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FABRICATION OF LIGNIN-BASED FIBROUS COMPOSITES BY ELECTROSPINNING FOR ENERGY STORAGE APPLICATIONS

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Abstract. Lignin-based electrodes are generating significant interest as a promising solution to address the growing demand for cheap, sustainable, and environmentally responsible materials for modern energy storage devices. The global energy transition necessitates replacing traditional, limited carbon sources with abundant, renewable alternatives like lignin. As the second most common organic polymer in nature, lignin possesses a number of characteristic advantages, including high carbon content, structural diversity, and the presence of reactive functional groups, making it an attractive raw material for producing advanced electrochemical materials. The main purpose of this work is to summarize the latest achievements in the field of obtaining, refining, and chemical modification of lignin, as well as its transformation into porous carbon structures suitable for electrochemical application. Methodologically, this review explores modern fabrication technologies, including electrospinning, followed by critical processing stages such as thermal stabilization and carbonization, with a focus on the continuous production of lignin-based fibrous composites for supercapacitors. The results show significant progress in the development of lignin-based electrodes; for instance, activated carbon derived from lignin has achieved a specific capacitance of 263.46 F/g at 40 mA/g current density, and electrospun carbon nanofibers have reached up to 442.2 F/g. This performance confirms lignin's potential as an eco-friendly, low-cost, and high-performance electrode material. Its wide availability and customizable chemical composition establish lignin as a promising candidate for the next generation of sustainable energy storage technologies.

Keywords: energy storage, lignin, battery, electrodes, supercapacitor

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ЭНЕРГИЯ САҚТАУ ЖҮЙЕЛЕРІНДЕ ҚОЛДАНУҒА АРНАЛҒАН ЛИГНИН НЕГІЗІНДЕГІ ТАЛШЫҚТЫ КОМПОЗИТТЕРДІ ЭЛЕКТРОСПИННИНГ ӘДІСІМЕН АЛУ

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Аннотация. Лигнин негізіндегі электродтар заманауи энергия сақтау құрылғылары үшін арзан, тұрақты және экологиялық таза материалдарға деген өсіп келе жатқан сұранысты шешудің перспективалы жолы ретінде үлкен қызығушылық тудыруда. Жаһандық энергетикалық көшу дәстүрлі, шектеулі көміртекті көздерін лигнин сияқты мол, жаңартылатын баламалармен алмастыруды қажет етеді. Табиғаттағы екінші ең көп таралған органикалық полимер бола отырып, лигниннің жоғары көміртекті құрам, құрылымдық әртүрлілік және реактивті функционалдық топтардың болуы сияқты бірқатар сипаттамалық артықшылықтары бар, бұл оны жетілдірілген электрохимиялық материалдарды өндіру үшін тартымды шикізат етеді. Бұл жұмыстың негізгі мақсаты – лигнинді алу, тазарту және химиялық модификациялау, сондай-ақ оны электрохимиялық қолдануға жарамды кеуекті көміртекті құрылымдарға айналдыру саласындағы соңғы жетістіктерді қорытындылау. Әдістемелік тұрғыдан, бұл шолу суперконденсаторлар үшін лигнин негізіндегі талшықты композиттерді үздіксіз өндіруге баса назар аудара отырып, электроспиннингті, одан кейінгі термиялық тұрақтандыру және карбонизация сияқты маңызды өңдеу кезеңдерін қамтитын заманауи өндіріс технологияларын зерттейді. Нәтижелер осы электродтарды дамытудағы елеулі өнімділік прогресін көрсетеді; мысалы, лигниннен алынған белсендірілген көмір 40 мА/g төмен тоқ тығыздығында 263,46 F/g айтарлықтай меншікті сыйымдылыққа қол жеткізді, ал күрделі электроспиннингті көміртекті наноталшықтар 442,2 F/g дейінгі ерекше мәндерді көрсетті. Бұл өнімділік лигниннің экологиялық таза, арзан және жоғары өнімді электродты материал ретіндегі әлеуетін растайды. Оның кең қолжетімділігі мен реттелетін химиялық құрамы лигнинді тұрақты энергия сақтау технологияларының келесі буыны үшін перспективалы кандидат ретінде бекітеді.

Түйін сөздер: энергия сақтау, лигнин, аккумулятор, электродтар, суперконденсатор

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ПОЛУЧЕНИЕ ВОЛОКНИСТЫХ КОМПОЗИТОВ НА ОСНОВЕ ЛИГНИНА МЕТОДОМ ЭЛЕКТРОСПИННИНГА ДЛЯ ПРИМЕНЕНИЯ В СИСТЕМАХ ХРАНЕНИЯ ЭНЕРГИИ

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Аннотация. Электроды на основе лигнина вызывают растущий интерес как перспективное решение для удовлетворения увеличивающегося спроса на дешёвые, устойчивые и экологически безопасные материалы для современных устройств хранения энергии. Глобальный энергетический переход обусловливает необходимость замены традиционных, исчерпаемых углеродных ресурсов на обильные и возобновляемые альтернативы, такие как лигнин. Являясь вторым по распространённости природным органическим полимером, лигнин обладает рядом уникальных преимуществ, включая высокое содержание углерода, структурное разнообразие и наличие реакционноспособных функциональных групп. Эти характеристики делают его привлекательным сырьём для получения передовых электрохимических материалов. Основная цель данной работы — обобщить современные достижения в области выделения, очистки и химической модификации лигнина, а также его последующего превращения в пористые углеродные структуры, пригодные для электрохимического применения. С методологической точки зрения в обзоре рассматриваются актуальные технологии получения электродных материалов, включая электроспиннинг (электроформование), за которым следуют ключевые стадии обработки, такие как термическая стабилизация и карбонизация. Особое внимание уделено непрерывным технологическим маршрутам формирования волокнистых композитов на основе лигнина, предназначенных для суперконденсаторов. Полученные результаты демонстрируют значительный прогресс в создании высокоэффективных электродов. Так, активированный углерод, синтезированный из лигнина, достиг удельной ёмкости 263,46 Ф/г при плотности тока 40 мА/г, а сложные углеродные нановолокна, сформированные методом электроспиннинга, показали исключительные значения удельной ёмкости до 442,2 Ф/г. Эти показатели подтверждают потенциал лигнина как экологически чистого, недорогого и высокоэффективного электродного материала. Его широкая доступность и вариативный химический состав закрепляют за лигнином статус одного из наиболее перспективных кандидатов для технологий хранения энергии следующего поколения.

Ключевые слова: хранение энергии, лигнин, аккумулятор, электроды, суперконденсатор

1. Introduction. The rapid development of the global economy and the increasing human demand for energy storage devices are leading to a sharp rise in global energy consumption. Currently, the extraction and consumption of energy from the world's resources and fossil fuels are causing an energy crisis. It is well known that these resources are finite and cannot be used continuously (Abolghasemi Fakhri L et al, 2012). Projections suggest that by 2040-2050, the world's energy supply needs will double, requiring significant additional funding for the development of energy production technologies. The current reserves of global fossil fuels are expected to be depleted soon. Therefore, the development and advancement of cutting-edge technologies in energy storage and production is a crucial issue (Al-Abduljabbar & Farooq, 2023).

The design and improvement of energy-providing devices require the use of durable and environmentally friendly materials. In this regard, the use of traditional metallurgical metals is inefficient due to their high density (weight) and relatively low fatigue resistance. Consequently, interest in composite materials is growing (Ago et al, 2016). They possess mechanical and strength characteristics similar to metals while being lighter compared to other materials. The focus of global scientists is increasingly directed towards the research of new energy sources and energy storage devices. One promising solution in this research direction is the use of lignin as an electrode material for energy storage devices (Ago et al, 2016). Lignin can improve the efficiency of energy storage devices, reduce their cost and toxicity, and enable the production of "green" energy devices.

Lignin, the second most common organic polymer in nature, possesses a number of characteristic advantages, including high carbon content, structural diversity, and the presence of reactive functional groups, which makes it a very attractive raw material for the manufacture of advanced electrochemical materials (Liu et al, 2021).

However, there is a lack of comprehensive research in the scientific literature on lignin-based electrode materials for energy storage devices. Therefore, the main purpose of this work is to summarize the latest achievements in the field of obtaining, refining, and chemical modification of lignin, as well as its transformation into porous carbon structures suitable for electrochemical use. This article primarily provides a review of lignin-based electrode materials for energy storage. The article will first discuss the classification and extraction processes of lignin, as well as the preparation methods of lignin-based electrode materials and their detailed applications in energy storage devices, including supercapacitors and batteries. (Fig. 1) (Liu et al, 2021).

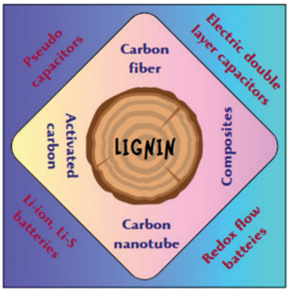

Figure 1 - Graphical representation of lignin-based electrode materials in energy storage application

2.Materials and methods

2.1 Lignin: characterization and modification methods

Lignin is a promising, low-cost, non-toxic, and highly effective modifier suitable for use as graphene-based supercapacitor electrode materials (Ago et al, 2016). Lignin can be mixed with graphene oxide in any ratio and contributes to the stabilization of reduced graphene oxide through π-π interactions. One study reported the synthesis of lignin-based bio-slag/graphene composites using a rapid and simple co-precipitation method (Melati et al, 2019). Lignin prevents the restacking (re-agglomeration) of graphene oxide and promotes the formation of small graphitic domains that enhance its electrical conductivity. Lignin is a large-volume byproduct of the wood processing industry and represents an environmentally sustainable and recyclable natural raw material (Nazhipkyzy et al, 2024). As shown in Figure 2, lignin consists of three main monomers (sinapyl alcohol, coumaryl alcohol, and coniferyl alcohol) and various functional groups (carboxyl and methoxyl) (Wang et al, 2023).

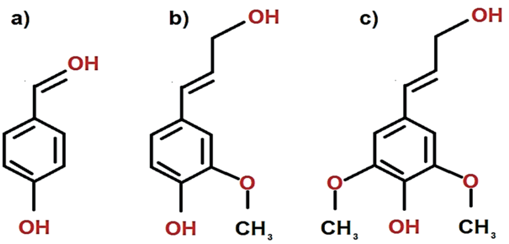

Figure 2 - The three main constituent monomers of lignin

Lignin's interaction with various polymeric compounds, including synthetic polymers (e.g., polyethylene oxide (PEO) and polypropylene) and biodegradable biopolymers (e.g., soy protein, polylactic acid (PLA), and bacterial cellulose), to form stable polymer composites has been extensively studied. As the second most abundant natural polymer after cellulose, lignin can be obtained in large quantities and at low cost as a byproduct from the cellulose-paper industry (Pakkang et al, 2022). Thus, utilizing lignin as a precursor is significantly advantageous (Pakkang et al, 2020). For example, the use of lignin for producing high-performance electrode materials such as carbon nanofibers has been widely reported. Currently, there is an increasing demand for high-performance composite materials in energy storage systems. We aimed to explore the potential of electrospinning in the morphology of carbon nanofibers using biomass-derived lignin as a renewable source, while surface area, porosity, and flexibility play a crucial role in supercapacitor electrochemistry.

Lignin's traditional applications are well-established in areas like cement additives, wood adhesives, and drilling fluids for oil wells. However, its low cost and abundant availability necessitate the exploration of novel, high-value applications. Recent investigations have demonstrated the successful utilization of lignin-based polymers as sorbents, flocculants, antioxidants, and components in energy storage layers (Lievonen et al, 2016). The molecular weight distribution of lignin exhibits significant heterogeneity, influenced by both the inherent structural variations across different plant species and the specific extraction methodologies employed. The number-average molecular weight (Mn) of lignin typically fluctuates between approximately 1000 and 5000 g/mol, while the weight-average molecular weight (Mw) can extend from 2000 to 50,000 g/mol, underscoring the intricate and heterogeneous nature of lignin. Lignin is broadly categorized into three primary types:

- softwood lignin, predominantly composed of guaiacyl (G) units (around 90%);
- hardwood lignin, which consists of a blend of guaiacyl (G) and syringyl (S) units;
- herbaceous lignin, encompassing all three units – guaiacyl (G), p-hydroxyphenyl (H), and syringyl (S) (Tiz et al, 2024).

Among the array of functional groups present, hydroxyl and carboxyl groups play a particularly influential role in dictating the polymer's properties. These functional groups establish a delicate equilibrium between the hydrophilic and hydrophobic characteristics of lignin macromolecules, concurrently modulating their susceptibility to hydrolytic degradation under diverse reaction conditions. The type of lignin and the composition of its structural units vary considerably depending on the plant species. For instance, herbaceous plants contain all three types of structural units, with the content of H units ranging approximately from 10% to 25%, while G and S units each constitute about 25% to 50%. Softwood consists solely of G units; in contrast, hardwood contains a moderate amount of G units (25%–50%) alongside a significantly higher proportion of S units (50%–75%).

Furthermore, the proportion of specific linkage types differs among various lignins. Ether linkages (C–O) represent the dominant type, accounting for approximately 70% of the total linkages. Following this are β-O-4 (40%–60%), α-O-4 (5%–7%), and 4-O linkages. The remaining 30% comprises carbon-carbon (C–C) linkages, with the most prevalent being 5-5 (6%–16%), β-5 (6%–11%), β-1, β-β, and others (Melati et al, 2019).

2.2 Electrospinning method

Electrospinning is a versatile, yet simple and cost-effective method for fabricating nanofibers and nanofibrous membranes in a wide range of applications, from medicine to environmental and energy fields (Al-Abduljabbar & Farooq, 2023, Wang et al, 2023). It can produce non-woven mats made of continuous fibers with small diameters, leading to reduced weight, increased flexibility, and high active surface area. Nevertheless, electrospinning is an inherently complex process influenced by various parameters such as molecular entanglement, viscosity, surface tension, and conductivity. Typically, polyacrylonitrile (PAN) is used for electrospinning nanofibers due to its excellent solubility, solution entanglement, and process stability (Jauhari et al, 2021). However, the high cost of this petrochemical-based synthetic polymer is an economic factor limiting its widespread use in both high-level development and commercialization. Therefore, other alternative and practical sources for carbon-based electrospun nanofibers have been extensively sought (Tiz et al, 2024).

Lignin, extracted from the constituent part of plant cell walls, is the second most abundant natural biopolymer. It can be obtained from several byproducts of biorefineries, such as in the cellulose-paper industry. More than 70 million tons of lignin are accumulated annually. The globular molecules of lignin contain a high aromatic content, making them an efficient carbon source. Furthermore, lignin exhibits thermal stability, biodegradability, and a stable chemical structure, making it a promising candidate for producing carbon nanofibers for supercapacitor electrodes. Recent studies show that activated lignin-based carbon fibers exhibit relatively high specific capacitance and power density (Melati et al, 2019).

Supercapacitors primarily consist of electrode materials, electrolytes, current collectors, and separators. Among these, electrode materials, as the core component for energy storage, critically influence the electrochemical performance of supercapacitors. The efficacy of supercapacitors is intrinsically linked to the nature of the electrode material. Electrospinning emerges as a straightforward yet potent technology employed across medical, environmental, and energy sectors for the creation of nanofibers and membranes (Pakkang et al, 2019). When a high-voltage electric field is applied to a polymer solution, the initiation of fibers occurs at the apex of the "Taylor cone". Initially, the trajectory of the fiber is predominantly linear (stable region). Beyond a certain threshold distance, the fiber's path transitions into a complex configuration (bending instability region).

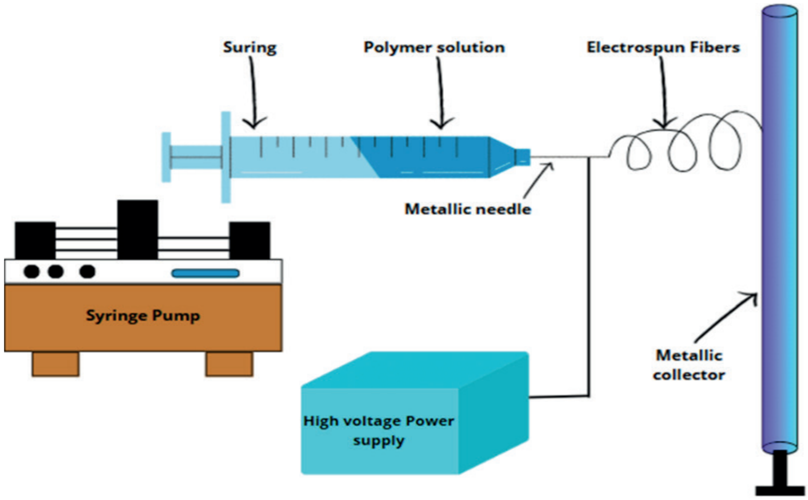

Figure 3 - Schematic diagram of fiber production from polymer solution via electrospinning, redrawn and adapted from (Liu et al, 2021)

2.3 Lignin production methods

2.3.1 Industrial relevance and applications of lignin

Lignin is an abundant, renewable biopolymer with significant potential in various industrial applications. Its incorporation into biodegradable polymers enhances mechanical and thermal properties; for example, the thermal stability of polylactic acid (PLA) improves upon lignin integration. Lignin is also used to reinforce carbon fibers and enhance polymer composites in the rubber industry. Traditionally, lignin has been applied in adhesives for wood panels due to its abundance of phenolic groups, making it a promising replacement for phenol in phenol-formaldehyde (PF) resins. PF resins are widely used in plywood, particleboard, and other wood composites; however, they exhibit high toxicity and price volatility. Replacing PF resins with environmentally friendly lignin is economically and ecologically advantageous, although industrial utilization is limited by the low reactivity of native lignin (Yuan et al, 2014).

In their study, Yuan et al (2014) developed a bio-based adhesive by combining ammonium lignosulfonate (MAL) with polyethylenimine (PEI). The resulting MAL/PEI adhesive demonstrated superior mechanical strength, modulus, and adhesion compared to unmodified MAL or PEI-based adhesives, highlighting the potential of chemically modified lignin for high-performance applications.

The solubility of lignin in organic solvents also restricts its utilization. For example, Kraft lignin can be partially depolymerized using basic catalysis in supercritical methanol and subsequently converted into lignin polycarboxylic acid (LPCA). LPCA functions effectively as a curing agent for epoxy resins, performing comparably to commercial anhydride-based hardeners. Despite being the second most abundant biopolymer after cellulose, only a small fraction of lignin's annual production is applied in material science and chemical industries due to structural complexity, heterogeneity, and incompatibility with many matrices (Tong et al, 2023).

2.3.2 Biosynthesis of native lignin

The biosynthesis of lignin has been studied for over a century. Native lignin is synthesized via enzymatic polymerization of three main alcohol precursors: sinapyl alcohol, coniferyl alcohol, and p-coumaryl alcohol. These precursors are produced from L-phenylalanine catalyzed by specific enzymes, transported to the cell wall by glucosides, and polymerized through the action of laccase and peroxidase enzymes, forming lignin (Al-Abduljabbar & Farooq, 2023).

The primary monolignols give rise to three structural units: syringyl (S), guaiacyl (G), and p-hydroxyphenyl (H), differing by the degree of methoxylation on the benzene ring. Softwood lignin mainly consists of G units (90–95%), hardwood lignin contains a mix of S and G units, while herbaceous plants include all three types. The ratios of S, G, and H units depend on plant species and pretreatment methods, and these ratios critically influence lignin's properties.

Lignin monomers are linked via ether or carbon-carbon bonds, forming a diverse array of substructures. The β-O-4′ ether linkage predominates, accounting for approximately 50% of internal linkages, and is highly reactive during depolymerization. Other linkages include β-β′, β-5′, β-1′, and 5-5′, with varying abundance depending on lignin type. Functional groups such as hydroxyl, benzyl, methoxyl, ether, and carboxyl contribute to lignin's amphiphilic nature and reactivity. Hydroxyl groups, categorized as aliphatic or phenolic, are particularly important for chemical modifications including alkylation, esterification, and phenolation. Carboxyl groups, though present in small amounts in native lignin, can increase after chemical modification, enhancing solubility and reactivity.

2.3.3 Lignin isolation and production methods

In laboratory settings, lignin is often extracted for structural characterization using several methods.

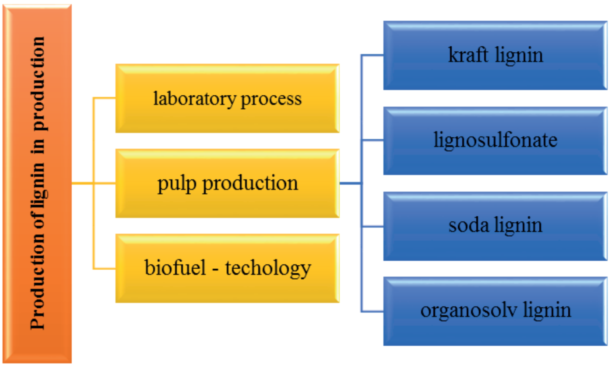

Figure 4 - Classification of industrial methods for lignin production

Milled Wood Lignin (MWL) is obtained from milled biomass using water and neutral solvents, such as dioxane, under reflux. This method preserves the lignin structure but typically yields less than 40% and may contain residual carbohydrates. Cellulolytic Enzyme Lignin (CEL) is produced by hydrolyzing cellulose, resulting in higher lignin yield while maintaining its structural integrity. An improved version, Enzymatic Mild Acidolysis Lignin (EMAL), incorporates a small amount of hydrochloric acid during extraction, achieving yields of up to 70% with approximately 90% purity and fewer lignin-carbohydrate complexes.

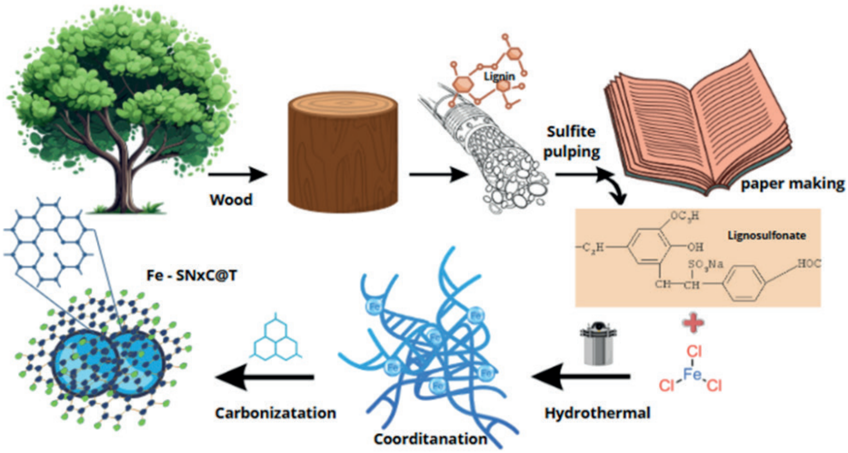

Figure 5 - Methods of lignin production and conversion, redrawn and adapted from (Liu et al, 2019)

On an industrial scale, lignin is obtained through various pulping processes. Kraft lignin is produced via alkaline pulping using sodium hydroxide and sodium sulfide, which cleaves α- and β-ether linkages and allows lignin precipitation upon acidification. Kraft lignin contains hydrophobic thiol groups, contributing to a sulfur content of 1–2%. Sulfite lignin is derived using acidic pulping, producing water-soluble lignosulfonates that contain hemicellulose and find applications in adhesives, batteries, dispersants, and surfactants. Soda lignin, obtained from soda or soda-anthraquinone pulping, has high purity, low molecular weight, and is sulfur-free, making it suitable for chemical modification. Organosolv lignin is extracted with organic solvents such as ethanol or acetic acid, exhibits high solubility in alkaline solutions and many organic solvents, possesses a uniform molecular weight, is sulfur-free, and requires minimal modification, making it attractive for biomaterial synthesis.

Aims at comprehensive utilization of biomass by separating cellulose, hemicellulose, and lignin. Pretreatment (chemical, physical, or physicochemical) is crucial to enhance enzymatic hydrolysis efficiency. Alkaline and acidic media differently affect lignin structure, while steam explosion and hot water treatment partially dissolve lignin. Integration of pretreatment methods improves production efficiency, but further research is needed to maximize lignin utilization in biorefineries (Tong et al, 2023).

2.3.4 Challenges and opportunities in lignin utilization

Despite its abundance, lignin's industrial application is limited due to low solubility, heterogeneous molecular weight, and incompatibility with many matrices. Chemical modification, such as formation of MAL/PEI adhesives, LPCA, or functionalized derivatives, enhances reactivity and widens potential applications. Optimizing extraction, depolymerization, and chemical modification techniques remains a major focus to unlock high-value applications in materials science and energy storage.

3.Results and discussion

3.1 Application of lignin-based electrodes in energy storage systems

3.1.1 Energy storage mechanisms

The energy storage mechanism of supercapacitors depends on the charge accumulation and conversion capabilities of their electrode materials, leading to their classification into electrochemical double-layer capacitance (EDLC) and pseudocapacitance (PC). Devices storing energy via the electrochemical double layer are termed EDLCs, while those employing pseudocapacitance are designated as PCs (Fig. 6) (Liu et al., 2021).

EDLCs store energy at the electrode–electrolyte interface. Carbonaceous materials—including activated carbon, carbon fibers, carbon nanotubes, graphene, and carbon aerogels—are widely used as electrodes for EDLCs due to their high specific surface area, porosity, abundant active sites, and favorable electrical conductivity. These properties facilitate short electronic or ionic transport pathways, granting EDLCs high power density and long cycling stability.

Pseudocapacitors, on the other hand, store energy via rapid and reversible redox reactions at or near the electrode surface (Wang et al., 2023). They typically exhibit higher specific capacitance and energy density than EDLCs but lower power density and shorter cycling life. Conductive polymers, transition metal oxides, and sulfides are common electrode materials for PCs.

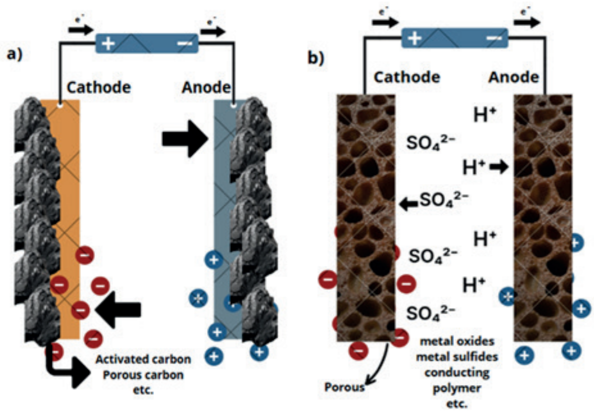

Figure 6 - Schematic diagram of the energy storage mechanism for (a) electric double-layer capacitors (EDLCs) and (b) pseudocapacitors (PCs), redrawn and adapted from (Liu et al, 2021)

3.1.2 Lignin as an electrode precursor

Lignin-derived carbon materials are attracting attention for EDLCs due to their high carbon content and low cost (Jauhari et al., 2021). The quinone structures in lignin and its derivatives provide redox activity, enabling their application in pseudocapacitors. The specific preparation methodologies and energy storage mechanisms of lignin-based electrodes will be detailed in Section 3.2 (Schlee et al., 2019).

Carbon fibers, derived from renewable plant fibers such as bamboo or cannabis, possess low density, high mechanical strength, and excellent conductivity, making them suitable for supercapacitors and batteries. Polymers like polyacrylonitrile (PAN), polyethylene glycol (PEG), and polyvinyl alcohol (PVA) serve as precursors, with PAN being the most widely used due to its mechanical strength and high carbon content. However, its high cost motivates the search for alternative, low-cost precursors. Lignin, with a carbon content exceeding 60%, is a promising candidate for producing carbon fibers (Schlee et al., 2019).

Activated carbon (AC) is commonly used for EDLC electrodes due to its large specific surface area, electrical conductivity, chemical and thermal stability, and well-developed porous structure (Tong et al., 2023).

3.2 Comparative performance summary of lignin-based electrodes

3.2.1 Physical and chemical activation methods

Lignin-based activated carbon (AC) can be prepared via physical or chemical activation.

Physical activation typically involves two stages: carbonization followed by activation, in which oxidizing gases (O_2, CO_2, or steam) generate a porous architecture through chemical gasification.

Chemical activation entails mixing lignin-derived carbon with activating agents (e.g., $ZnCl_2$, KOH, K_2CO_3, H_3PO_4) and heating in an inert atmosphere. Carbonization and activation often occur simultaneously, producing hierarchical porous structures. Chemical activation generally yields higher specific surface areas.

Studies show that different activating agents influence electrochemical performance. AC activated with $ZnCl_2$ exhibited the lowest specific surface area, as $ZnCl_2$ primarily acts as a catalyst during dehydroxylation and dehydration. AC activated with K_2CO_3 achieved a surface area of 1585 m²/g, with a specific capacitance of 263.46 F/g at 0.04 A/g (Yu et al., 2021). KOH activation combined with microwave heating and humidified N_2 gas yielded porous carbon with abundant micropores and hierarchical structures, achieving 173 F/g capacitance (Jin et al., 2012). Hydrothermal carbonization of lignin from corn stalks followed by KOH/$Ca(OH)_2$ activation resulted in AC with hierarchical porosity and oxygen-enriched functional groups, demonstrating high energy density even at high power densities (Yu et al., 2021).

3.2.2 Performance comparison

Table 1 summarizes the performance of various lignin-based electrodes:

Table 1. Summary table of lignin-based electrodes

Precursor and method	Activation method	Specific Capacitance (F/g)	Current Density (A/g)	Cycle Stability	Ref.
Lignin (Electrospinning)	Modification by $NaNO_3$	192	0,2	~90% (after 5000 cycles)	(Schlee et al, 2019)
Lignin (Electrospinning)	KOH activation	442,2	0.1	~91% (after 5000 cycles)	(Ma et al, 2018)

Lignin (AC)	K_2CO_3 Activation	263,46	0.04	~97% (after 5000 cycles)	(Jin et al, 2012)
Lignin (AC)	$KOH/Ca(OH)_2$	291,3	0,5	~96,1% (after 5000 cycles)	(Yu et al, 2021)

This summary demonstrates that lignin-based electrodes, when appropriately activated, achieve high specific capacitance, excellent cycling stability, and hierarchical porous structures suitable for supercapacitor applications.

4. Conclusion.

Lignin and its derivatives have garnered substantial interest in energy storage systems in recent years owing to their high carbon content, abundant functional groups, natural abundance, and low cost. This review synthesizes recent advancements in the design and fabrication of lignin-based electrode materials for energy storage devices, encompassing supercapacitors and batteries. Lignin can serve as a precursor for porous carbonaceous materials, while lignin and its derivatives can be directly employed as active materials, both presenting as promising electrode candidates for energy storage. The key finding shows that while activated carbon derived from lignin has achieved a high specific capacitance, reaching 263.46 F/g, electrospun carbon nanofibers can achieve superior performance, such as 442.2 F/g, demonstrating the high potential of engineered fibrous structures.

Nevertheless, the development of lignin-based electrode materials remains in its nascent stages, necessitating further research for practical implementation in real-world energy storage devices. The porosity and pore dimensions of electrode materials exert a significant influence on the electrochemical performance of energy storage devices. Currently, the production of porous carbonaceous materials from lignin predominantly yields microporous structures. Achieving well-engineered pore architectures in lignin-derived carbon remains a complex and costly endeavor, thus demanding intensified efforts to obtain multi-layered porous lignin-derived carbon materials with controlled mesopore and macropore distributions. Future research should focus on designing lignin-derived carbon with hierarchical pore structures and improving the cycling stability of lignin/conductive polymer hybrid electrodes to fully realize their potential in energy storage applications

References

Abolghasemi Fakhri L., Ghanbarzadeh B., Dehghannya J., & Entezami A.A. (2012) The effects of montmorillonite and cellulose nanocrystals on physical properties of carboxymethyl cellulose/poly (vinyl alcohol) blend films. Journal of Industrial & Polymer Science and Technology, DOI: 10.22063/JIPST.2013.610 (in English).

Al-Abduljabbar A., Farooq I. (2023) Electrospun Polymer Nanofibers: Processing, Properties, and Applications. Polymers, 15(1). — P. 65. (in English)

Ago M., Borghei M., Haataja J.S., & Rojas O.J. (2016) Mesoporous carbon soft-templated from lignin nanofiber networks: Microphase separation boosts supercapacitance in conductive electrodes. RSC Advances, 6(89). — P. 85802–85810. (in English)

Liu H., Xu T., Liu K., Zhang M., Liu W., Li H., Du H., & Si C. (2021) Lignin-based electrodes for energy storage application. Industrial Crops and Products, 165. — P. 113425. (in English)

Melati R.B., Shimizu F.L., Oliveira G., Pagnocca F.C., de Souza W., Sant'Anna C., & Brienzo M. (2019) Key factors affecting the recalcitrance and conversion process of biomass. BioEnergy Research, 12. — P. 1–20. (in English)

Nazhipkyzy M., Maltay A. B., & Seilkhanov T.M. (2024) Synthesis of Carbon Nanofibers from Lignin Using Nickel for Supercapacitor Applications. Fibers, 12(10), 87. DOI: 10.3390/fib12100087 (in English)

Wang H., Fu F., Huang M., Feng Y., Han D., Xi Y., Xiong W., Yang D., & Niu L. (2023) Lignin-based materials for electrochemical energy storage devices. Nano Materials Science, 5(2). — P. 141–160. DOI: 10.1016/j.nanoms.2022.01.002 (in English).

Jauhari J., Suharli A.J., Nawawi Z., & Sriyanti I. (2021) Synthesis and characteristics of polyacrylonitrile (PAN) nanofiber membrane using electrospinning method. Journal of Chemical Technology and Metallurgy, 56(4). — P. 698–703. (in English)

Pakkang N., Suzuki S., Shigetomi K., & Uraki Y. (2022) Assembly of electric double-layer capacitors with hardwood kraft lignin-based electrodes and separator together with ionic liquid electrolyte. Holzforschung, 77(2). DOI: 10.1515/hf-2022-0143 (in English).

Pakkang N., Kumar M., Taira S., Koda K., Shigetomi K., & Uraki Y. (2020) Preparation of kraft lignin-based activated carbon fiber electrodes for electric double layer capacitors using an ionic liquid electrolyte. Holzforschung, 74(6). DOI: 10.1515/hf-2019-0291 (in English).

Lievonen M., Valle-Delgado J.J., Mattinen M.-L., Hult E.-L., Lintinen K., Kostiainen M.A., Paananen A., Szilvay G.R., Setälä H., & Österberg M. (2016) A simple process for lignin nanoparticle preparation. Green Chemistry, 18(5). — P. 1416–1422. (in English)

Tiz D.B., Tofani G., Vicent, F.A., Likozar B. (2024) Chemical synthesis of monolignols: Traditional methods, recent advances, and future challenges in sustainable processes. Antioxidants, 13(11). — 1387 p. (in English)

Pakkang N., Koda K., Uraki Y. (2019). Development of lignin-based electrode for high performance electric double layer capacitor with ionic liquid as an electrolyte. Holzforschung, 73(10). — P. 913–920. (in English)

Yuan Y., Guo M., & Liu F. (2014) Preparation and Evaluation of Green Composites Using Modified Ammonium Lignosulfonate and Polyethylenimine as a Binder. BioResources, 9(1). — P. 836–848. (in English).

Tong Y., Yang J., Li J., Cong Z., Wei L., Liu M., Zhai S., Wang K., & An Q. (2023) Ligninderived electrode materials for supercapacitor applications: progress and perspectives. Journal of Materials Chemistry A, 11. — P. 1061–1082. DOI: 10.1039/D2TA07203C (in English)

Schlee P., Herou S., Jervis R., Shearing P.R., Brett D.J.L., Baker D., Hosseinaei O., Tomani P., Murshed M.M., Li Y., Mostazo-López M. J., Cazorla-Amorós D., Jorge Sobrido A.B., & Titirici M.-M. (2019) Free-standing supercapacitors from Kraft lignin nanofibers with remarkable volumetric energy density. Chemical Science, 10. — P. 2980-2988. DOI: 10.1039/C8SC04936J (in English).

Ma C., Li Z., Li J., Fan Q., Wu L., Shi J., & Song Y. (2018) Lignin-based hierarchical porous carbon nanofiber films with superior performance in supercapacitors. Applied Surface Science, 456. — P. 568–576. DOI: 10.1016/j.apsusc.2018.06.189 (in English).

Jin X.-J., Yu Z.-M., & Wu Y. (2012) Preparation of activated carbon from lignin obtained by straw pulping by KOH and K_2CO_3 chemical activation. Cellulose Chemistry and Technology, 46(1–2). — P. 79–85. (in English).

Yu L., Hsieh C.-T., Keffer D.J., Chen H., Goenaga G.A., Dai S., Zawodzinski T.A., & Harper D.P. (2021) Hierarchical lignin-based carbon matrix and carbon dot composite electrodes for high-performance supercapacitors. ACS Omega, 6(11). — P. 7709–7718. https://doi.org/10.1021/acsomega.1c00448 (in English).

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