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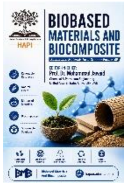

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Lignin-Based Composites Processing, Properties, And Their Applications: A Review

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Abstract:
Lignin, the most significant aromatic renewable natural resource available globally, it can be used in a wide range of value-added applications as a sustainable and environmentally acceptable substitute feedstock for chemicals and polymers obtained from fossil fuels. The emergence of lignin-based composites for packaging materials, wastewater remediation, biomedical engineering, additive manufacturing, automotive construction, and energy storage systems has been accelerated by recent developments in lignin valorisation. With an emphasis on lignin extraction techniques, processing methods, compatibilisation tactics, surface changes, and structure-property connections, this review article provides current advancements in lignin-based composites. The performance and sustainability of composites are examined in connection to several manufacturing techniques, such as extrusion molding, compression molding, resin transfer molding, and 3D printing. According to recent research, the compatibility between lignin and polymer matrices is greatly improved by chemical modifications. This improves mechanical strength, thermal stability, UV resistance, flame retardancy, and interfacial adhesion. Despite these developments, commercialisation is still severely hampered by problems with lignin heterogeneity, processing variability, and large-scale industrial standardization. Thus, scalable lignin modification approaches, improved additive manufacturing, integration of the circular economy, and the generation of high-performance multifunctional bio composites should be the focus of upcoming research. In conclusion, lignin-based composites provide a highly promising pathway to environmentally sustainable and high-value materials that can replace petroleum-derived goods in a variety of industrial sectors.

Keywords: Lignin-based composites, Bio composites, Techniques, Sustainability, Processing,

Properties, Biodegradable.

Introduction
Biodegradable materials have grown in popularity in the industrial sector for development, material and energy integration, recycling, and product life. There is an immense need to investigate innovative alternatives in chemical industries due to concerns regarding the environmental impact of non-renewable resources, raw material availability, and product end-of-life. (Thakur et al., 2014). The primary chemical constituents of plant fibre raw materials are cellulose, lignin, and hemicellulose. Lignin, a macromolecule found in wood and other plants, has emerged as a promising sustainable biomass resource for addressing these difficulties. Despite its historical use in energy cogeneration, lignin is now widely acknowledged as a competitive alternative to conventional components in a range of applications. (Kai et al., 2016; Y. Liu et al., 2022; Wang et al., 2016).
Chemically, lignin is one of the most prevalent polymeric compounds of biological origin, with a complicated polyaromatic structure (Balakshin et al., 2020; Popa et al., 2008). It holds great promise for green technology (Balakshin et al., 2021). Lignin is an essential part of plant cell walls; it serves as a binder between cellulose and hemicellulose (Khan et al., 2019). The process of separating lignin from wood and agricultural waste is widely used. Precipitation techniques are a useful tool for separating lignin from

industrial liquors, which are produced when biomass is delignified, i.e., black liquors (Hidayati et al., 2020). Lignin has many polar functional groups that allow it to form chemical bonds with other molecules. Additionally, lignin is a good filler for composites due to its strong reinforcing qualities. With growing research and development efforts over the years, use of lignin-based materials and composites has already become a major area of focus (Kai et al., 2016; Lizundia et al., 2021; Österberg et al., 2020; Parvathy et al., 2021). To acquire a thorough knowledge of lignin's importance in many applications, namely composites, it is beneficial to acknowledge its complicated nature as a polymer made up of three phenylpropanoid monomers: coniferyl, coumaryl, and sinapyl alcohol. With various sites for polymerization provided by each monomer unit, lignin has a non-uniform 3-D framework that enables a wide variety of linkages between units. A vital role is played by lignin composition, which differs among various plant species. On a dry weight basis, lignocellulosic biomass typically comprises 18-25% lignin, 25-31% hemicellulose, and 45-52% cellulose (Meraj et al., 2023). Furthermore, particular plant species have an impact on the monomer structure of lignin (Meraj et al., 2025; Poletto, 2018).

However, lignin is highly variable in both its manufacturing processes and chemical composition, owing mostly to industrial extraction procedures utilized on lignocellulosic biomass. This diversity differentiates it from cellulose. Nowadays, lignin may be extracted from lignocellulosic biomass using a variety of techniques, many of which are included in pulping procedures. Pulping processes can be broadly categorised into chemical, semi-mechanical, and mechanical methods, often combined to achieve specific results. Mechanical pulping, typically used in low-cost paper production, mainly involves non-resinous softwoods and some hardwoods, producing yellowish lignin without chemical additives, using only water or steam. Hardwoods, which generally yield lower-quality pulp, often undergo a mix of chemical and mechanical pulping. Chemical pulping produces various types of technical lignin, such as kraft, soda, and lignosulphonates, widely used in the paper industry, while forms like hydrolysis, ionic liquid, and organosolv lignin are produced in smaller quantities (Berlin & Balakshin, 2014; Vishtal & Kraslawski, 2011).

In addition, many researchers worldwide are interested in developing lignin-based composites due to the long-term detrimental environmental effects of composites. When integrated into commercial polymers, lignin can improve biodegradability, resulting in green or eco-friendly composites. Lignin's chemical structure enables it to function as a filler, stabilizer, and reinforcement in composites. For the majority of membrane materials produced worldwide, which are made from petroleum-derived polymers, the resulting membranes have low environmental compatibility. The potential of using renewable lignin to manufacture membrane materials is a possible solution to the challenges of getting more and more significant environmental contamination and the lack of fossil-based polymers. Nonetheless, related research on materials that make membranes reveals that long-chain molecules with exceptionally extended branched or regular frameworks generally have good membrane-forming capabilities. (Mulder, 2012; Osman et al., 2024). Lignin's 3-D complicated network structure has poor regularity. Mechanical characteristics for membrane formation are not optimal; in the majority of current investigations, lignin is incorporated with other materials to generate a composite membrane. In order to its large number of active functional groups, lignin can readily engage at interfaces with various polymer types to improve integration and produce more uniform composite membrane material. Thus, these membrane materials can be extensively employed in industrial production processes since they are both affordable and adaptable. (Fernandes et al., 2006; Pham et al., 2024).

However, several reviews on lignin valorization and lignin-based materials have been reported; a thorough analysis that incorporates processing methods, compatibilization strategies, structure-property relationships, and emerging multifunctional applications of lignin-based composites is still lacking. Furthermore, recent breakthroughs in additive manufacturing, energy storage systems, and sustainable composite technologies require an in-depth and thorough analysis of the field's current status.

This review article critically summarizes recent advances in lignin-based composites, with emphasis on lignin extraction methods, processing technologies, compatibilization strategies, structure–property relationships, and multifunctional applications. Furthermore, important issues related to lignin heterogeneity, interfacial compatibility, and large-scale commercialization are explored, as well as future research prospects for high-performance sustainable composite materials. Lastly, lignin-based composites are believed to have interesting uses in a variety of industries.

Processing Of Lignin-Based Composites

The primary factors that influence the processing of natural fiber composites are the composite's temperature, moisture content, type of fiber, and volume fraction. Before processing, the fibers and the matrix moisture content must be managed, and if moisture is present, the necessary modification is required (Ahmed et al., 2025; Campilho, 2015). The processing, sustainability, and performance of composites are also significantly impacted by the fiber's length, aspect ratio, and chemical structure (Campilho, 2015). The fiber volume fraction of the composite enhances its strength, stiffness, and water absorption while decreasing its deformability (Campilho, 2015). An additional crucial element is the processing temperature. The highest temperature that can be applied during processing to prevent most natural fibers from degrading is ~198 ºC for 20 minutes (Araújo et al., 2008; Basiji et al., 2025; Stark, 1999). As depolymerization, oxidation, hydrolysis, decarboxylation, dehydration, and recrystallization alter the chemical, physical, and mechanical properties of natural fibers, any temperature above this threshold can result in degradation, shrinkage, and poor performance of natural fiber composites (Murad et al., 2025; Yildiz et al., 2006). Resin transfer molding, injection molding, extrusion molding, and compression molding are the main processes used in the production of natural fiber composites. However, **Table 1** summarizes some key functions of lignin composite materials along with their modifications.

In *Resin Transfer Molding (RTM)*, preheated resin that is that is poured into a holding chamber instead of pouring the material into an open mold (Sebe et al., 2000; Silveira et al., 2025). The use of this equipment is best suited to medium-volume manufacturing of large-sized components.

Layers of material are placed in the solid mold before the resin is introduced to impregnate the preforms. Vacuum is frequently utilized to prevent air bubbles and draw the resin into the cavity. (Richardson & Zhang, 2000; Goh et al., 2025). **Figure 1** represents the process diagram of the RTM technique.

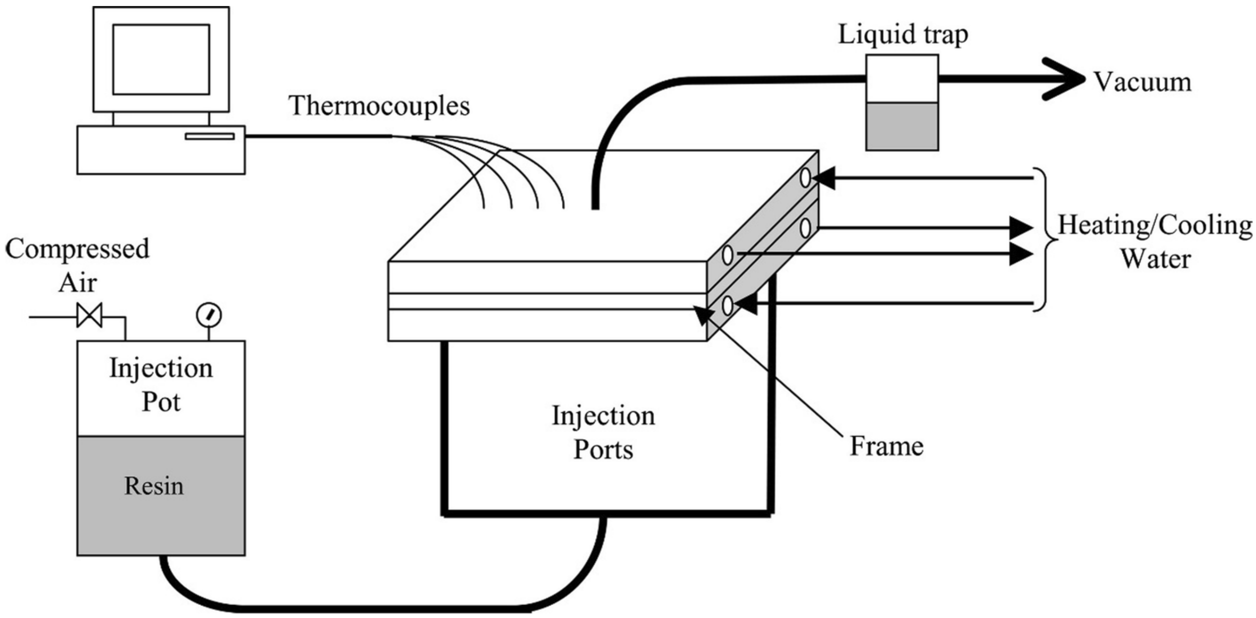

Figure 1. Process flow illustration of resin transfer molding technique for composite manufacturing (Dai & Fan, 2014)

In *Injection Molding*, the most popular method to generate mass-produced materials is injection molding. To initiate this process, the substances are placed in the hopper as pellets or granules and heated until they melt. After that, the molten components are poured into a split die mold chamber and then placed there. Before opening the mold, the melt is refrigerated until it solidifies.

In *Extrusion Molding*, is one of the most widely used procedures in the manufacturing process of natural fiber composites. This method is favored because of the composite's high rigidity and strength as well as how effortless it is to produce them (Campilho, 2015). This method starts with the material being kept in a hopper as pellets or grains. After that, they are sent to a heated barrel to melt. The necessary shape of the composite is then made using the melted polymers. The final stage is cooling the product (Campilho, 2015).

In *Compression Molding*, since the 1990s, compression molding has been utilized for thermoplastic composites due to the growing need for materials that are both lightweight and effective (Campilho, 2015). Using this method, the molding chamber is initially utilized with hot materials. The mold's core side then compresses and distorts them while applying intense pressure to the cavity. (Campilho, 2015). The composite is kept under high pressure until it solidifies before the mold is opened and the composite is removed.

The volume of material, heating duration, mold pressure, and cooling time are the crucial factors that need to be considered when using this method. (Araújo et al., 2008; Shinggu & Jacob, 2025). One such technique, sheet molding, is a commonly used processing method for composite manufacture, as shown in **Figure 2.**

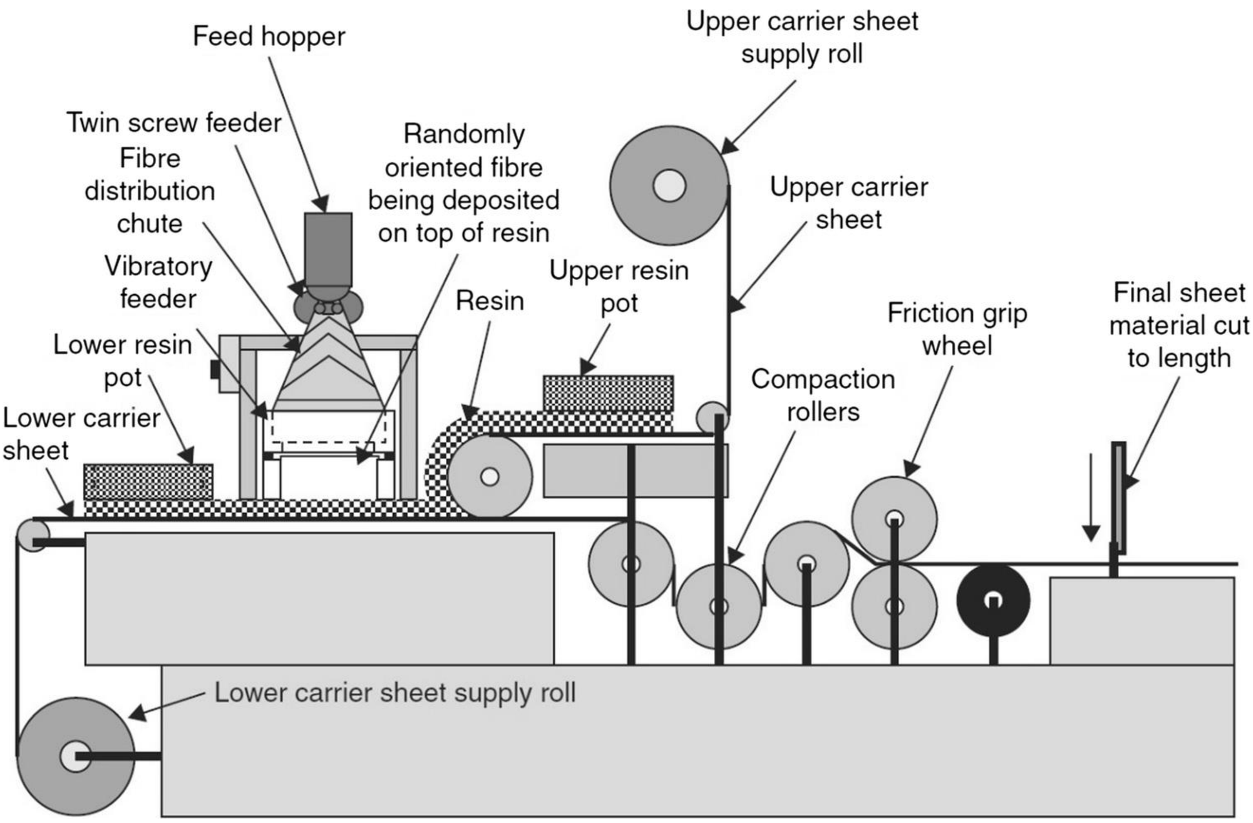

Figure 2. Process flow illustration of the sheet molding technique for composite manufacturing (Dai & Fan, 2014)

Table 1. Functional roles of lignin in composite materials and corresponding modification strategies

Function	*Essential roles of lignin in composites*	*Modifications*	*References*
Reinforcement/ Toughening	Increases modulus, stiffness, and occasionally tensile strength; impact is very dependent on alteration and suitability.	In PLA, PI, PBAT, and hydrogels, modified lignin improves tensile strength.	(Gordobil et al., 2015; Gordobil et al., 2014; Mu et al., 2014; Wang et al., 2025; Wang et al., 2023; Ye et al., 2023; Zhang, et al., 2024; Zhang et al., 2021)

Compatibilizer	improves interfacial bonding and adhesion between polymers or between polymers and fibers	Kraft lignin enhances adhesion at low loadings, while lignin PLA compatibilizer enhances PLA blending	(Luo et al., 2017; Ye et al., 2023)
Functional Additive	Offers fire resistance, antibacterial, antioxidant, and UV blocking qualities	Lignin/PLA films provide UV protection, 3D printing systems benefit from antioxidants, and lignin-shelled phosphates offer fire resistance.	(Kim et al., 2017; Tian et al., 2025; Ye et al., 2023)
Nanostructured Reinforcement	Lignin nanoparticles (LNPs) improve dispersion, stability, and functionality.	LNPs offer greater efficacy and regulated morphology in adhesives, hydrogels, and composites.	(Lu & Sun, 2026; Meng et al., 2021; Moreno & Sipponen, 2024)
Carbon fiber precursor	Utilizes lignin chemistry to generate renewable, high-carbon fibers with adjustable modulus and strength	Qualities are determined by structural characteristics.	(Jiang et al., 2025; Mohammed et al., 2025; Sidharth et al., 2026)

In lignin-based composites, poor interfacial adhesion between lignin and polymer matrices frequently restricts the mechanical performance and durability of lignin-based composites due to lignin's natural polarity, heterogeneity, and complex aromatic structure. To improve interfacial interactions between lignin and polymers, several compatibilization and surface-modification techniques have been investigated. Lignin can be chemically modified to decrease its hydrophilicity and increase its compatibility with hydrophobic polymer matrices through esterification, acetylation, graft copolymerization, and salinization. However, by adding covalent or hydrogen-bonding interactions, compatibilizers such as maleic anhydride-grafted polymers, coupling agents, and reactive additives further enhance interfacial bonding. (Poor et al., 2025).

The key strategies of compatibilizers, which improve lignin-polymer adhesion by forming interfacial bridges, covalent bonds, or reactive interphases. **Table 2** summarizes key strategies with their mechanism along with their evidence.

Table 2. Compatibilization strategies for improving for interfacial adhesion in lignin-polymer composites

Types of compatibilizers	**Mechanism**	**Evidence**	**References**
Reactive compatibilizers e.g., maleated PP, epoxidized natural rubber	Increases interfacial coupling by adding reactive groups that form bonds with lignin hydroxyls	Mechanical characteristics and PP-lignin adhesion are greatly enhanced by MAPP and EBGMA; PLA and lignin, epoxidized natural rubber, produce interfacial reactions that close gaps and improve tensile characteristics	(Abdelwahab et al., 2019; Liu et al., 2022; Ou et al., 2023)
Lignin derived compatibilizers	Chemically modified lignin works as a compatibilizer, enhancing bonding and dispersion.	Butylated and alkylated lignin enhances interfacial shear strength in polypropylene carbon fiber composites	(Sakai et al., 2018; Tan et al., 2023)
Graft polymer compatibilizers e.g., lignin PLA, lignin styrene	Grafting produces lignin surfaces that are compatible with polymers to lessen phase separation	Lignin maleic anhydride PLA increases toughness and strength by bridging PLA and lignin; Grafting polyacrylates enhances PLA elongation; Lignin-polystyrene grafts increase adherence and decrease the size of scattered particles	(Kun & Pukánszky, 2017; Liu et al., 2025; Ou et al., 2023)
Multifunctional compatibilizers	Integrates the responsibilities of reactive, polar, and interfacial energy matching	The morphology and UV barrier of PLA/PBAT blends are enhanced with lignin styrene glycidyl methacrylate compatibilizer	(Kim et al., 2025)

However, surface modification tunes lignin chemistry or polymer-filler surfaces to improve adhesion, dispersion, and interfacial stress transfer. It directly modifies the chemistry and morphology of lignin, which makes it very useful for polymers that need particular polar interactions, as shown in **Table 3.**

Table 3. Surface modification approaches for enhancing adhesion and dispersion in lignin-based composites

Type of modification	Mechanism	Evidence	References
Chemical modification of lignin	Promotes covalent or hydrogen bonding by adding functional groups and modifying polarity	Acetylation improves PLA-lignin compatibility and decreases lignin aggregation; PBS and PBAT matrix bonding is improved by esterified lignin; Stronger H bonding is made possible by demethylation, which boosts phenolic–OH.	(Esakkimuthu et al., 2024; Johansson et al., 2024; YUE et al., 2016; Zhang et al., 2024; Zhang et al., 2024; Zhou et al., 2026)
Graft polymerization	forms a compatible shell that resembles polymers	Grafted rubber-compatible groups improve the binding between lignin and rubber; Lignin-grafted carbon nanotubes enhance carbon-fiber composites.	(Wang et al., 2016; Zhang et al., 2026)
Silane treatments	Si–O–cellulose and Si–O–polymer bridges at interface	Enhances PLA–lignin adhesion through covalent bonding; salinization is frequently utilized in natural fiber composites	(Sayam, 2026; Wang et al., 2020)
Physical modification	Boost surface area or activate functional groups	Polypropylene adhesion and dispersion are enhanced by freeze-dried sheet-like lignin; In wood and fiber surfaces, plasma adds polar groups and improves adhesion.	(Chen et al., 2016; Oladzadabbasabadi et al., 2025; Tang et al., 2015)

In situ surface modification	Alter lignin when it's being extruded or formed into a composite	PLA/lignin mechanical characteristics are enhanced by solvent-free interfacial modification; Wood plastic composite adhesion is improved by DES-based lignin regeneration.	(Qi et al., 2024; Wang et al., 2020)

Both surface modification and compatibilization are proven methods for enhancing lignin–polymer interfacial adhesion.

The optimum compatibility occurs with hydrophobic or chemically inert polymers (PP, PBAT, PLA). Surface modification is the most effective way to adjust the structure of lignin to match the chemistry of polymers and improve certain interactions such as van der Waals, covalent bonding, and H-bonding.

Comparative Impact of Lignin Types on Composite Properties

Technical lignin's derived via Kraft, soda, organosolv, and sulfite pulping methods have specific structural and physicochemical characteristics that affect their efficacy in composite materials. Kraft lignin has substantial β-O-4 cleavage and strong condensation, resulting in a sulfur-based, highly aromatic structure with phenolic hydroxyl groups and C-C linkages (Mansouri & Salvadó, 2006). This condensed form typically yields low or intermediate molecular weights with occasionally narrow dispersion (Alzahrani et al., 2016). Although it has strong thermal stability, it is incompatible with hydrophobic polymers like PLA, resulting in complex mixtures with poor mechanical qualities (Mimini et al., 2019). Furthermore, Comparative structural characteristics and composite-performance implications of Soda, Organosolv, and Lignosulfonate lignins are summarized in **Table 4.**

Table 4. Comparison of lignin types and their composite properties

Lignin Type	Chemical structure	Purity & Impurities	Molecular Weight (Mw) Characteristics	Influence on composite properties	References
Kraft Lignin	Highly condensed, substantial β-O-4 cleavage, phenolic OH, enhanced C-C bonds, and sulfur content	High purity with minimal carbohydrate, contains sulfur.	Mostly low or mild Mw, often broad but occasionally monodisperse	Inadequate compatibility with multiple polymers, Low miscibility (e.g., with PLA), increases stiffness, adequate thermal	(Mansouri & Salvadó, 2006; Scolari et al., 2025; Utami et al., 2026)

				stability, and significant antioxidant properties	
Soda	Sulfur-free, preserves more β-O-4 links, appears more linear in nature, and has more S/G/H ratio variability	Moderate purity; may retain hemicellulose, less soluble than organosolv	Usually lower Mw than kraft, narrow polydispersity, high chain orientation	Carbon fibers benefit from their linearity and β-O-4 content. It also improves alignment and has modest miscibility, making it excellent for antioxidants and composites	(Latif et al., 2022; Alzahrani et al., 2016; Kim & Um, 2020)
Organosolv	High β-O-4 retention, low condensation, and sulfur-free	High purity, minimal ash/sugars, low contaminants	Low to moderate Mw, smaller dispersion, and excellent structural homogeneity	Compatibility with polymers, outstanding miscibility (PLA, chitosan, polyurethane), adequate binding ability, enhances mechanical properties of composites, good solubility	(Cherif et al., 2020; Kim & Um, 2020; Malyar et al., 2019)
Lignosulfonate	Extremely sulfurous, highly water soluble, polyelectrolyte, significantly changed from native lignin	Very high ash, low purity, significant chemical alteration	Commercial lignins have the highest Mw and maximum polydispersity	Effective dispersion, suitable for flocculation and additives, low dissolution with hydrophobic polymers until modified	(Scolari et al., 2025; Wang et al., 2025; Wibowo & Park, 2023)

Properties Of Lignin-Based Composites

Lignin-based composites exhibit a distinctive combination of properties, rendering them highly suitable for sustainable material development. These properties encompass mechanical, thermal, and chemical characteristics, which can be optimized through the selection of lignin type, matrix material, and processing techniques. The versatility in tailoring these composites enables fine-tuning of their structural and functional attributes, making them promising candidates for various applications in sustainable technologies.

Thermal And Mechanical Properties

It is widely known that the aromatic structure and phenolic backbone of lignin contribute to its heat stability (Sánchez & Alvarez, 1999; Sadeghifar & Argyropoulos, 2015). The aromatic structure breaks down between 400 and 600°C, while the phenolic backbone itself breaks down between 200 and 450°C (Sun et al., 2001). The resulting composite film showed a modest reduction in thermal deterioration when modified kraft lignin (KL) was added to PVA (Fernandes et al., 2006). The increase in the temperature of thermal degradation corresponds with the amount of lignin. When lignin was added to polyethylene terephthalate (PET), Canneti and Bertini found that it significantly affected the thermal stability of the composites. On the other hand, ($T_{decomposition}$)decreased with increasing lignin loading (Canetti & Bertini, 2009). The preparation process has an impact on the thermal characteristics of lignin/PLA composites (Domenek et al., 2012). During the initial deterioration (T_{onset}) and decomposition up to 70°C, lignin incorporation was increased by 0.5 and 5%. Compared to the composite containing the acetylated sample, the composite containing KL shows greater thermal stability. The quantity of char residue decreased after the addition of lignin. However, Sahoo et al. found that the char residue increased in the composites upon lignin introduction (Sahoo et al., 2011).

By incorporating lignin, the melting temperature, $T_{m,}$ and thermal transition temperature, $T_{g,}$ of polymers seem to be unaffected (Sen et al., 2015). However, there has been no significant shift in T_g when lignin is added to PLA (Gordobil et al., 2015). According to a similar study, adding lignin to PLA did not significantly alter the composite's ability to degrade thermally (Xie et al., 2015). According to another study, the addition of lignin raised the decomposition temperature but reduced the mechanical characteristics of lignin/PLA composites (Li et al., 2019). Furthermore, the most challenging issue of producing lignin as a filler is its enormous particle size. Lignin particle size has been decreased using a variety of techniques, such as ball milling, acidic treatment, and hybrid binders (Bahl et al., 2014; Jungwirth & Kustas, 2022; Miao & Hamad, 2017; Tian et al., 2025). When compared to other methods, ball milling is considered to be simple, cost-effective, and ecologically beneficial (Pucciariello et al., 2010). Solid particles are broken down by the ball milling process, which increases the impact energy of the spinning grinding media. However, the poor compatibility of lignin with the polymer matrix has been caused by the possibility of contaminants and lignin in different forms and sizes (Piras et al., 2019).

To improve the compatibility between lignin and polymer matrix, lignin was modified using a variety of techniques, such as surface grafting(Park et al., 2019), hydroxy methylation (Aini et al., 2019), epoxidation (Sun et al., 2016), alkylation (Chen et al., 2011; Maldhure & Ekhe, 2017), esterification (Vila et al., 2016), carboxymethylation (Shweta & Jha, 2016), and sulfonation (Aro & Fatehi, 2017). The impact and adhesion strength were strengthened by modification of lignin, which effectively stopped the cross-linking rate from decreasing. Alternatively, the mechanical characteristics of the composite were comparable to those of the clean polymer when esterified lignin was added to low-density polyethylene (LDPE) (Dehne et al., 2017; Sailaja & Deepthi, 2010). When lignin was modified using esterification agents such as butyric anhydride mixed with PLA, Young's modulus and elongation at break were higher than those of PLA. Several esterified lignins have enhanced the mechanical characteristics of lignin/PLA composites (Kim et al., 2017). The detrimental impact of the lignin might be lessened even when the mechanical qualities of neat LDPE remain unchanged. It appears that further investigation is required to enhance the lignin integration and matrix of polymer molecules, such as by incorporating a compatibilizer, even with all efforts to improve lignin's capacity to strengthen the mechanical features of polymeric materials. Lignin can scavenge free radicals and stop oxidation processes. By inhibiting the activity of free radicals or stopping their generation, stabilizers are substances that help prevent polymer breakdown brought on by oxidation processes with an increase in temperature or light exposure. Since lignin prevents UV transmission, it functions as a UV barrier. In order to make PP easier to break down after usage, lignin is added to PP to speed up the photooxidation process. Lignin is usually used as an additive at quantities below 5% due to its significant antioxidant and anti-UV effects. These qualities were attributed to the presence of oxygen and the phenolic group as functional groups in lignin (Alzagameem et al., 2019; Ogan et al., 2020).Lignin's characteristics have led to its use in wound dressings and anti-inflammatory biomaterials (Sugiarto et al., 2022).

Applications Of Lignin-Based Composites

1.Packaging Materials

With the escalating environmental hazards from petroleum-based packaging products, demand for bio-based materials has increased. However, materials from bio-based resources, such as starch, protein, and pectin, lack essential properties, such as a poor barrier to moisture and gas, low mechanical strength, and low thermal stability required for food packaging (Sun et al., 2023). Additionally, the growing concern of consumers over additive-free food has driven research towards the development of smart and active food packaging (Hararak et al., 2022). Active packaging is known as a smart food packaging technique providing versatile functions beyond the containment of food products (Kadirvel et al., 2025). In the food packaging applications, degradation of color and nutrients present in food products, especially in transparent packages, is commonly observed on exposure to light, resulting in alteration of chemical bonds leads spoilage and quality loss (Verduin et al., 2020). To overcome spoilage from UV degradation, light blockers are incorporated into the food packages. Thus, lignin is a potential light absorber with several chromophore functional groups to absorb light. The mechanism of light absorption, the presence of biphenyl, α-carbonyl, and ring conjugated double bonds present in lignin compositions, act as UV light absorbers. Other functional groups, such as aromatic rings, carbonyl groups, and C=C double bonds, are also present and work as visible light absorbers (Lv et al., 2023; Sadeghifar & Ragauskas, 2020; Zhang et al., 2018). These light absorption properties can aid in protecting light sensitive food products and promote longer shelf life. In the previous study, by applying lignin rich films (6 % w/w) displayed more than 96.1 UVA and UVB blocking. This UV blocking performance was superior to cellulose-based films, 60.6 ± 0.35 % UVB blocking, 27.7 ± 0.58 % UVA blocking, highlighting the potential of lignin as an effective light blocker for light-sensitive products (Sadeghifar & Ragauskas, 2020). Such enhanced UV resistance is attributed to the presence of aromatic rings, phenolic hydroxyl groups, and conjugated chromophoric structures in lignin that effectively absorb UV radiation. In addition to UV shielding, the lignin-rich films exhibited improved thermal stability, further supporting the multifunctional role of lignin as a sustainable and effective additive for light-protective packaging materials. In another study by (Tian et al. 2024), the incorporation of lignin-based nanoparticles into poly (vinyl alcohol) based films reported a significant enhancement in UV blocking with simultaneous improvement in the functional properties. The developed composite film displayed a UV shielding effect due to the presence of phenylpropane structure and phenolic hydroxyl groups in lignin. Additionally, incorporation of lignin nanoparticles improved hydrophobicity, mechanical strength and thermal stability of the composite films with enhanced antibacterial and antioxidant properties of the material. Moreover, lignin incorporation in food packaging material has proven to influence the optical properties of biobased polymer-based composites. In the case of improving optical properties, a thin film based on lignin was prepared from bamboo powder and demonstrated exceptional ultraviolet shielding performance (Feng et al., 2023).

The growing demand for additive-free, safe and secure food products has also driven the interest towards the incorporation of antimicrobial and antioxidant additives. In this context, the presence of a phenolic structure helps in imparting bioactive properties to the material. The available phenol groups are known to provide antibacterial properties by binding to the bacterial cell membrane, resulting in cell death (Kirar et al., 2024; Winotapun et al., 2022). In a recent study by (Riaz et al., 2024), lignin was used as a reinforcing agent in carboxymethyl cellulose (CMC) based films. In addition to improvement in physico-chemical properties, antibacterial as well as antioxidant performance was also observed, showcasing the versatile potential of lignin in the food packaging industry. With the increased lignin concentration from 5 to 15% w/w of CMC, a significant increment in inhibition zone diameter was observed against *Escherichia coli* ATCC 25,922, *Salmonella typhimurium* ATCC 14,028, *Staphylococcus aureus* ATCC 25,923, and *Listeria monocytogenes* DSM 20,649. Additionally, antioxidant activity increased readily with increasing lignin concentration. This activity was tested by following DPPH and ABTS radical scavenging methods and demonstrated the effective radical scavenging capability of lignin. Collectively, these studies demonstrate that lignin and lignin-based nanoparticles function as efficient UV absorbers while imparting antibacterial and antioxidant functionality, and simultaneously enhancing the thermal, mechanical, and surface properties of materials.

2. Wastewater Treatment

As previously mentioned, lignin consists of diverse functional groups, which enable the adsorption of contaminants from wastewater. The available groups, such as carbonyl, alcohol hydroxyl, and methoxyl, exhibit adsorption of heavy metal ions through ion exchange (Wang et al., 2022). This mechanism results in the substitution of positively charged ions present on the adsorbent surface with contaminants such as metal ions. Additionally, other adsorption mechanisms involve hydrophobic interactions, pi-pi interactions, and hydrogen bonding (Camargos et al., 2025). Hydrophobic interactions are developed when nonpolar groups, present in the pollutants, form nonspecific interactions with hydrophobic adsorbents to minimize contact with water molecules. During hydrogen bonding interactions, adsorbates act as hydrogen acceptors or donors onto the adsorbent's active site. This interaction is stronger than pi-pi interactions, which are formed by sharing aromatic functional groups between adsorbents and pollutants with the development of π-electron acceptors/donors. Another effective adsorption process involves pore filling, which follows diffusion as the main mechanism. A high surface area of adsorbent promotes diffusion of contaminants present in the wastewater into the pores of the adsorbent. Electrostatic interactions are also utilized as an effective adsorption strategy involving attraction between oppositely charged adsorbates and adsorbents. However, the adsorption efficiency of pure lignin in aqueous media is lower, which can be improved through the modification of lignin (Sajjadi et al., 2021). Such modifications enhance the affinity of lignin towards certain wastewater pollutants, making it a potential adsorption material compared to conventional ones.

One such effective lignin modification using chitosan was studied by (Vedula & Yadav, 2022). In this study, recyclable lignin chitosan composite membranes were developed to extract methylene blue dye (MBD) from wastewater. They observed that 95% of MBD removal was achieved by the suggested membrane, which showed remarkable adsorption performance. The adsorption of the MBD dye was primarily regulated by electrostatic interactions between the positively charged MBD and the negatively charged oxygen-containing functional groups present in lignin. Moreover, the role of hydrogen bonding between lignin chitosan membrane due to the presence of hydroxyl groups and the aromatic heterocyclic rings of MBD significantly facilitated the removal of dye. The membrane technology for the removal of dye can be improved by the reusability of the membrane. Another reliable and scalable technique for water purification is adsorption by porous carbon (activated carbon). Even though porous carbon has a great deal of potential for eliminating contaminants from wastewater, its conventional production requires the use of alkali for carbon activation. To overcome these limitations, there is increasing interest in producing porous carbon using a precursor made from lignin. This lignin also provides the carbonaceous structures with a large surface area due to increased porosity, excellent reusability, and rapid adsorption kinetics, making them desirable material for wastewater treatment.

In a recent study, a lignin-derived porous carbon material to evaluate the removal efficiency of Azure B and Orange II from wastewater (Zhu et al., 2022). The designed lignin-derived material demonstrated exceptional adsorption capabilities, with dye adsorption efficiencies of more than 98% for both Azure B and Orange II. It's interesting to note that the generated porous carbon showed the ability to simultaneously remove both dyes from a hybrid dye solution, achieving complete removal in the first adsorption cycle. With removal efficiencies of up to 66% for Orange II and 86% for Azure B, the material retained a substantial adsorption capacity after the third cycle of reuse of lignin carbon material. The material's ability to be recycled demonstrates its practical suitability for frequent use. These findings demonstrate lignin's role as an inexpensive, renewable membrane and an active functional component that contributes to the development of recyclable, sustainable, and financially feasible materials for wastewater treatment applications.

3. Biomedical Applications

Lignin has become a viable option to meet industrial demands and replace traditional biomedical materials made from synthetic polymers, driven by the growing demand for eco-friendly materials, especially biopolymers. The biomedical industry benefits greatly from lignin's biodegradability, biocompatibility, and functional flexibility. Because lignin is biodegradable, it breaks down naturally, reducing its negative effects on the environment and enabling the body to use it temporarily without accumulating over time. Studies showing low toxicity and biocompatibility make it an ideal choice for use in biomedicine (Taib et al., 2026).

Lignin, due to its biocompatible nature, is being used in drug delivery with the aid of lignin-coated nanoparticles. Apart from this, lignin hydrogels are also being used in tissue engineering (Morena & Tzanov, 2022). Antimicrobial resistance is one of the most pressing health challenges in this era. AMR is caused by excessive use of antibiotics, because of which the microbes have now developed resistance against them (Llor & Bjerrum, 2014). Lignin-coated nanoparticles (LigNPs) are a promising alternative to traditional antibiotics as they can be used for targeted killing of microbes with more efficacy due to their high surface area to volume ratio, which increases their reactivity (Chelliah et al., 2023). Moreover, lignin itself has antimicrobial properties due to the presence of the phenolic group and its membrane-attaching behaviour. The properties of LigNPs are different from their bulk counterparts, which makes them suitable for use in drug and gene delivery systems (Alqahtani et al., 2019; Chaudhary & Sinha, 2023).

A hydrogel is a cross-linked polymer, linked mainly by covalent bonds and hydrophobic interactions. It swells in water but doesn't dissolve in it (Ho et al., 2022). Hydrogels can be used for 3D printing, in tissue engineering, and regenerative medicine due to their water-retaining and holding capacity (Ho et al., 2022). The hydrophobic nature of hydrogels and their capability to swell in water are important properties in targeted drug delivery (Taib et al., 2026). The use of lignin hydrogels is also being used extensively as inks in 3D bio-printing due to their adhesive and biocompatible nature, which provides strength to the material (Wu et al., 2024). Lignin is a material of choice for tissue engineering as it gets integrated with the existing tissue environment due to its chemical composition, and apart from this, due to its biocompatible, biodegradable, and non-toxic properties (Creteanu et al., 2024). Due to the natural existence of lignin, its applications in hydrogels can also be used in wound dressings due to its antioxidant, anti-inflammatory, and antibacterial properties (Shan et al., 2025). Lignin composites, hydrogels, nanogels, and cryogels can be used to make 3D scaffolds in tissue engineering and regenerative therapy. Lignin is also being used in making electrodes, thus opening the possibility of it being used to make biosensors. (Taib et al., 2026).

Because lignin-based particles are non-toxic and environmentally safe, they have great promise for use in biomedicine, but there are still a number of obstacles to overcome. Further research is required to comprehend lignin's toxicity, impact on DNA, ROS generation, and interaction with living systems because chemical changes of lignin can decrease its biodegradability and pose health hazards. The medical application of lignin is additionally restricted by issues like lack of standardization, difficulty in large-scale synthesis, and variance in lignin structure due to various extraction techniques. To permit their dependable and long-lasting use in biomedicine, future research should concentrate on strengthening the drug transport and antibacterial capabilities of lignin-based materials as well as their safety, consistency, and functionalization. **Figure 3** summarizes the major biomedical applications of lignin-based materials, including drug delivery, tissue engineering, regenerative medicine, and biosensor development.

Figure 3. Overview of biomedical applications of lignin-derived materials

4. Automotive & Construction Materials

The automotive industry is shifting toward more environmentally responsible materials as emissions regulations tighten and vehicle mass becomes a limiting factor for electric vehicle (EV) range. One material receiving increasing attention is lignin, which can serve as a reinforcing phase in both thermoplastic and thermoset composites due to its aromatic structure and intrinsic stiffness. Experimental work shows that biocarbon produced from lignin via pyrolysis at 600-900 °C can improve the mechanical properties of secondary polymers, including recycled polyamide 6 (nylon). When 25 % (w/w) lignin-derived biocarbon is incorporated into recycled nylon, flexural strength increases by about 18% and tensile strength by 8%. These composites also burn far more slowly, with reported reductions in burning rate exceeding 77% (Lignin-Based Composites, 2026). This combination of high strength and flame resistance makes such materials suitable for interior components and under-the-hood parts where heat exposure and durability are critical. Lignin is also being examined as a feedstock for the preparation of carbon fiber (CF) due to its high strength properties. Conventional CFs are primarily manufactured from polyacrylonitrile (PAN) from fossil resources, which requires energy-intensive processing for their preparation. Therefore, it is suggested that by blending lignin with small amounts of PAN or selected plasticizers, researchers have produced melt-spun fibers that meet the performance requirements of non-structural automotive components, such as interior panels and trim elements (Yan et al., 2025). Because lignin contains a high proportion of aromatic carbon, it delivers relatively high carbon yields during carbonization. Combined with its lower cost, this makes lignin a realistic option for producing carbon fibers intended for high-volume automotive applications where ultra-high strength is not required.

In the construction sector, significant effort has been directed toward replacing petroleum-based phenol–formaldehyde (PF) and epoxy resins with lignin-based systems. Lignin can partially replace phenol in PF resins due to its phenolic functionality, although early formulations often showed slow curing behavior. More recent work has addressed this limitation through chemical modification and fractionation techniques, including phenolation, hydroxy methylation, and solvent-based separation. Acetone-fractionated lignin, which exhibits a narrower molecular weight distribution, has been used to produce bio-based epoxy thermosets with tensile strengths of 4.6 MPa and elongation at break values as high as 315.5%. These values exceed those reported for conventional bisphenol A (BPA) based epoxies (Zou et al., 2023)supporting their use in engineered wood products with high strength properties, designing structural panels, and making construction adhesives. Recently, it was observed that lignin has emerged in cement and asphalt systems as an adhesive. In belite-rich cement production, the use of lignin can function as a biofuel during clinker formation, while also acting as a dispersant that improves fresh concrete workability and long-term durability (Chen et al., 2025). In the case of asphalt binders, lignin's antioxidant behavior slows oxidative ageing, which helps extend their service life and reduces long-term degradation under traffic and environmental exposure (Ha & Ko, 2025).

5. 3-D Printing And Additive Manufacturing

Additive manufacturing (AM), especially vat-based methods such as stereolithography (SLA) and digital light processing (DLP), has been slow to adopt sustainable feedstocks and has reported potential side effects. This limitation is largely due to strict rheological and curing requirements that constrain material selection for 3D printing and additive manufacturing. Despite these limitations, lignin has demonstrated its versatility when used as an active filler while it helps in manufacturing. Modifying the existing process by adding a trace amount of lignin can result in a significant improvement in the SLA and DLP properties. In the case of DLP systems, incorporating as little as 0.025% (w/w) lignin into epoxy acrylate resins increases tensile strength from 44.9 to 62.2 MPa and improves adhesive properties, while maintaining dimensional accuracy in printed parts. (Ha & Ko, 2025). While increasing the lignin component limits higher lignin loadings in photocurable resins, due to its strong UV absorbance, which interferes with light penetration and slows down the polymerization process. This issue can be resolved by using chemical modification to produce acrylated lignin. In this form, the presence of acrylate groups in lignin participates directly in network formation rather than acting as a dispersed filler due to polymerization. Using this approach, successful 3D printing has been demonstrated at lignin concentrations up to 30 (w/w). The resulting materials, due to their blending with lignin, show increased strength in terms of Young's modulus and also exhibit non-cytotoxic behaviour due to lignin content, supporting their potential use in biomedical components (Vigogne et al., 2025).

In fused deposition modeling (FDM), lignin can be blended with conventional thermoplastics (PLA or ABS) to improve strength properties. Increasing lignin concentration in blending increases brittleness, which limits mechanical performance. However, changing the source of lignin helps improve plasticizer properties from the organosolv lignin, which displays improved compatibility with synthetic polymers, enabling the fabrication of filaments with higher toughness and print stability. These developments expand the applicability of lignin-containing filaments beyond purely decorative parts. Lignin has also attracted interest in emerging "4D printing" concepts, where printed structures change shape or function in response to environmental conditions. This change can be adjusted by its innate natural UV shielding capacity and antioxidant behaviour, making it suitable for composites designed to resist degradation while subjected to external conditions. Such properties support the development of materials capable of sensing environmental exposure and also help in developing material shows increased self-life (Wu et al., 2025). In direct ink writing (DIW), chemical modification of lignin has been shown to improve interfacial bonding within complex printed architectures, reducing the likelihood of mechanical failure during service (Georgs et al., 2025).

6. Energy Storage & Electronics

With the new concern of energy and its storage, as lithium availability increases, the energy storage sector has begun to place greater emphasis on sodium-ion batteries (SIB) as a viable alternative for energy storage. In this context, the structure of lignin plays an important role in making hard carbon (HC) anodes, which are an essential part of SIB. Unlike graphitic carbon, lignin-derived hard carbon forms a largely disordered, non-graphitizable network. This structure features expanded interlayer spacing, a characteristic that accommodates the large sodium ions used in systems (Kitchamsetti & Mhin, 2025).

The previous work indicates that multi-step thermal processing plays a key role in optimizing the performance of lignin-based hard carbon. In this context, a two-stage route combining initial pyrolysis with subsequent high-temperature carbonization promotes atomic rearrangement within the carbon matrix. Due to this treatment, it forms closed pore structures, which contribute to higher retention of sodium storage capacity. The use of lignin helps in increasing 60% carbon by weight; it offers higher carbon yields and improved structural integrity compared with cellulose-derived counterparts as precursors (Wang et al., 2025).

Lignin-based carbons are also being investigated for use in supercapacitor electrodes. In this context, the use of hybrid electrode architectures gives more enhanced properties, which incorporate lignin-derived graphene or carbon nanofibers (CNFs), often combined with inorganic additives (silver nanoparticles or molybdenum disulfide), have demonstrated specific capacitance values up to 432 F/g while retaining almost 90% capacitance after 10,000 charge-discharge cycles (Chen et al., 2025). The presence of oxygen species in its structure on lignin-derived carbon surfaces supports pseudo-capacitive behaviour, which contributes to increased energy density in these devices, which helps in the storage of charge.

In the development of electronic and electrochemical systems, lignin has also been explored as a component of green gel electrolytes (LGEs). The lignin-derived LGE materials exhibit high ionic conductivity and have been applied in flexible electronic devices and zinc-ion battery configurations. In aqueous zinc-ion batteries, the use of lignin-based coating on the zinc anode suppresses dendrite growth and limits hydrogen evolution reactions, extending operational lifetimes (up to 2,800 hours) (Chen et al., 2025). In addition to lignin's printed sustainable circuit boards and sensor synthesis, the dielectric properties are being extensively investigated, which offers a bio-based alternative to conventional electronic materials. (Wu et al., 2025).

Commercialization Challenges of lignin-based composites

Despite enormous development in lignin valorization, commercialization of lignin-based composites has remained a challenge. The costs of lignin synthesis, filtration, modification, and composites manufacture remain greater than those of conventional petroleum-based materials. Whereas lignin is widely available as an industrial byproduct, even more processing is often needed to improve its compatibility with polymer matrix materials, enhancing production costs. Scalability continues to be an issue because the majority of reported lignin-based composite systems have been produced at laboratory levels, while large-scale production requires constant feedstock quality and predictable processing environments. Additionally, lignin varies greatly depending on the biomass source and extraction method, resulting in changes in molecular composition, functional groups, and composite efficiency. This unpredictability hinders the quality control and standardization efforts essential to industrial production. A further challenge is industrial acceptability, since manufacturers frequently choose existing petroleum-derived materials with proven efficacy and access to supply chains. Therefore, to establish the consumer viability and efficacy of lignin-based composites in industrial applications, extensive techno-economic assessments, life span analysis, and long-term durability studies are necessary.

Borregaard of Norway is the world's top lignosulfonate producer, having developed innovative procedures for separating lignin and lignosulfates from wood. Trades across four continents and claims to produce sustainable lignin-based goods, namely battery components, ceramic components, binding elements for livestock feed, briquettes, fabric colors, insecticides, and concrete dispersion agents (Borregaard, 2026). Furthermore, Renmatix, a biorefinery in the United States, developed the Plantrose process, which uses a supercritical water reactor to convert biomass into lignin, cellulose, and hemicellulose, thereby commercializing the production of bio-based goods.

Domsjö Fabriker of Sweden is the next largest producer, producing around 120,000 tons of powder lignin each year from its biorefinery facility. Its primary external markets are for concrete and feeding additives, crop production, and road construction. Aditya Birla, the parent company, owns 50 firms in nearly 40 countries and operates 130 industrial facilities (Fabriker, 2026).

The commercialization of lignin and carbon-based lignin is motivated by the growing demand for environmentally friendly supplies and approaches that require a substitute for carbon from fossil fuels. Indeed, the worldwide bio-based materials market size was assessed at approximately 41 billion US dollars in 2023 and is predicted to reach 396 billion US dollars by 2033. Whereas there has been progress toward commercializing technological carbons derived from lignin, it is still largely in the development and pilot stage. Some of the challenges that lignin carbon processing and marketing still face include continuity in lignin quality, economic viability, and rivalry with other carbon sources.

Despite the diverse array of products described above, and although cellulose is the most readily available biopolymer, lignin remains largely underutilized, and its valorization is in its early stages. However, several mature firms have demonstrated that it is a very significant and novel biorefinery resource for producing highly efficient, sustainable biofuels, biomaterials, and bio-derived products.

Finally, overcoming legislative barriers and ensuring that performance satisfies industry requirements are important to their widespread acceptance. Thus, ongoing research and investment are critical for overcoming current difficulties and realizing the potential of the market.

Challenges and Future Perspectives

Compared to many petroleum-based synthetic materials, lignin-based composites are less expensive, renewable, and biodegradable. However, lignin's cost, availability, and quality might differ greatly based on the extraction method and biomass source. Since the pulp, paper, and biorefinery industries are the main sources of lignin as a by-product, changes in industrial production and processing techniques may have an impact on its steady supply and cost. Furthermore, the performance and reproducibility of lignin-based composites may be impacted by the structural heterogeneity of lignin from various sources, posing difficulties for large-scale industrial applications. For constant material qualities and continuous manufacturing, lignin must be sourced, stored, and standardized effectively. There is concurrence among various bio-based materials in terms of performance, availability, and economic viability, even though lignin is typically seen as an affordable and sustainable substitute for synthetic additives and fillers.

Despite considerable progress, several challenges remain in optimizing lignin-based composites for industrial applications. The variability in lignin structure due to its diverse sources and extraction methods affects the consistency of composite properties, posing a barrier to large-scale adoption. Addressing these challenges requires continued research into standardizing lignin extraction processes, improving the compatibility of lignin with various polymer matrices, and developing cost-effective and scalable methods for lignin-based composite production.

Future research should focus on exploring high-value applications where lignin’s unique properties, such as UV resistance, antioxidant capabilities, and biodegradability, provide clear advantages. Emerging technologies in lignin valorization, such as catalytic depolymerization and enzyme-assisted modification, also offer promising directions for creating more functional and versatile lignin derivatives. Collaborations between academia, industry, and government agencies could drive the development of standardized lignin-based materials for diverse applications, from eco-friendly packaging solutions to biomedical devices. Beyond the widely established applications, various potential multifunctional applications of lignin-based composites are gaining substantial research exploration. These include electromagnetic interference (EMI) shielding materials, in which lignin-derived carbon-based structures can offer light-weight and environmentally friendly alternatives to traditional metallic shields. In light of lignin's tunable electrical and chemical properties, the emergence of lignin-based smart sensors for ecological surveillance, medical services, and structural integrity evaluation is a potential research area. Additionally, self-repairing lignin composites capable of automatically fixing small fractures have the potential to greatly improve the durability and service life of modern materials. Recyclable conductive composites made from lignin-derived carbon fiber materials, graphene-based structures, and conductive networks are gaining popularity for use in adaptable electronics, energy-saving devices, and wearable devices. Developing these multifunctional uses would boost lignin-based composites' position as next-generation sustainable resources.

For Lignin-based composite materials, more sophisticated methods and technologies, such as 3D printing and screen processing, should be formulated. Furthermore, additional uses for lignin-derived materials should be developed, including nanogenerators, thermal management, biomedical applications, and so on. Another promising avenue lies in lignin’s role in circular economy models, where lignin-derived materials can be designed to be reusable or recyclable, reducing waste and promoting sustainable production practices. The incorporation of lignin into circular economy frameworks could help industries comply with environmental regulations while meeting the growing demand for environmentally friendly and sustainable materials.

Conclusions

Lignin-based composites offer immense potential as sustainable materials, presenting an eco-friendly alternative to traditional petrochemical-based composites. These materials leverage lignin's natural abundance, biocompatibility, and biodegradability, positioning them as promising candidates for diverse applications ranging from packaging to advanced structural materials. Key properties, such as enhanced mechanical strength, thermal stability, and the ability to serve as UV and antioxidant agents, make lignin composites particularly advantageous in sectors prioritizing sustainability. Moreover, advances in lignin modification and processing techniques have improved its compatibility with various polymers, broadening its applicability in composite formulations.

Future studies should concentrate on maximizing lignin adherence with polymer matrices using efficient modification techniques like acetylation, silane-based treatment, esterification, and graft polymerization, which have shown substantial improvements in mechanical performance, thermal stability, and interfacial adhesion. Biodegradable packaging, treatment of wastewater, biomedical engineering, additive manufacturing, automotive components, and energy storage units appear to be highly promising due to the growing desire for environmentally friendly and advanced materials. Despite these advancements, some important challenges remain, including lignin variability, a lack of standardized extraction and processing processes, limited large-scale production capabilities, and inadequate long-term efficiency assessments. Advancing the commercialization and broad acceptance of lignin-based composites as sustainable substitutes for materials derived from petroleum will require bridging these research gaps through flexible and scalable alteration technologies, sophisticated processing techniques, and global industry standardization.

Author Contributions:

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