ISSN: 2224-5286 (Print)
ISSN: 2518-1491 (Online)

ACADEMIC SCIENTIFIC JOURNAL OF CHEMISTRY

№4
2025

ISSN 2518-1491 (Online),
ISSN 2224-5286 (Print)

CENTRAL ASIAN ACADEMIC
RESEARCH CENTER

ACADEMIC SCIENTIFIC JOURNAL OF CHEMISTRY

4 (465)

October – December 2025

PUBLISHED SINCE JANUARY
1947 PUBLISHED 4 TIMES A YEAR

ALMATY, NAS RK

ACADEMIC SCIENTIFIC JOURNAL OF CHEMISTRY
ISSN 2518-1491 (Online),
ISSN 2224-5286 (Print)

Owner: «Central Asian Academic Research Center» LLP (Almaty).

The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Social Development of the Republic of Kazakhstan **№ KZ23VPY00121156,**
issued 05.06.2025

Thematic scope: *organic chemistry, inorganic chemistry, catalysis, electrochemistry and corrosion, pharmaceutical chemistry and technology.*

Periodicity: 4 times a year.

http://chemistry-technology.kz/index.php/en/arhiv

Editorial address: JSC «D.V. Sokolsky institute of fuel, catalysis and electrochemistry», 142, Kunayev str., of. 310, Almaty, 050100, tel. 291-62-80, fax 291-57-22, e-mail: orgcat@nursat.kz

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«ACADEMIC SCIENTIFIC JOURNAL OF CHEMISTRY»
ISSN 2518-1491 (Online),
ISSN 2224-5286 (Print)
Меншіктенуші: «Орталық Азия академиялық ғылыми орталығы» ЖШС (Алматы қ.).
Қазақстан Республикасының Ақпарат және қоғамдық даму министрлігінің Ақпарат комитетінде 05.06.2025 ж. берілген **№ KZ23VPY00121156** мерзімдік басылым тіркеуіне қойылу туралы куәлік.
Тақырыптық бағыты: *органикалық химия, бейорганикалық химия, катализ, электрохимия және коррозия, фармацевтикалық химия және технологиялар.*
Мерзімділігі: жылына 4 рет.
http://chemistry-technology.kz/index.php/en/arhiv

Редакцияның мекенжайы: 050100, Алматы қ., Қонаев к-сі, 142, «Д.В. Сокольский атындағы отын, катализ және электрохимия институты» АҚ, каб. 310, тел. 291-62-80, факс 291-57-22, e-mail:orgcat@nursat.kz

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«ACADEMIC SCIENTIFIC JOURNAL OF CHEMISTRY».
ISSN 2518-1491 (Online),
ISSN 2224-5286 (Print)

Собственник: Республиканское общественное объединение ТОО «Центрально-азиатский академический научный центр» (г. Алматы).

Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и общественного развития Республики Казахстан **№ KZ23VPY00121156,** выданное 05.06.2025 г.

Тематическая направленность: *органическая химия, неорганическая химия, катализ, электрохимия и коррозия, фармацевтическая химия и технологии.*

Периодичность: 4 раз в год.

http://chemistry-technology.kz/index.php/en/arhiv

Адрес редакции: 050100, г. Алматы, ул. Кунаева, 142, АО «Институт топлива, катализа и электрохимии им. Д.В. Сокольского», каб. 310, тел. 291-62-80, факс 291-57-22, e-mail:orgcat@nursat.kz

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ACADEMIC SCIENTIFIC JOURNAL OF CHEMISTRY
ISSN 2224–5286
Volume 4.
Number 465 (2025), 250–265

https://doi.org/10.32014/2025.2518-1491.335

UDC 678.744:628.4.04

© G. Toleutay[1,4], R.N. Tuleyeva[1,2,3], A. Taubatyrova[1,2], N.N. Gizatullina[1,2]*, 2025.
[1] Satbayev University, Almaty, Kazakhstan;
[2] Research Institute of Advanced Materials, Almaty, Kazakhstan;
[3] Al-Farabi Kazakh National University, Almaty, Kazakhstan;
[4] University of Tennessee, Knoxville, USA.
E-mail: gizatullinanargiz.nz@gmail.com

RECENT ADVANCES IN THE APPLICATION OF LIGNIN FOR BIOBASED PACKAGING MATERIALS

Toleutay Gaukhar — PhD, Department of Chemical and Biochemical Engineering, K. Turyssov Institute of Geology and Oil and Gas Business, Satbayev University, Almaty, Kazakhstan; University of Tennesee, Knoxvile, USA,
Email: gaukhar.toleutay@gmail.com; https://orcid.org/0000-0003-0381-6665;
Tuleyeva Rysgul — PhD Candidate, Al-Farabi Kazakh National University; Research Scientist, Research Institute of Advanced Materials, Almaty, Kazakhstan,
Email: rysgultuleyeva@gmail.com; https://orcid.org/0000-0002-9691-4274;
Taubatyrova Anel — Master of Department of Chemical and Biochemical Engineering, Geology and Oil-Gas Business Institute Named After K. Turyssov, Satbayev University, Almaty, Kazakhstan; Research Scientist, Research Institute of Advanced Materials, Almaty, Kazakhstan,
Email: 0ani.lani9@gmail.com, https://orcid.org/0009-0001-1329-0372;
Gizatullina Nargiz — Master of Department of Chemical and Biochemical Engineering, Geology and Oil-Gas Business Institute Named After K. Turyssov, Satbayev University, Republic of Kazakhstan; Research Scientist, Research Institute of Advanced Materials, Almaty, Kazakhstan,
Email: gizatullinanargiz.nz@gmail.com; https://orcid.org/0000-0003-4230-1031.

Abstract. The global shift toward environmentally responsible materials has heightened interest in lignin as a sustainable alternative for the development of bio-based packaging systems. As a widely available and renewable biopolymer originating from plant biomass and industrial side streams, lignin offers unique chemical and functional properties that make it a promising component in biodegradable packaging. This review aims to provide a comprehensive analysis of recent advances in the utilization of technical lignin and lignin-based nanostructures for improving the performance of biopolymer packaging materials. The study employs a comparative analysis of scientific literature, focusing on polymer matrices such as PLA, PBAT, PVA, and starch, with particular attention to chemical modification methods including esterification, epoxidation, amidation, glyoxalation, and transamination, and their influence on interfacial compatibility, dispersion, and functional behavior. The results indicate that incorporation of lignin into biodegradable polymers enhances mechanical strength, thermal stability, barrier characteristics, UV-shielding efficiency, and antioxidant performance, while modified lignin derivatives and lignin nanoparticles contribute to improved composite homogeneity and enable advanced functionalities such as recyclability and self-healing. Key limitations including structural heterogeneity, restricted dispersion, and regulatory considerations are also discussed. Overall, the findings confirm lignin's strong potential as a high-value component for next-generation sustainable packaging materials, providing a scientific basis for the development of optimized lignin–polymer systems aimed at reducing environmental impact while maintaining or enhancing material performance.

Keywords: lignin; biopolymers; biodegradable packaging materials; nanoparticles; sustainable development

Financing. *This research was conducted as part of the targeted funding program for the project IRN BR27199103, titled "Development of Eco-Friendly Packaging Materials from Recyclable Paper and Biomass Waste with Adaptive and Enhanced Protective Properties".*

© Г. Төлеутай [1,4], Р.Н. Тулеева[1,2,3], А. Таубатырова[1,2], Н.Н. Гизатуллина[1,2]*, 2025.

[1]Сәтбаев Университеті, Алматы, Қазақстан;
[2]Жетілдірілген Материалдар Ғылыми-Зерттеу Институты, Алматы, Қазақстан;
[3]Әл-Фараби атындағы Қазақ Ұлттық Университеті, Алматы, Қазақстан;
[4] Теннесси Университеті, Ноксвилл, АҚШ.
E-mail: gizatullinanargiz.nz@gmail.com

ЛИГНИННІҢ БИОНЕГІЗДІ ҚАПТАМА МАТЕРИАЛДАРЫНДА ҚОЛДАНЫЛУЫНЫҢ СОҢҒЫ ЖЕТІСТІКТЕРІ

Төлеутай Гаухар — PhD, химиялық және биохимиялық инженерия кафедрасы, Қ. Тұрсынов атындағы Геология және мұнай-газ бизнесі институты, Сәтбаев университеті, Алматы, Қазақстан; Теннесси университеті, Ноксвилл, АҚШ,
Email: gaukhar.toleutay@gmail.com; https://orcid.org/0000-0003-0381-6665;
Тулеева Рысгуль — PhD докторант, Әл-Фараби атындағы Қазақ ұлттық университеті, Алматы, Қазақстан; Зерттеуші ғалым, Жетілдірілген материалдар ғылыми-зерттеу институты, Алматы, Қазақстан,
Email: rysgultuleyeva@gmail.com; https://orcid.org/0000-0002-9691-4274;
Таубатырова Анель — химиялық және биохимиялық инженерия кафедрасының магистры, Қ. Тұрсынов атындағы Геология және мұнай-газ бизнесі институты, Сәтбаев университеті; Зерттеуші ғалым, Жетілдірілген материалдар ғылыми-зерттеу институты, Алматы, Қазақстан,
Email: 0ani.lani9@gmail.com; https://orcid.org/0009-0001-1329-0372;
Гизатуллина Наргиз — химиялық және биохимиялық инженерия кафедрасының магистры, Қ. Тұрсынов атындағы Геология және мұнай-газ бизнесі институты, Сәтбаев Университеті, Алматы, Қазақстан; Зерттеуші ғалым, Жетілдірілген материалдар ғылыми-зерттеу институты, Алматы, Қазақстан,
Email: gizatullinanargiz.nz@gmail.com; https://orcid.org/0000-0003-4230-1031.

Аннотация. Экологиялық тұрғыдан жауапты материалдарға жаһандық бетбұрыс биоыдырайтын қаптама жүйелерін әзірлеуде лигнинге деген қызығушылықты күшейтті. Өсімдік биомассасынан және өнеркәсіптік өндірістің жанама ағындарынан алынатын кең қолжетімді әрі жаңартылатын биополимер ретінде лигнин ерекше химиялық және функционалдық қасиеттерге ие, бұл оны биополимерлі қаптама материалдарының перспективалы құрамдас бөлігі етеді. Осы шолудың мақсаты — техникалық лигнин мен лигнин негізіндегі наноқұрылымдарды биополимерлі қаптама материалдарының қасиеттерін жетілдіруде қолданудың соңғы ғылыми жетістіктеріне жан-жақты талдау беру. Зерттеу ғылыми әдебиетке салыстырмалы талдау жүргізуге негізделген және PLA, PBAT, PVA және крахмал сияқты полимерлік матрицаларға, сондай-ақ эстерификация, эпоксидтеу, амидтеу, гликоксация және трансаминация сияқты химиялық модификация әдістеріне және олардың композиттердің үйлесімділігіне, дисперсиясына және функционалдық мінез-құлқына әсеріне назар аударады. Нәтижелер лигнинді енгізу биополимерлердің механикалық беріктігін, жылулық тұрақтылығын, тосқауылдық қасиеттерін, УФ-қорғанысын және антиоксиданттық белсенділігін айтарлықтай арттыратынын көрсетеді. Модификацияланған лигнин мен лигнин нанобөлшектері композиттердің біркелкілігін жақсартып, қайта өңдеу немесе өзін-өзі қалпына келтіру сияқты кеңейтілген функцияларды іске асыруға мүмкіндік береді. Сонымен қатар құрылымдық әртектілік, дисперсияның шектелуі, қолданылатын технологиялардың күрделілігі, материалдардың ұзақ мерзімді тұрақтылығы және реттеушілік талаптар сияқты маңызды шектеулер қарастырылады. Бұл шолу лигниннің тек экологиялық таза қаптама материалдарының жаңа буынын дамыту үшін ғана емес, сонымен қатар өнеркәсіптік өндірісте тиімді, функционалды және инновациялық шешімдер ұсынуда да маңызды рөл атқаратынын көрсетеді. Жалпы алғанда, зерттеу нәтижелері лигниннің биополимерлі қаптама технологияларын жетілдіру үшін жоғары әлеуетке ие, экологиялық, функционалды және көпқырлы құнды компонент екенін растайды.

Түйін сөздер: лигнин; биополимерлер; биоыдырайтын қаптама материалдары; нанобөлшектер; тұрақты даму

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[1]Сатпаев Университет, Алматы, Казахстан;
[2] Научно-исследовательский институт передовых материалов, Алматы, Казахстан;
[3] Казахский национальный университет имени аль-Фараби, Алматы, Казахстан;
[4] Университет Теннесси, Ноксвилл, США.
E-mail: gizatullinanargiz.nz@gmail.com

ПОСЛЕДНИЕ ДОСТИЖЕНИЯ В ПРИМЕНЕНИИ ЛИГНИНА ДЛЯ БИОПОЛИМЕРНЫХ УПАКОВОЧНЫХ МАТЕРИАЛОВ

Толеутай Гаухар — PhD, кафедра химической и биохимической инженерии, Институт геологии и нефтегазового дела имени К. Турышева, Университет Сатпаева, Алматы, Казахстан; Университет Теннесси, Ноксвилл, США,
Email: gaukhar.toleutay@gmail.com, https://orcid.org/0000-0003-0381-6665;
Тулеева Рысгуль — аспирант PhD, Казахский национальный университет имени аль-Фараби, Алматы, Қазақстан; Научный сотрудник, Научно-исследовательский институт передовых материалов, Алматы, Казахстан,
Email: rysgultuleyeva@gmail.com, https://orcid.org/0000-0002-9691-4274;
Таубатырова Анель — магистр кафедры химической и биохимической инженерии, Институт геологии и нефтегазового дела имени К. Турышева, Университет Сатпаева, Алматы, Казахстан; Научный сотрудник, Научно-исследовательский институт передовых материалов, Алматы, Казахстан,
Email: 0ani.lani9@gmail.com, https://orcid.org/0009-0001-1329-0372;
Гизатуллина Наргиз — магистр кафедры химической и биохимической инженерии, Институт геологии и нефтегазового дела имени К. Турышева, Университет Сатпаева, Алматы, Казахстан; Научный сотрудник, Научно-исследовательский институт передовых материалов, Алматы, Казахстан,
Email: gizatullinanargiz.nz@gmail.com, https://orcid.org/0000-0003-4230-1031.

Аннотация. Глобальный переход к экологически безопасным материалам значительно усилил интерес к лигнину как устойчивой и многообещающей альтернативе при разработке биоразлагаемых упаковочных систем. Лигнин, являющийся широко доступным и возобновляемым биополимером растительного происхождения, а также побочным продуктом промышленных процессов, обладает уникальными химическими и функциональными свойствами, что делает его перспективным компонентом для создания высокоэффективных биополимерных материалов упаковки. Цель данного обзора — представить всесторонний анализ современных достижений в области использования технического лигнина и лигниновых наноструктур для улучшения эксплуатационных характеристик биополимерных композитов. В исследовании проведён сравнительный анализ научных публикаций, охватывающий полимерные матрицы PLA, PBAT, PVA и крахмала, а также ключевые методы химической модификации лигнина, включая эстерификацию, эпоксидирование, амидирование, гликоксалирование и трансаминирование, и их влияние на совместимость, дисперсию и функциональное поведение композитов. Полученные данные свидетельствуют, что внедрение лигнина способствует повышению механической прочности, термической стабильности, барьерных свойств, эффективности УФ-защиты и антиоксидантной активности биополимеров. Модифицированный лигнин и лигниновые наночастицы обеспечивают улучшенную однородность композитов и формируют расширенный функциональный потенциал, включая самовосстановление, возможность повторной переработки и адаптивное поведение в различных условиях эксплуатации. Кроме того, обсуждаются ограничения, связанные со структурной неоднородностью, проблемами диспергирования, долговечностью и соблюдением регуляторных требований. В целом, результаты подтверждают высокий потенциал лигнина как ценного, многофункционального и экологически безопасного компонента для создания нового поколения биополимерной упаковки с улучшенными эксплуатационными характеристиками и перспективами промышленного применения.

Ключевые слова: лигнин; биополимеры; биоразлагаемые упаковочные материалы; наночастицы; устойчивое развитие

Introduction. The widespread use of petroleum-derived plastics in packaging has led to significant environmental challenges, including persistent pollution, microplastic accumulation, and growing concerns about resource depletion and waste management (Figueiredo, 2021: 100703). In response, the development of bio-based, environmentally friendly packaging materials is gaining momentum as a strategy to mitigate ecological impact and promote a circular bioeconomy. Among potential alternatives, lignin – the second most abundant natural polymer on Earth – has emerged as a particularly promising candidate.

Each year, millions of tons of technical lignin are generated as a byproduct of the pulp and paper industry and biorefinery processes. However, only a small proportion is currently utilized in value-added applications beyond combustion (Figueiredo, 2021: 100703). Owing to its aromatic backbone, high content of functional groups (e.g., phenolic, hydroxyl, and carboxyl), inherent antioxidant properties, and hydrophobic nature, lignin has recently attracted considerable interest in the field of sustainable packaging. Lignin-based composites have demonstrated distinctive features such as ultraviolet (UV) protection, antimicrobial activity, and improved barrier performance – properties that are typically lacking in conventional fossil-derived polymers (Zubair, 2024: 467–482).

Between 2020 and 2025, research into lignin-based packaging materials has advanced considerably, with a growing body of literature addressing various aspects of their design and functionality. In this context, the work of Zubair et al. provides a comprehensive overview of lignin-based bionanocomposites tailored for active food packaging, with an emphasis on physicochemical optimization and processing strategies (Zubair, 2024: 467–482). Javed et al. demonstrated the feasibility of integrating lignin into cardboard coatings at pilot scale, supporting its industrial applicability (Javed, 2021: 1595). Furthermore, the development of oxypropylated polylactic acid-lignin composites has shown enhanced mechanical, thermal, and UV-resistant properties, indicating a viable route toward scalable production (Liu, 2023: 116552).

This review aims to provide a comprehensive overview of recent advancements in the utilization of lignin for bio-based packaging applications. Particular attention is given to lignin sources, structure-property relationships, functional performance in comparison to synthetic polymers, and chemical modification strategies such as esterification and transamination. In addition, the current limitations are discussed, and future research directions are proposed to support the transition from laboratory-scale innovations to commercially viable packaging solutions.

Materials and Methods. This review was conducted using a systematic literature survey and comparative analysis approach to evaluate recent advancements in lignin-based materials for bio-based packaging applications. Peer-reviewed journal articles, conference proceedings, and authoritative reviews published between 2020 and 2025 were selected to ensure up-to-date coverage of chemical modifications, material properties, and functional performance of lignin composites. The primary databases consulted included Web of Science, Scopus, PubMed, ScienceDirect, and Google Scholar, using keywords such as "lignin," "biopolymer packaging," "lignin nanoparticles," "chemical functionalization," "esterification," "epoxidation," "amidation," "glyoxalation," "transamination," "barrier properties," and "mechanical performance."

Inclusion criteria focused on studies reporting structural characterization of lignin, types of lignin used (kraft, organosolv, soda, or lignin nanoparticles), chemical modification strategies, and evaluation of mechanical, thermal, barrier, UV, and antioxidant properties in polymer matrices such as PLA, PBAT, PVA, and starch. Articles were also included if they provided comparative assessments of lignin's performance relative to conventional petroleum-derived polymers or described potential industrial applicability.

Data extraction involved collecting information on lignin source, molecular structure, functional group content, composite preparation methods, and resulting material properties. Where available, numerical values of tensile strength, Young's modulus, barrier performance, UV-blocking efficiency, thermal stability, and biodegradability were recorded. Structural–property relationships were summarized in tables to facilitate comparison of modification strategies, polymer compatibility, and performance outcomes. The methodology emphasizes critical evaluation of trends, limitations, and future prospects in the field of lignin-based sustainable packaging materials.

Results and discussions. ***Sources and Types of Lignin Used in Packaging Applications.*** Lignin is a structurally complex, heterogeneous aromatic polymer predominantly located in the secondary cell walls of vascular plants. Its composition and properties vary significantly depending on botanical origin. Softwoods (gymnosperms) generally contain 28-32 wt% lignin, which is primarily composed of guaiacyl (G) units. In contrast, hardwoods (angiosperms) contain 18–25 wt% lignin, comprising a mixture of guaiacyl and syringyl (S) units. Grasses (monocotyledons), on the other hand, exhibit a lignin content ranging from 10 to 30 wt%, characterized by the presence of p-hydroxyphenyl (H), guaiacyl, and syringyl units (Li, 2015: 11559–11624). The relative abundance and distribution of these monolignol-derived units (H/G/S ratio) significantly affect the physicochemical characteristics of lignin, including its reactivity, degree of crosslinking, solubility, and thermal stability. These properties are essential in determining the suitability of lignin for specific packaging applications and influence the design of functional materials based on lignin (Figure 1) (Li, 2015: 11559–11624; Norgren, 2014: 409–416).

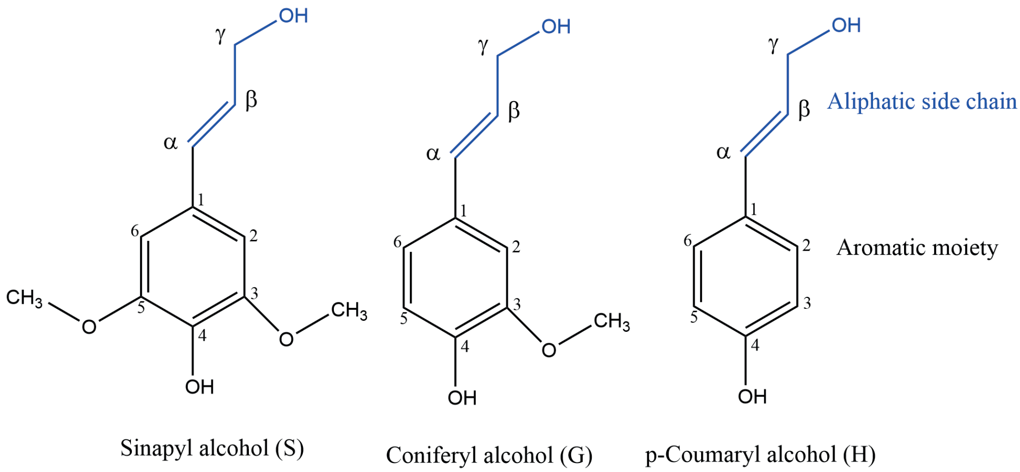

Figure 1 - Chemical structures of monolignols: the primary building blocks of lignin. Adapted from (Li, 2015: 11559–11624)

Industrial lignin fractions are derived through various pulping and biorefinery processes, each yielding materials with distinct structural and chemical characteristics. Kraft lignin is obtained under alkaline conditions in the presence of sulfur-containing compounds. This process promotes extensive cleavage of β–O–4 ether linkages and leads to the formation of condensed, guaiacyl-rich structures. As a result, kraft lignin typically exhibits high molecular weight and a high degree of crosslinking, which can pose challenges for reactivity and dispersion in polymer matrices (Wang, 2019: 449–461). Organosolv lignin is extracted using organic solvents such as ethanol, methanol, or acetone under relatively mild, often acid-catalyzed, conditions. The process yields a sulfur-free lignin with low molecular weight and minimal condensation, resulting in high purity and enhanced functionality – traits that make it particularly attractive for material applications, including packaging (Kai, 2016: 1175–1200; Qian, 2014: 2156–2163). Soda lignin, produced via sulfur-free alkaline pulping (typically from non-wood plants or agricultural residues), is less commonly investigated for packaging purposes. However, it offers a promising sulfur-free alternative, generally characterized by moderate molecular weight and good reactivity (Norgren, 2014: 409–416). The purity, molecular structure, and abundance of functional groups - such as phenolic and carboxylic moieties – differ markedly among these lignin types, thereby influencing their processability, compatibility with polymer matrices, and ultimate performance in composite packaging systems.

The suitability of various lignin types for packaging applications is influenced by multiple interrelated factors, including molecular characteristics, chemical composition, and end-use requirements. Organosolv lignin typically possesses a lower molecular weight and a higher proportion of cleavable β–O–4 linkages, which facilitates its chemical modification and enhances its miscibility with polymer matrices (Kai, 2016: 1175–1200). Kraft lignin, in contrast, contains a higher concentration of phenolic and aliphatic hydroxyl groups, offering considerable binding potential. However, due to its high degree of structural condensation, it often requires chemical pretreatment to improve its dispersibility and reactivity within composite systems (Wang, 2019: 449–461). The presence of residual sulfur compounds in kraft lignin can be a limiting factor in food-contact applications. In contrast, organosolv lignin is sulfur-free and generally exhibits higher purity, thereby presenting fewer regulatory and sensory concerns (Qian, 2014: 2156–2163). In paper-based systems, coatings incorporating organosolv lignin have been reported to enhance moisture resistance without significantly compromising mechanical strength (Javed, 2021: 1595). Alternatively, kraft lignin–derived nanoparticles demonstrate notable UV-blocking and antioxidant properties, primarily attributed to their phenolic content (Wang, 2019: 449–461).

Structural Features and Functional Properties of Lignin. Lignin is a complex polyphenolic biopolymer composed of three principal monolignol units: *p*-coumaryl alcohol (H), coniferyl alcohol (G), and sinapyl alcohol (S). Its highly heterogeneous and irregular structure gives rise to variable amounts of phenolic, aliphatic hydroxyl, and carboxyl groups, which in turn influence its chemical reactivity and interaction potential with diverse polymer matrices (Javed, 2021: 1595; Wang, 2024: n.p.). For example, lignin fractionated from wheat straw using an alkaline deep eutectic solvent (DES) system exhibited a phenolic hydroxyl content of up to 9.6 mmol/g and carboxyl group content of up to 2.5 mmol/g, significantly enhancing its reactivity and compatibility with polymeric systems (Wang, 2024: n.p.)

In addition to its functional versatility, lignin displays inherent thermal stability, making it a promising additive for improving the heat resistance of biopolymer-based composites. Polylactic acid (PLA)/lignin nanocomposites incorporating kraft lignin have shown enhanced thermal resistance relative to neat PLA, although a slight reduction in the onset temperature of thermal degradation was observed at higher lignin loadings (Ge, 2020: n.p.). The aromatic and phenolic components of lignin also contribute to its barrier properties, enabling it to reduce oxygen permeability and block ultraviolet (UV) radiation. These attributes, combined with its intrinsic antioxidant activity, offer protection against photooxidative degradation and support its application in active and functional packaging systems (Figure 2) (Javed, 2021: 1595). Moreover, the biodegradability of lignin-rich composites is closely influenced by their functional group composition. In particular, the presence of carboxyl and hydroxyl groups increases hydrophilicity and microbial accessibility, thus facilitating more efficient biodegradation.

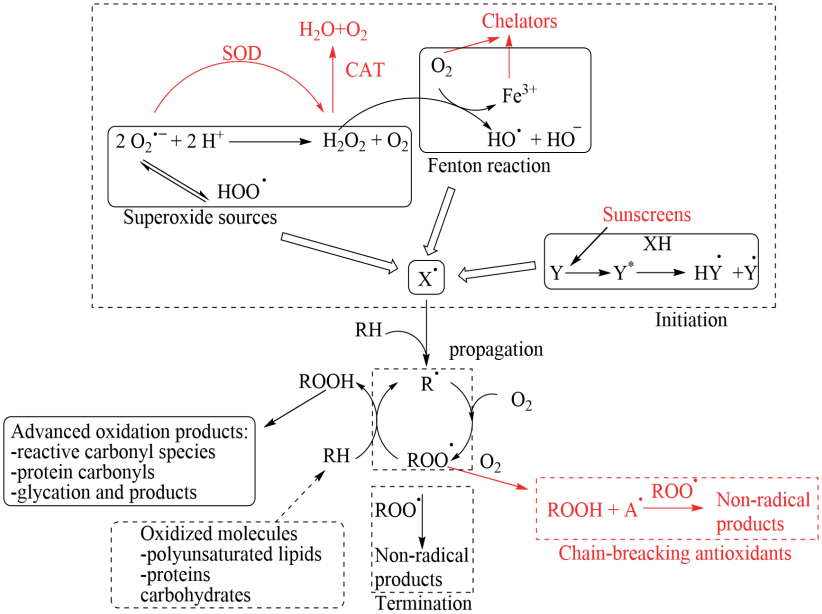

Figure 2 - Representative reactions illustrating the antioxidant mechanisms of lignin. Adapted from (Zubair, 2024: 467–482)

Compared to conventional synthetic polymers, lignin-based composites offer a unique combination of advantages and limitations that are highly dependent on the polymer matrix and modification strategy employed. For instance, polylactic acid (PLA) blends reinforced with lignin have demonstrated improved mechanical strength; however, they often exhibit a reduction in thermal transition temperatures, including the glass transition (Tg) and melting point (Tm), relative to neat PLA (Ge, 2020: n.p.). In the case of biodegradable polyesters such as poly (butylene adipate-co-terephthalate) (PBAT), the incorporation of silane-grafted lignin has been shown to enhance tensile strength, elastic modulus, and biodegradation rate – achieving up to 96% biodegradability compared to unmodified PBAT (Brodin, 2021: n.p.). Furthermore, studies on barrier performance indicate that the hydrophobic aromatic structure of lignin contributes to improved resistance against oxygen permeation and ultraviolet (UV) radiation. However, challenges related to dispersion uniformity and interfacial adhesion within the composite matrix remain significant factors that must be addressed to optimize the overall material properties (Zubair, 2024: 467–482; Boarino, 2023: 1065-1077).

Packaging Applications of Lignin–Based Materials. Lignin is increasingly utilized as a functional additive in paper coatings and biodegradable polymer films due to its capacity to enhance barrier performance and confer bioactive properties. Laboratory-scale investigations have demonstrated that the incorporation of kraft lignin into starch-based coatings significantly reduces water solubility and increases surface hydrophobicity, particularly when used in combination with crosslinking agents such as ammonium zirconium carbonate (AZC). However, certain drawbacks have been reported, including the formation of pinhole defects that may compromise coating uniformity. To overcome such limitations, hybrid formulations incorporating lignin, tannin, and ZnO nanoparticles have been developed, resulting in paper-based packaging materials with improved mechanical strength, moisture resistance, and air impermeability (Li, 2021: n.p.).

In the context of biodegradable polymer films, lignin and lignin nanoparticles (LNPs) have been successfully integrated into various matrices, including polylactic acid (PLA), polyvinyl alcohol (PVA), starch, and poly (butylene adipate-co-terephthalate) (PBAT). These lignin-based composite films exhibit enhanced mechanical properties and improved resistance to oxygen, moisture, and ultraviolet (UV) radiation, while maintaining their inherent biodegradability (Ruwoldt, 2023: n.p.; Gaikwad, 2023: n.p.).

The functionality of lignin-enriched packaging materials is strongly influenced by the dispersion quality of lignin within the polymer matrix and the nature of interfacial interactions between the components. Uniformly dispersed lignin nanoparticles have been shown to significantly improve mechanical strength, antioxidant capacity, and overall material integrity, whereas poor interfacial compatibility often results in phase separation and a decline in performance efficiency (Gaikwad, 2023: n.p.). Experimental findings suggest that incorporating lignin at moderate concentrations – typically below 10 wt% achieves an optimal balance between ultraviolet (UV) protection and visual transparency. In contrast, higher lignin loadings may adversely affect film clarity and aesthetic quality (Ruwoldt, 2023, n.p.). The antioxidant and UV-shielding properties of lignin are primarily attributed to its conjugated phenolic and carbonyl chromophores, which absorb UV radiation and function as effective radical scavengers, thereby enhancing the oxidative stability of the packaging material (Parit, 2022: n.p.; ACS review, 2023: online first).

Lignin-containing composites generally exhibit improved tensile strength and elastic modulus relative to conventional biopolymers, although these enhancements are largely dependent on the degree of compatibility between lignin and the polymer matrix, as well as on the uniformity of filler dispersion. Notably, lignin-based thermoset films and coatings have been reported to maintain high transparency in the visible spectrum while simultaneously offering effective UV protection and antioxidant functionality (Gaikwad, 2023: n.p.). In polylactic acid (PLA) systems, the grafting of lignin nanoparticles onto compatible polymers has been shown to facilitate more homogeneous dispersion, leading to increased tensile strength and enhanced oxidative stability (Gaikwad, 2023: n.p.). Recent studies consistently indicate that lignin contributes to improved barrier performance, radical scavenging activity, and UV resistance in biodegradable packaging films, provided that appropriate strategies for interfacial compatibility and dispersion are implemented (Ruwoldt, 2023: n.p.).

Chemical Functionalization of Lignin: Esterification, Epoxidation, Amidation, Glyoxalation, Transamination. Chemical modification is essential to enhance the reactivity, compatibility, and functionality of lignin for its use in packaging materials. Among the most widely used strategies are esterification, epoxidation, amidation, glyoxalation, and transamination. These pathways enable structural tailoring of lignin, facilitating better dispersion, interfacial adhesion, and integration within biodegradable polymer matrices.

Esterification with carboxylic acids, anhydrides, or acid chlorides (e.g., acetic, maleic, and succinic acids) introduces aliphatic fragments linked via ester bonds, thereby increasing hydrophobicity and enhancing polymer-filler interactions (Figure 3) (Libretti, 2024: 1234–1256). This method has been successfully applied to improve UV absorption and thermal stability.

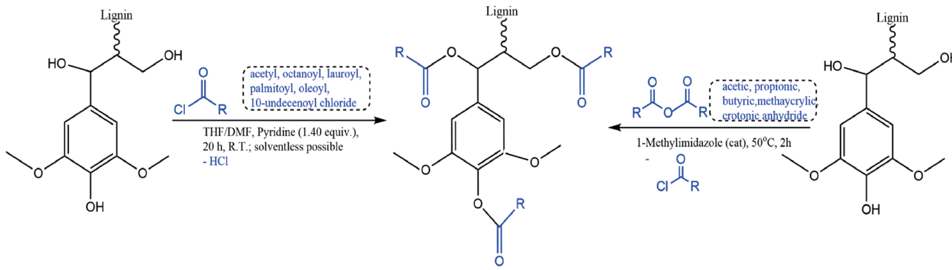

Figure 3 - Schematic representation of lignin esterification with acyl chlorides (left) and acid anhydrides (right). Adapted from (Libretti, 2024: 1234–1256)

Epoxidation, typically achieved through the reaction of lignin with epichlorohydrin under alkaline conditions, incorporates epoxy functionalities that allow lignin to act as a reactive crosslinker in thermosetting systems such as epoxy resins and polyurethanes (Figure 4) (Karoki, 2024: 7075–7096).

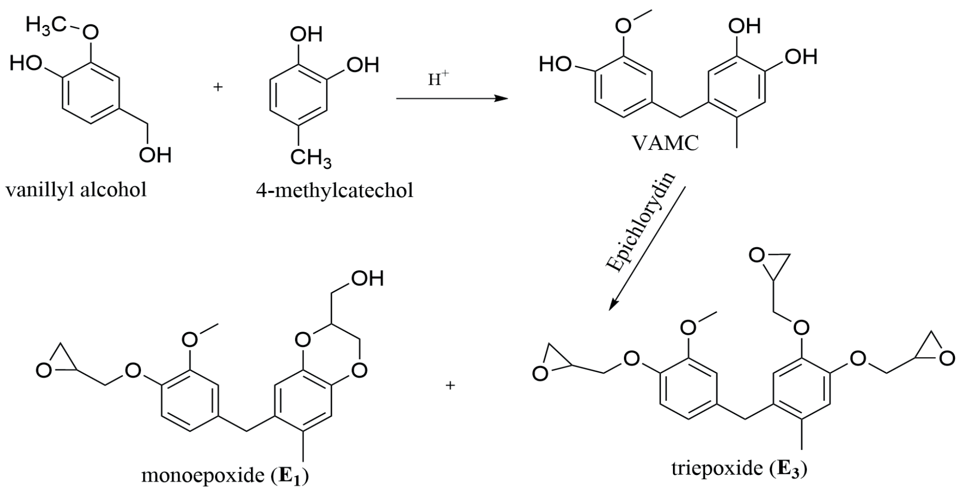

Figure 4. Schematic representation of vanillin-based epoxide synthesis. Adapted from (Karoki, 2024: 7075–7096)

Amidation and related amination strategies, such as transamination, enable the incorporation of nitrogen-containing functional groups into the lignin structure. These modifications enhance interfacial interactions with polymer matrices and enable dynamic covalent bonding, which is particularly relevant for the design of covalent adaptable networks (CANs). Notably, lignin-based vitrimers incorporating such functionalities exhibit self-healing behavior, recyclability, and thermal reprocessability (Esakkimuthu, 2022: 7075–7096).

Glyoxalation and other aldehyde-based modifications improve the crosslinking potential of lignin by introducing reactive aldehyde groups capable of forming covalent bonds with lignin's hydroxyl functionalities. This results in enhanced mechanical strength and improved adhesion within composite materials (Libretti, 2024: 1234–1256). In particular, transamination reactions involving the dynamic exchange of boronate esters or aminoacetoacetate linkages provide reversible bonding mechanisms, further facilitating the development of reprocessable and thermally re-formable lignin-based vitrimer systems (Esakkimuthu, 2022: 7075–7096).

The chemical functionalization of lignin plays a pivotal role in tailoring its performance within composite materials. Esterification enhances the compatibility of lignin with hydrophobic polymer matrices such as polylactic acid (PLA) and polybutylene succinate (PBS), promoting uniform dispersion and mechanical reinforcement, particularly at low filler loadings (≤ 10 wt.%) (Libretti, 2024: 1234–1256). Epoxidized lignin functions as a reactive compatibilizer and crosslinking agent in epoxy and polyurethane systems, leading to improved tensile strength, thermal stability, and interfacial adhesion (Karoki, 2024: 7075–7096).

Amidated and transamidated lignin derivatives support the formation of dynamic covalent networks, as exemplified by lignin-based vitrimers that exhibit self-healing properties, thermal reprocessability, and enhanced adhesion. These materials demonstrate tensile strengths approaching 17 MPa and efficient stress relaxation behavior, with activation energies ranging from 50 to 110 kJ/mol due to transamination-based exchange mechanisms (Esakkimuthu, 2022: 7075–7096).. Glyoxylated lignin, enriched in aldehyde functionalities, facilitates covalent crosslinking with hydroxyl groups, thereby improving film cohesion and water resistance – attributes that are particularly beneficial in coating formulations and flexible packaging applications (Libretti, 2024: 1234–1256).

Future Prospects and Industrial Challenges. Despite considerable progress at the laboratory scale, the industrial-scale production of lignin-based packaging materials remains constrained by several technical and regulatory challenges. One of the primary limitations is the variability in lignin composition, which depends on the botanical source and isolation method, leading to inconsistencies in physicochemical properties and impeding standardization. Moreover, the inherent polarity and limited compatibility of lignin with hydrophobic polymer matrices often result in phase separation and poor dispersion, unless compatibilizers or surface modification strategies are applied – thereby increasing process complexity and cost. Regulatory ambiguity, particularly in relation to the safety of food-contact materials and the potential migration of lignin-derived compounds, further hinders commercialization efforts (Boarino, 2023: 1065-1077).

Nonetheless, lignin holds substantial promise as a multifunctional additive in sustainable packaging systems. Its incorporation into biodegradable polymers such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and polyvinyl alcohol (PVA) can significantly enhance oxygen barrier properties, ultraviolet resistance, and antioxidant activity. Particularly, lignin nanoparticles (LNPs) have demonstrated effectiveness at low loadings (typically 3-10 wt.%), offering performance improvements without sacrificing optical transparency or biodegradability. However, the prevention of nanoparticle aggregation remains a key technical hurdle. With optimized formulation and improved interfacial compatibility, lignin-based composites may emerge as viable alternatives to conventional plastics in targeted applications such as active food packaging and fully biodegradable film technologies (Zubair, 2024: 467–482).

From an economic standpoint, lignin represents a cost-effective raw material, as it is abundantly available as a by-product of the pulp and paper industry and emerging biorefinery processes. Its valorization offers the potential to enhance the overall profitability of biomass processing chains. However, to achieve economic competitiveness with petroleum-derived polymers, it is essential to reduce the costs associated with lignin upgrading, including fractionation, purification, and chemical functionalization. Technologically, the integration of lignin valorization pathways into existing pulp mills and biorefineries offers synergistic benefits, such as improved resource efficiency and reduced greenhouse gas emissions, thereby supporting the principles of the circular bioeconomy (Boarino, 2023: 1065-1077).

Nevertheless, regulatory considerations present additional barriers. The limited availability of comprehensive data on the migration behavior and toxicological safety of lignin and its derivatives complicates their approval for food-contact applications. Achieving regulatory compliance demands extensive safety testing and the generation of detailed toxicological and analytical documentation, which often requires significant financial and institutional investment (Gaikwad, 2023: n.p.).

To provide a comparative overview of lignin-based composites, Table 1 summarizes the key structural features, modification strategies, and resulting changes in mechanical and barrier properties. It highlights how chemical and physicochemical modifications—such as oxypropylation, nanoparticle formation, silane grafting, esterification, epoxidation, transamination, glyoxalation, and hybridization with tannins or metal oxides—affect tensile strength, Young's modulus, and functional performance, including UV-shielding, water resistance, and oxygen permeability. The table facilitates identification of structure–property relationships and guides the evaluation of lignin-derived materials for sustainable biopolymer packaging applications.

Table 1. Structure–property relationships in modified lignin-based composites

Structure	Type of modification	Mechanical properties	Barrier / functional properties	Notes / Source
PLA/lignin blends	Unmodified lignin; reactive extrusion	Tensile strength at low loading increases; slight thermal transitions decreases	Oxygen permeability decreases; UV-blocking increases	Ge et al., 2020; experimental, low lignin loading

Oxypropylated lignin (PLA)	Oxypropylation (etherification)	Tensile strength increases, Young's modulus decreases; improved ductility	UV-shielding increases; moderate water vapor resistance decreases	Liu et al., 2023; confirmed at low to moderate loading
Kraft lignin nanoparticles (PLA, PBAT matrices)	Nanoparticle formation (self-assembly)	Tensile strength 10-40% depending on loading increases; improved stiffness	Strong UV-blocking; O_2 transmission decreases; moderate water barrier	Zubair et al., 2024; experimentally verified
PBAT/lignin composites with silane grafting	Silane grafting	Young's modulus and tensile strength increase; biodegradability up to 96%	Water resistance increases; gas permeability decreases	Brodin et al., 2021; experimentally verified
Organosolv lignin (paper coatings)	Unmodified; coating formulation	Improved stiffness; enhanced surface hardness	Moisture resistance increases; wettability decreases	Javed et al., 2021; confirmed for paper coatings
Kraft lignin–starch hybrid coatings	Blending; partial crosslinking	Minor in mechanical strength increases	Hydrophobicity increases; possible pinholes affecting barrier uniformity	Javed et al., 2021; data limited
Lignin/tannin/ ZnO nanoparticle coatings	Hybrid modification	Not quantified	Strong UV-blocking; water absorption decreases; air permeability decreases	Li et al., 2021; prospective / experimental data limited
Epoxidized lignin (thermoset systems)	Epoxidation	Tensile strength increases; improved crosslink density; enhanced thermal stability	Barrier properties not reported	Karoki et al., 2024; data limited to thermosets
Esterified lignin (PLA, PBS systems)	Esterification (acylation, anhydrides)	Young's modulus increases; improved dispersion; better toughness at ≤10 wt%	Hydrophobicity reported; gas barrier data limited	Libretti et al., 2024; partial data
Amidated / transaminated lignin (vitrimers)	Amidation & transamination	Tensile strength up to ±17 MPa; self-healing	Barrier properties not classical; moisture resistance improved	Esakkimuthu et al., 2022; data limited to vitrimers
Glyoxalated lignin	Glyoxalation (aldehyde crosslinking)	Cohesion increases; mechanical strength in coatings increases	Water resistance increases; film durability data limited	Libretti et al., 2024; data mainly for adhesive/ coating systems
Lignin nanoparticles (PVA-based films)	Grafting onto cellulose nanofibers	Tensile strength increases; modulus increases; improved flexibility	Strong UV protection; oxygen permeability increases	Parit et al., 2022; experimentally verified
Functional lignin coatings (LNPs + functionalization)	LNPs + functionalization	Mechanical reinforcement depends on substrate	UV-blocking; oxygen scavenging; antimicrobial	Ruwoldt et al., 2023; data limited, substrate dependent

Conclusion. Lignin is a promising component for the development of sustainable packaging materials due to its natural abundance, biodegradability, and multifunctional properties. Incorporation of lignin into biopolymer matrices improves mechanical strength, water and gas barrier performance, and provides antioxidant and UV-shielding effects. The use of lignin nanoparticles and chemically modified derivatives allows for better dispersion and enhanced compatibility with polymers such as PLA, PBAT, starch, and PVA.

Esterification, epoxidation, amidation, and other chemical functionalization methods improve interfacial interactions and enable the design of advanced material systems, including recyclable networks and self-healing composites. Despite considerable progress, challenges remain related to the heterogeneity of lignin sources, phase separation in composite systems, and limited regulatory data for food-contact applications.

Further research is needed to standardize lignin feedstocks, optimize modification techniques, and ensure compliance with safety regulations. With proper dispersion and functionalization strategies, lignin-based composites can serve as efficient, environmentally responsible alternatives to fossil-derived polymers in various packaging applications.

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ISSN 2518-1491 (Online), ISSN 2224-5286 (Print)

Ответственный редактор *А. Ботанқызы*
Редакторы: *Д.С. Аленов, Т. Апендиев*
Верстка на компьютере *Г.Д. Жадырановой*

Подписано в печать 23.12.2025.
Формат 60x88 1/8. Бумага офсетная. Печать – ризограф.
13,5 п.л. Заказ 4.

«Central Asian Academic Research Center» LLP
Алматы, Қонаев к-сі, 142