utilization: functionalization (modifying a material's surface chemistry to add new functions or properties) or depolymerization (the process of converting a polymer back into its constituent monomers). Lignin, as a natural polymer, can directly modify/functionalize or improve the properties of existing polymeric materials, but its widespread application is hampered by its poor mechanical properties, low reactivity, and limited compatibility with other polymers. Lignin can be functionalized through chemical and enzymatic routes to develop value-added chemicals for industries [1,47,87]. Chemical modification can improve the reactivity of lignin and expand its usefulness. The selection of lignin type is crucial, as ES–lignin can sometimes offer high purity for applications

such as biomedical materials. Furthermore, lignin-based smart materials hold promises for various current and future applications. Recently, lignin has been also explored to produce ES conductive gel, further expanding its potential. The aromatic nature of lignin makes it a potential feedstock for platform chemicals and hydrocarbon fuel production through processes such as pyrolysis or hydrogenolysis. Another application is the biological conversion of lignin achieved through microbial degradation. Unfortunately, the biological conversion of lignin remains challenging compared to carbohydrate conversion. Furthermore, ES–lignin can be used as a feedstock in biomaterials applications. Various lignin-based materials have been studied, such as carbon materials, absorbents, thermosets, fillers, plastic films, hydrogels, and nanoparticles [1,7,47].

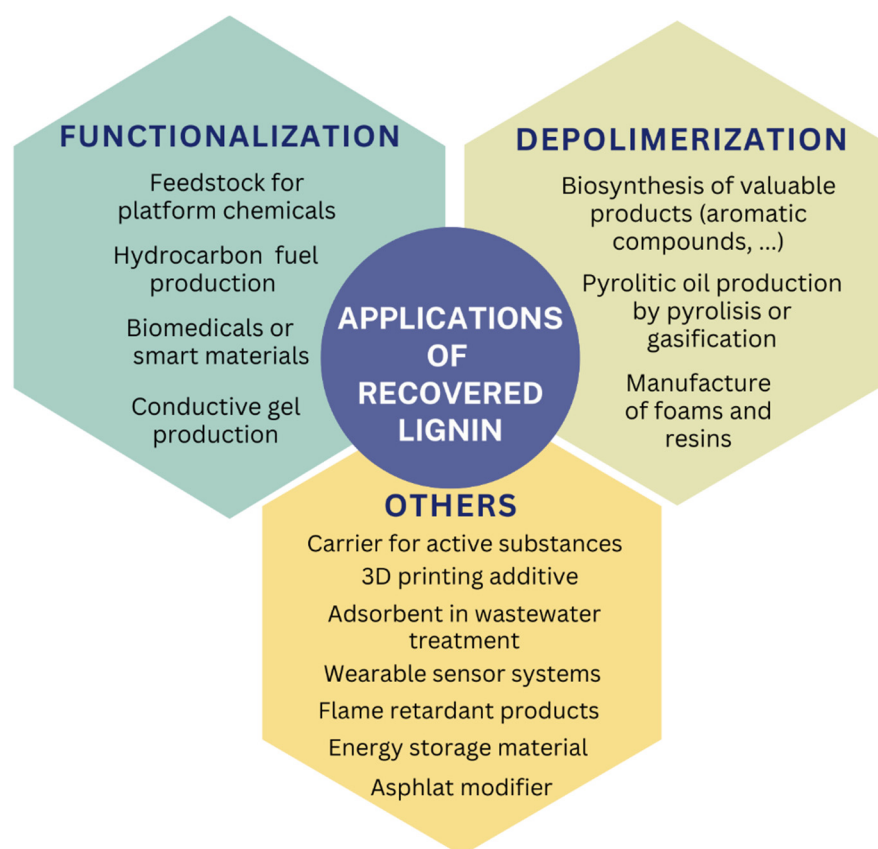


Figure 4. Applications of lignin recovered after biomass delignification.

As for, depolymerizing lignin into monomers and oligomers as platform chemicals offers a promising avenue for its valorization through various methods, including biological, thermochemical, and electrochemical routes [1,7,47]. The selection of the type and quality of lignin is essential for its effective use in various applications. The hydroxyl group content in lignin significantly affects its hydrophilicity and its role in both depolymerization and polymerization processes. Moreover, the molecular size of lignin is crucial for its solubility, influencing the choice of solvent for depolymerization and other applications. After depolymerization, lignin can be used in target applications for the biosynthesis of valuable products, the production of pyrolytic oil through pyrolysis and gasification, or the manufacture of resins and foams [1,7,57]. Notably, recent studies have shown that it is also possible to depolymerize lignin obtained from lignocellulosic biomass into aromatic compounds (e.g., catechol, eugenol, vanillin, syringaldehyde, and quinones) using intensification techniques and/or eutectic solvents [47,88,89]. Microwave-assisted technology is highly effective in the liquefaction or solvolysis of lignin, thanks to its rapid heating and high efficiency [88]. Since both ES and lignin absorb microwaves, leading to a higher degree of depolymerization in microwave-treated samples compared to conventional heating,

selective bond cleavage is promoted [13]. This technology has been successfully used to depolymerize lignin into phenolic monomers by selectively breaking C α –C β linkages [89]. The phenolic compounds produced through depolymerization can be further transformed into functional polymer materials [47]. Moreover, greener depolymerization methods, such as ES-based depolymerization, show an excellent performance and reduce the use of aggressive and corrosive chemicals [88]. The current potential of lignin applications goes far beyond the mentioned uses. For instance, it can act as a carrier for biologically active substances in plant protection, nanomedicine, and biocatalysis. Additionally, it can be used as an asphalt modifier in pavement engineering, in 3D-printing applications, in wearable sensors for real-time monitoring, in the production of bio-based adsorbents for wastewater treatment, in flame-retardant products, and in energy storage materials [87,90].

In particular, lignin recovered after treatment with eutectic solvents can have many applications in several of these fields. Pawale et al. [91] demonstrated that the application of ES–lignin in bio-based polylactic acid (PLA) composites improves performance due to its high purity, ultrafine particle size, low heterogeneity, and reduced molecular weight. Studies by Zhan et al. [92] and Cheng et al. [93] have also demonstrated ES–lignin’s potential for use in natural resin adhesive formulations, thanks to its effective binding properties and favorable thermal characteristics. Due to its structure, it has been shown that ES–lignin can be successfully used as an adsorbent material for the removal of pollutants as dyes from wastewater [94] or CO₂ adsorption [95]. ES–lignin can also be converted or used as a feedstock for the synthesis of high-value chemicals or biofuels that contribute to renewable energy production [1,96]. ES–lignin’s antioxidant and antimicrobial properties suggest great potential for pharmaceutical and cosmetic applications; however, research in these fields remains limited [97,98]. Similarly, recent biomass-delignification methods using combined ES and intensification techniques show promise for converting lignin into higher-value chemicals or improving the properties of the materials in which it is applied. When analyzing the applications of the obtained lignin, it is crucial to evaluate how each process affects lignin structure, depolymerization, functional groups, and molecular weight. Combining UAE or MAE with eutectic solvents enhances direct heating, which facilitates the breaking of lignin bonds and further improves its solubility. As mentioned in the previous section, the use of UAE produces high-purity lignin with a lower molecular weight, more reactive functional groups, and better solubility, making it ideal for applications in biofuels, bioplastics, or composites [15,99]. Regarding the use of MAE, which can alter the lignin structure more extensively, accelerate depolymerization through rapid and selective bond breaking, and increase the exposure of reactive functional groups, facilitating also its use as a precursor in biofuels, it can serve as a reinforcing agent in composites and applications in platform chemicals and functional materials [1,100]. However, studies on the applicability of these methods remain limited to date, despite encouraging prospects that are expected to drive further research.

7. Solvent Recycling

Another crucial aspect to consider when using solvents in the evaluation of biomass fractionation and delignification is the recyclability of solvents, due to their cost and environmental impact. Eutectic solvents have shown great promise as agents for lignocellulosic biomass fractionation. However, a significant and concerning challenge remains regarding their effective recovery and recycling after use. This issue, which hinders their competitiveness against conventional solvents, is crucial for economic viability, environmental friendliness, and implementation in large-scale biorefinery processes [1,8]. A solvent with good recyclability or an efficient recycling method reduces the need for new solvents, minimizes waste generation, and lowers overall costs, thereby enhancing resource efficiency [1]. The amount of recovered solvent is among the key factors influencing operational costs in ES-based treatment processes [101].

These solvents are generally considered reusable, as they typically do not undergo chemical reactions during lignocellulosic biomass fractionation [8]. Moreover, in the case of

using NAESs, composed of plant-based primary metabolites, these have the advantage that they could be applied directly in cosmetics, pharmaceuticals, and food products without requiring further extraction or processing [102,103]. Although they are normally applied after precipitation and recovery of lignin from the ES suspension using antisolvents (water, ethanol, ethanol/water, and acetone/water) or methods such as pressurized liquid ultrafiltration, solvent recovery would proceed [1,8]. Antisolvents disrupt the hydrogen bonding between HBAs and HBDs, precipitating solubilized components by altering the polarity of the medium [57]. ESs are commonly recovered and recycled by evaporating the antisolvent using a rotary evaporator with or without impurity removal, followed by (ultra)filtration of the liquid phase. In addition to evaporation, other studies mention effective ES recycling methods, such as solid-phase extraction, lyophilization, crystallization, or membrane-based processes [1,8]. It is worth noting that ES recycling depends on both its physicochemical properties and its reaction conditions [8]. Recycling is limited by thermal instability; susceptibility to contaminants, degradation products, and extracts; and high energy consumption by techniques such as evaporation. ESs' reuse can be evaluated through the recovery yield and fundamental physicochemical and structural properties of the recycled ESs, as well as enzymatic hydrolysis and delignification performance [1,57]. Regarding the effect of recycling on ES composition, it has been observed that decreased effectiveness of recycled acid-based ESs may be attributed to losses of HBAs and/or HBDs during ES regeneration, affecting the overall acidity of the solvent [57].

In studies to date, although a slight negative impact on the lignin removal has been observed, it is still effectively within acceptable values for profitable and sustainable biorefinery development [73]. In the study by Quek et al. [65], recovered ESs were used to pretreat the empty oil palm fruit bunch (OPEFB), and their degree of delignification was re-evaluated. Although delignification still occurred, it decreased with the increasing number of recycling cycles. This indicated that the reused ESs are less able to solubilize the lignin in the OPEFB, reducing the accessibility of the cellulose, due to the presence of water and impurities. Furthermore, Zhang et al. [22] observed in their recent study that ChCl/lactic acid recovered after rotary evaporation of the remaining spent antisolvents showed good reusability, with less than a 10% reduction in delignification efficiency after three cycles. Initially, fresh ES achieved nearly 51% delignification, which decreased slightly to 48% by the third cycle. Additionally, the recovered ES developed a slight brown color, but this coloration did not significantly impact lignin removal or the ES's recyclability. Contreras-Gómez et al. [57] attribute this to the fact that evaporating or distilling the antisolvent after recovering precipitated compounds does not eliminate soluble impurities, degradation products, or extractives. These residuals can accumulate in the ES with reuse, potentially compromising the entire biomass conversion process, which is a challenge to overcome. Despite the progress already made, further research is needed in the development of efficient ES recovery technologies and their consolidation at an industrial scale for biomass fractionation, delignification, and sustainable valorization [1,8,57].

8. Conclusions and Future Outlook

This work evaluates and highlights the use of eutectic solvents combined with intensification techniques to promote delignification and recover lignin from biomass waste. Recent applications of eutectic solvents as pretreatment agents for lignocellulosic biomass have shown promising results in delignification and bioconversion into bioproducts or energy. These solvents effectively recover substantial amounts of lignin, thereby enhancing its accessibility and facilitating the conversion of residues into fermentable sugars and other valuable bioproducts [1,2]. ES treatment operates at relatively low temperatures and pressures, reducing energy consumption and minimizing the risk of biomass degradation [2]. Additionally, the adaptability of ESs, including the ability to select and tune their composition for specific applications, as well as options for reuse and recycling, further reduces operational costs.

In addition, the combination with intensification treatment processes, such as ultrasound- and microwave-assisted methods, has led to significant advancements in the delignification of agricultural and/or forestry waste. Conventional methods typically achieve delignification rates of around 80%, primarily through chemical and physical processes, but these methods face various challenges. In contrast, emerging biological methods remove only 40–50% of lignin. However, combining intensification techniques with eutectic solvents helps to overcome some limitations of conventional methods. Studies using ultrasound have reported delignification rates ranging from 40% to 70–80%, with the advantage of achieving these results in a maximum of 60 min under mild-temperature conditions (room temperature to 50 °C). Microwave-assisted methods, on the other hand, dramatically reduce processing times to between 45 s and 30 min, typically operating at higher temperatures (150–160 °C), and have shown potential for achieving delignification efficiencies of up to 80–90%. The synergistic use of these techniques enhances the effectiveness of lignin structural breakdown, accelerates biomass fractionation, increases lignin extraction yields, and can improve lignin purity.

These greener methods offer several benefits, including lower environmental impact, reduced processing time, decreased energy consumption, and minimal chemical use. When combined with appropriate solvents, these techniques enhance the efficiency and selectivity of thermal and chemical delignification reactions [2,13]. Consequently, microwave and ultrasound methods hold great potential for advancing new lignocellulosic biomass-conversion processes, supporting the development of biorefineries and the broader bioeconomy [3]. Despite the encouraging results that support a promising potential in a biorefinery strategy, there are still aspects related to the use of these processes combined with alternative solvents that have not yet been fully explored, mainly related to ES and industrial scaling options, as highlighted in Figure 5. Often, their study or application is hindered by complexity, representing a significant bottleneck in the development of these treatment techniques. Regarding the challenges to be addressed [1–3,71], several significant and relevant issues are mentioned below:

- It is imperative to understand precisely how ESs interact with lignin, as this knowledge is pivotal for their efficient use in fractionation, dissolution, and valorization processes.
- Detailed studies on the structures and properties of ES-extracted lignin, comparing it with other types of technical lignin, and exploring potential applications, alongside customizing ESs and process conditions to produce tailored lignin, are crucial steps.
- Precise determination and standardization of the optimal water content are necessary for the combination of water with ESs to enhance their efficiency.
- Concerns persist regarding the potential toxicity of certain ESs and their decomposition products, as well as their environmental impact. Further research is needed to thoroughly assess their safety and environmental implications.
- Developing efficient ES recovery technologies is essential to improve the economic viability of ES-based biorefineries, as their recovery and reuse on an industrial scale is currently costly and energy-intensive.
- Compatibility with downstream processes and scalability issues due to the need for large quantities of ESs are critical concerns that must be addressed.
- For intensification techniques combined with ESs, future studies will face challenges such as uneven heating, limited penetration depth, induced degradation that may affect the quality of the pretreated biomass, safety issues, reaction control difficulties, energy efficiency, and high equipment costs. Detailed and comprehensive research is essential for the possible large-scale application of these techniques in advanced industries, especially in commercial biorefineries.
- Exploring the development of computational tools to optimize treatment conditions and analyze changes in the chemical structures of the involved components presents an attractive avenue for research.
- Additionally, extensive life-cycle assessments and techno-economic analyses of integrated approaches are crucial areas of research to better assess the viability of the fractionation and valorization of developed processes.



Figure 5. Outline of the challenges associated with delignification using ESs and methods of intensification, as well as potential future directions.

Addressing all of these challenges is no simple feat, given the multitude of ES varieties, the different possible conditions to be used in the intensification methodologies, the time and considerable resources required, and the difficulties in scaling up. Despite the obstacles that remain to be overcome that constitute the lines on which the efforts of the research community should be focused, the progress achieved has the potential to revolutionize the use of lignocellulosic biomass and to offer various application possibilities in the biorefinery sector, as well as in other sectors. It is therefore expected that studies related to the subject matter of this review will increase exponentially in the coming years and will also rely on computational approaches.

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Abbreviations

ChCl	Choline chloride
ES	Eutectic solvent
G	Guaiacyl
H	p-Hydroxyphenyl
HBA	Hydrogen-bond acceptor
HBD	Hydrogen-bond donor
MAE	Microwave-assisted extraction

NAES	Natural eutectic solvent
NADES	Natural deep eutectic solvent
OPEFB	Oil palm empty fruit bunch
S	Syringyl
S:L	Solid/liquid
UAE	Ultrasonic-assisted extraction ChCl/choline chloride

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