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SUSTAINABLE DYNAMIC POLYMER NETWORKS FOR PACKAGING: DEVELOPMENT AND PROSPECTS OF BIO-BASED VITRIMERS

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Abstract. *Introduction.* The development of biodegradable and recyclable polymer materials is a key priority in the context of the global environmental crisis and the growing accumulation of plastic waste. In recent years, a new class of materials-vitrimers-have been attracting significant interest due to their unique combination of thermoset-like mechanical strength and reprocess ability enabled by dynamic covalent bonding. *Objective of the study.* This review article presents current approaches to the synthesis and application of bio-based vitrimers, primarily derived from epoxidized vegetable oils (EVO). *Results and Discussion.* Chemical strategies for creating polymer networks are studied in detail, including transesterification mechanisms, catalyst selection, and crosslink density control. The potential for structural modification using natural additives such as cellulose and lignin is discussed with the aim of enhancing mechanical, barrier, and antioxidant properties. Particular attention is given to the functional performance of these materials, including thermal resistance, moisture stability, mechanical robustness, self-healing capacity, and biodegradability. Recent research highlights the potential of this eco polymers for practical implementation as packaging materials for various applications, including food, pharmaceutical, and active packaging systems with biofunctional barrier properties. *Conclusions.* Special emphasis is placed on the scalability of synthesis processes, durability under real-world conditions, and environmental safety.

Keywords. bio-based vitrimers, epoxidized vegetable oils, dynamic covalent bonds, transesterification, biodegradable packaging, cellulose, lignin, thermosetting polymers, sustainable materials, recyclability, functional polymers.

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Introduction

The accumulation of non-degradable plastic waste in global and aquatic ecosystems pose a serious risk to environmental sustainability and human health. Conventional thermosetting and thermoplastic polymers, widely used in packaging, construction, and consumer goods, are primarily synthesized from non-renewable petrochemical feedstocks and exhibit resistance to biological degradation and recycling. As of 2023, the worldwide annual production of plastics exceeds 390 million tons, with packaging accounting for more than 40% of total plastic waste [1, 2]. This situation has stimulated an active search for sustainable alternatives based on biodegradable and recyclable polymer systems for packaging applications.

Among the recent innovations, vitrimers - a class of polymer networks with dynamic covalent bonds - have attracted particular attention. These materials combine the mechanical strength and thermal resistance of traditional thermosets with recyclability and self-healing capabilities due to structural rearrangements under external stimuli [3–5]. Unlike conventional crosslinked materials, vitrimers possess the ability to undergo reversible topological rearrangements through bond-exchange reactions, such as transesterification, imine exchange, or disulfide bond exchange [6].

Current research trends focus on the development of bio-based vitrimers derived from renewable resources, including epoxidized plant oils (EPO), bio-acids, polyesters, and natural polymers such as cellulose, lignin, and starch [7,8]. Epoxidized oils - including soybean (ESO), linseed (ELO), and castor oils (ECO) -are particularly attractive as building blocks due to their availability, low toxicity, and high reactivity under dynamic crosslinking conditions [9]. Owing to their biodegradability, flexibility for modification y (via epoxidation, glycidylation, etc.), these oils serve as suitable platforms for the synthesis of next-generation biomaterials [10–12].

Thermally stable, recyclable, and partially biodegradable polymeric materials based on vitrimer chemistry have attracted increasing attention for applications in packaging, coatings, adhesives, and composites, with a growing body of research since the introduction of the vitrimer concept [13–15]. Research is focused on improving their mechanical, thermal, and dynamic properties, as well as expanding their application areas - including packaging, biomedical materials, self-healing coatings, and biodegradable composites [16–18].

A key feature of such systems is their tunability in terms of composition and structure: for example, the use of acids with varying functionality allows control over network density, relaxation dynamics, glass transition temperature, and biodegradability [19–21]. Simultaneously, there is increasing interest in systems with additional functional properties, including self-healing ability, shape-memory behavior, recyclability, and adaptive response to external stimuli. These features are enabled by the presence of dynamic bonds in the polymer structure - including boronic esters, disulfides, imines, and others.

The incorporation of natural polymers (such as nanocellulose and lignin) significantly enhances the mechanical strength, barrier properties, and UV resistance of vitrimer systems [22, 23]. Hybrid materials derived from bio-based sources hold great potential for the development of active packaging with antioxidant, antimicrobial, and controlled biodegradation properties [24]. Moreover, such materials have the potential to meet modern international standards for environmental safety, biodegradability, and recyclability [25, 26].

Despite the progress made, certain challenges remain. These include component compatibility, especially when combining natural fillers with synthetic matrices; retention of properties after multiple recycling cycles; scalability of synthesis; and the lack of standardized protocols for assessing durability and recyclability [27].

The purpose of this review is to systematize current knowledge on vitrimers, with a focus on their synthesis, physicochemical properties, potential for sustainable packaging solutions, and prospects for industrial implementation. Particular attention is given to systems based on transesterification of epoxidized oils and structural modification using cellulose and lignin.

Structural Features and Classification of Vitrimers.

Vitrimers represent a class of polymeric materials that combine the characteristics of thermosetting and thermoplastic systems through the incorporation of dynamically exchangeable covalent bonds into the polymer network. The key feature of vitrimers lies in the ability of their three-dimensional polymer networks to undergo topological rearrangements without loss of crosslinking, enabled by associative bond-exchange reactions such as transesterification, disulfide exchange, imine exchange, and urethane bond exchange [28–30].

Morphologically, vitrimers are classified as post-crosslinked network materials in which dynamic nodes enable reprocessing, self-healing, and stress relaxation at elevated temperatures while maintaining structural integrity under ambient conditions. Observed properties distinguish vitrimers from thermoplastics (which lack network structures) and conventional thermosets (which lack reversible rearrangement capability) [31, 32].

The structural basis of vitrimers relies on dynamically associative bond-exchange reactions that balance covalent stability with reversibility. The most common mechanism involves catalyzed transesterification between hydroxyl and ester groups, as found in systems derived from epoxidized plant oils and multifunctional organic acids [33,34].

Several subclasses of vitrimers can be distinguished based on the type of exchange mechanism: Ester-based vitrimers (the most extensively studied), where the primary mechanism is transesterification; Disulfide-based vitrimers, which rely on reversible exchange between S–S bonds; Imine-, boronic ester-, and urethane-based vitrimers, which utilize less common reversible exchange reactions. The functional properties of vitrimers - including activation

temperature, viscoelasticity, self-healing efficiency, and solvent resistance — are closely related to the type and density of dynamic bonds, the presence of catalysts, the degree of crosslinking, and the chemical nature of the polymer matrix [35–38].

Contemporary research focuses on the biotechnological adaptation of vitrimer systems by replacing petrochemical components with bio-based alternatives such as epoxidized plant oils, plant-derived polyols, and natural acids including citric, succinic, and tartaric acids [39]. These materials offer not only resistance to thermo-oxidative degradation but also meet key criteria for biodegradability and compatibility with food and biomedical applications.

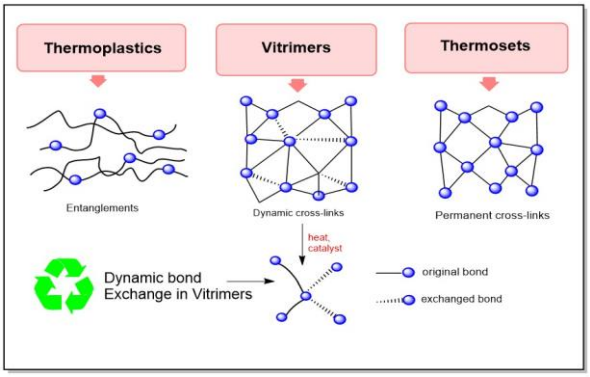


Figure 1 – Schematic comparison of the network topology of thermoplastics, thermosetting polymers, and vitrimers.

The structural features of vitrimers are determined not only by the type of covalent bonds but also by their spatial distribution within the polymer matrix. Figure 1 illustrates a comparative topology of thermoplastics, thermosets, and vitrimers, along with the mechanism of bond exchange in the presence of a catalyst. Table 1 summarizes the key differences between these classes of polymer materials in terms of process ability, thermal resistance, and the presence of dynamic bonding mechanisms.

Table 1– Comparison of Main Types of Polymeric Systems

Characteristic	**Thermoplastics**	**Thermosets**	**Vitrimers**
Type of Bonds	Secondary (physical)	Covalent (permanent)	Covalent (dynamic)
Recyclability	Yes	No	Yes (upon heating)
Self-Healing Ability	No	No	Possible
Processing Temperature	Moderate	High	Moderate/High
Solvent Resistance	Moderate	High	High
Dynamic Bonds	No	No	Yes

A promising strategy also involves the development of hybrid vitrimers containing natural modifiers (such as cellulose and lignin), which enhance mechanical and barrier properties while providing adhesion, antioxidant activity, and biocompatibility [40,41].

Renewable Components for Vitrimer Networks: Epoxidized Oils, Polyesters, and Organic Acids

The development of bio-based vitrimers requires the selection of efficient monomers and crosslinking agents that not only exhibit high reactivity but also align with the principles of sustainable development. In this context, epoxidized vegetable oils, polyesters, and organic acids derived from renewable sources are of particular interest. Such components play a key role in the formation of dynamically crosslinked networks with recyclability, self-healing capabilities, and adaptive behavior.

Epoxidized vegetable oils (EVOs), particularly ESO, ELO, and ECO, are widely used as low-toxicity, modifiable epoxy monomers in vitrimer synthesis due to their reactive oxirane groups, with studies demonstrating their effective crosslinking with natural acids, thermal resistance, and recyclability enhanced by catalysts such as $Zn(acac)_2$ or TBAB [42–46]. Bio-based polyesters such as poly(butylene succinate) (PBS), polylactic acid (PLA), and poly(ethylene adipate) are actively used as elastomeric matrices or soft segments in vitrimer systems. These materials offer a high degree of biodegradability and good compatibility with epoxidized vegetable oils, allowing for the tuning of flexibility and mechanical strength. Polylactic acid can be functionalized with epoxy groups or incorporated into formulations as a reactive polyester [47–49]. Figure 2 illustrates examples of multifunctional organic acids used in the transesterification reactions for synthesizing substances from epoxidized plant oils. These include citric, tartaric, succinic, sebacic, maleic, and other acids, each contributing distinct properties to the resulting networks.

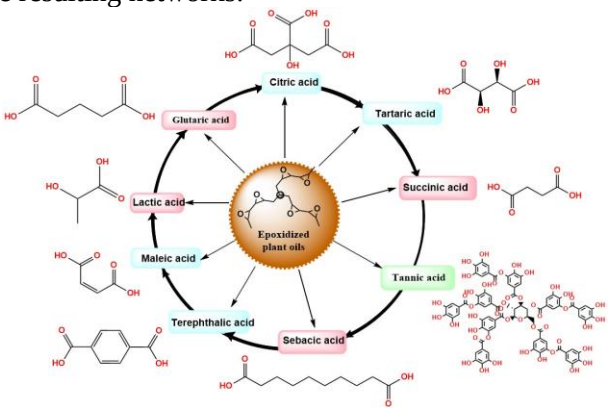


Figure 2 – Examples of monomers used in the transesterification reaction to obtain some bio-based vitrimers.

Multifunctional organic acids act as crosslinking agents due to their multiple carboxylic groups. They readily undergo transesterification with epoxide groups, forming dynamic covalent networks that are both elastic and recyclable. The choice of acid affects key material properties, such as crosslinking density, glass transition temperature (Tg), stiffness, and biodegradability. For instance, citric acid leads to denser networks, enhancing rigidity, whereas sebacic acid contributes to greater flexibility and elasticity [50–53].

There is also increasing interest in using aromatic bioacids (e.g., vanillic acid, ferulic acid) to impart antioxidant and UV-barrier properties as well as to improve thermal stability [54]. Table 2 presents a comparative overview of the key renewable components used in vitrimer systems.

Table 2 – Characteristics and Functions of Renewable Components for Vitrimers

Component	Chemical Nature	Role in Vitrimer Network	Application Features
Epoxidized Soybean Oil	Aliphatic epoxy compound	Primary epoxy monomer	Widely studied in bio-based vitrimer systems
Epoxidized Linseed Oil	Multifunctional epoxy	Crosslinking accelerator, high network density	Fast transesterification reactivity
Epoxidized Castor Oil	Hydroxy-functional epoxy	Elasticity, additional functionality	Compatible with polyesters and acids
Poly (butylene succinate)	Aliphatic polyester	Flexibility, biodegradability	Blended with ESO in hybrid systems
Poly (lactic acid)	α-Hydroxy acid-based polyester	Reinforcement, miscibility with EVOs	Transparency, biodegradability
Citric Acid	Tricarboxylic acid	Crosslinking agent, high network density	Commonly used in food packaging applications
Tartaric Acid	Dicarboxylic hydroxy acid	Tg enhancement, hydrophilicity	Provides rigidity and thermal stability
Succinic Acid	Aliphatic dicarboxylic acid	Flexibility, crosslinking, biodegradability	Low toxicity, high reactivity
Sebacic Acid	Long-chain aliphatic acid	Plasticity, thermal resistance	Increases elasticity without toxicity
Vanillic Acid	Aromatic acid with phenolic group	Antioxidant, thermal stabilizer	Imparts bioactivity and UV protection

Transesterification Mechanisms and Dynamic Bond Exchange

Transesterification, a key mechanism in vitrimer networks based on epoxidized vegetable oils, enables dynamic bond exchange between hydroxyl and carboxyl groups, with catalysts such as $Zn(acac)_2$, TBD, or triazabicyclo[4.4.0]dec-5-ene significantly enhancing stress relaxation and thermal reprocess ability, as demonstrated in systems using epoxidized soybean oil and glucuronic acid [55–56]. The transesterification mechanism in vitrimers is based on associative exchange, where a new bond is formed before the original one is broken. This contrasts with dissociative mechanisms and ensures structural continuity within the polymer network. As a result, this mechanism supports the retention of thermal resistance and mechanical strength while enabling reprocess ability and self-healing.

In addition to transesterification, other types of exchange reactions are also utilized in vitrimer systems, including: Disulfide bond exchange, which provides rapid response at moderate temperatures and is applicable in systems with aromatic or aliphatic diphenyl disulfides [57]; Imine and boronic ester exchanges, offering specific responses to moisture, acids, or bases [58]; Urethane bond exchange, which requires higher temperatures but provides enhanced strength and thermal stability [59].Depending on the chemical composition and the nature of functional groups, these exchange reactions can vary significantly in terms of kinetics, reversibility, and activation energies, allowing for precise tuning of vitrimer properties.

The incorporation of multiple dynamic bond types within a single system enables the development of multifunctional vitrimers with enhanced performance. For instance, the combination of transesterification and disulfide exchange can yield materials that are simultaneously reprocess able and self-healing under different thermal regimes [60].

As a result, the control of dynamic bond exchange mechanisms is a critical element in the design of bio-based vitrimers with targeted functional properties. Mechanisms of this type provide the foundation for developing sustainable next-generation polymers suitable for applications in packaging, healthcare, construction, and other industrial sectors.

Representative Formulations and Experimental Approaches

Developing of bio-based vitrimer systems requires the rational selection of starting monomers, crosslinking agents, catalysts, and functional additives to obtain polymer networks with targeted physicochemical properties. For instance, ESO contains approximately 4.5 to 6.0 epoxy groups per molecule, exhibits high reactivity, and is commercially available on an industrial scale. In contrast, ELO has a higher degree of epoxidation, which contributes to the formation of more rigid and thermally resistant networks, while castor oil, containing natural hydroxyl groups, can be used either in its native or modified form to impart additional flexibility [61–63].

Crosslinking agents are typically natural di- or polycarboxylic acids. The most frequently used acids include TA, CA, SA, and GA. Such acids undergo transesterification reactions with epoxy groups in the oils, forming ester linkages and enabling dynamic reprocessing. To achieve optimal crosslinking, a molar ratio of functional groups (COOH : epoxy) close to 1:1 is commonly established [64-66].

Reinforcement with biopolymers-such as nanocellulose (CNF, CNC) and lignin (organosolv or alkali types) - is typically carried out prior to crosslinking. Nanocellulose enhances mechanical strength and barrier properties, while lignin contributes antioxidant activity and UV resistance to the final formulation [67, 68]. These experimental approaches confirm the feasibility of creating sustainable and functional vitrimers with tailored performance characteristics.

Functional Role of Cellulose and Lignin in Vitrimer Systems

The incorporation of natural polymers such as cellulose and lignin into bio-based vitrimer formulations significantly enhances their functional performance. These components are not only biocompatible and renewable, but also play a critical role in modifying the structure, mechanical behavior, and stability of the resulting materials.

Cellulose and its Derivatives. Cellulose, including its nanostructured forms (CNC and CNF), is widely used as a reinforcing agent. Due to its high modulus, large specific surface area, and capacity for hydrogen bonding, cellulose contributes to enhanced mechanical strength improved thermal stability; reduced oxygen and moisture permeability through tighter packing in the polymer network; improved environmental safety, as it does not negatively affect the composite's toxicological profile.

Cellulose and lignin play crucial roles in enhancing the structural and functional properties of epoxy vitrimer systems based on epoxidized plant oils. Hydroxyl groups in cellulose actively participate in dynamic network rearrangement via hydrogen bonding and covalent interactions with residual epoxy or carboxyl functionalities. For instance, the incorporation of 3 wt.% cellulose nanofibers (CNF) into an ESO/citric acid vitrimer matrix led to a 40% reduction in water absorption and a 28% increase in elastic modulus, confirming its barrier and reinforcing effects [69–70].

Lignin enhances vitrimer systems by providing UV shielding, antioxidant and thermal stabilization, and by forming covalent and dynamic crosslinks through its phenolic and carboxylic groups, as shown in ESO/succinic acid/lignin composites with improved tensile strength and Tg elevation [71–72].

Figure 3 illustrates the sustainable development of epoxy vitrimers from biomass-derived feedstocks (e.g., straw, corn, wood, and lignin) and highlights the contribution of cellulose and lignin to key properties such as reprocess ability, self-healing, UV resistance, and moisture barrier.

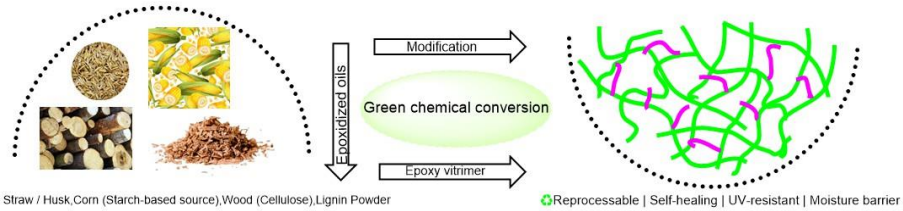


Figure 3 – Functional contribution of cellulose and lignin in epoxy vitrimer systems derived from biomass and epoxidized plant oils.

Physicochemical Properties and Functional Characteristics of Bio-Based Vitrimers

Bio-based vitrimers represent a class of dynamic polymer networks that uniquely combine the rigidity and strength of thermosets with the adaptability of reversible covalent chemistry. These materials exhibit a complex interplay between chemical composition, network architecture, and dynamic exchange reactions, allowing for the modulation of key performance parameters relevant to advanced material design. In particular, systems based on epoxidized plant oils and multifunctional organic acids demonstrate promising physicochemical characteristics aligned with the principles of sustainable development.

Mechanical robustness remains one of the critical properties defining the application potential of vitrimers. Through precise adjustment of the crosslinking density and strategic incorporation of reinforcing fillers, such as nanocellulose, it is possible to tailor tensile strength and elasticity. For instance, in an ESO-based matrix crosslinked with citric acid, the addition of 3 wt. percentage cellulose nanofibers resulted in a 28% increase in elastic modulus due to the formation of an extensive hydrogen-bonding network between the filler and the polymer matrix [73]. Such formulations provide not only structural reinforcement but also dimensional stability under stress.

Thermal properties of vitrimers, specifically the glass transition temperature (Tg) and thermal degradation onset, are strongly dependent on the chemical nature of the acid crosslinkers and catalysts employed. In systems utilizing $Zn(acac)_2$ as a catalyst, Tg values can reach 60–65 °C. Further enhancement is achieved through the introduction of polyester segments or rigid aromatic diacids such as ferulic or vanillic acid, enabling the elevation of Tg to approximately 80 °C while simultaneously improving resistance to thermal oxidation and UV degradation [74, 75]. These findings emphasize the potential of structural modification for the creation of thermally stable and environmentally resilient polymer networks.

One of the biggest advantages of vitrimeric systems lies in their intrinsic ability to undergo topological rearrangements under thermal activation, endowing them with a self-healing function. Dynamic transesterification is responsible for this phenomenon, as ester groups are capable of incessant exchange when subjected to appropriate environments. Reports indicate that complete self-healing of mechanical damage can be achieved within 30 minutes at 150 °C, without significant loss of mechanical integrity, making such materials highly attractive for protective coatings and packaging systems with prolonged service life [76].

Equally important is the reprocess ability of vitrimers, which arises from the associative mechanism of bond exchange that preserves crosslink density during reconfiguration. The inclusion of organic catalysts such as TBD or imidazole dramatically lowers the energy barrier for exchange reactions, allowing for effective reprocessing at moderate temperatures below 180 °C [77]. This feature offers a pathway toward the circular utilization of polymeric materials and aligns with the objectives of sustainable manufacturing practices.

In barrier-critical packaging, cellulose nanofillers improve moisture resistance by reducing permeability, while PLA–ESO composites show 60% biodegradation in 90 days. Integrating transesterification and disulfide exchange enables dual-responsive networks with self-healing, enhanced creep resistance, and durability, supporting versatile applications across various industries [78-80].

Such multifunctional networks offer new avenues for designing adaptive materials with customizable properties for diverse industrial sectors.

Applications of Bio-Based Vitrimers in Packaging and Environmental Considerations

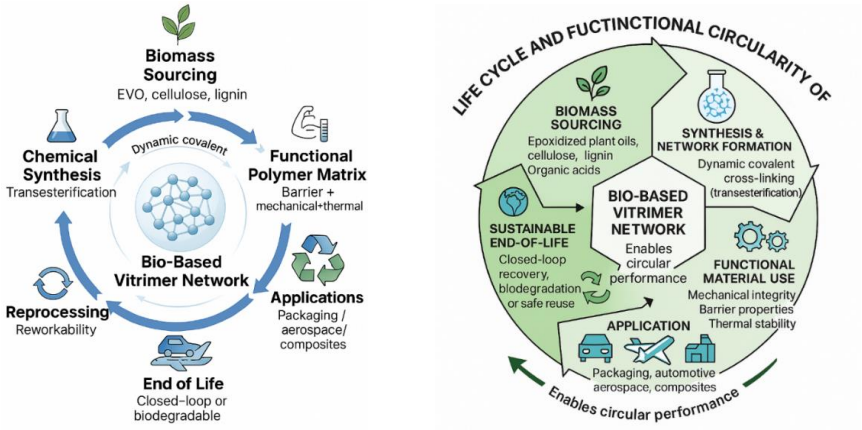
The tightening of international standards and increasing public demand for reducing plastic pollution drives the growing interest in environmentally friendly and functional packaging materials. Contemporary research is focused on the development of sustainable polymer systems that meet the requirements of biodegradability, recyclability, and carbon footprint reduction. In this context, bio-based vitrimers featuring dynamic covalent bonds demonstrate significant potential as innovative materials for packaging applications.

One of the key advantages of vitrimers derived from epoxidized vegetable oils and bio-organic acids is their reprocessability and self-healing capability, while maintaining high thermal and mechanical stability. These properties are particularly valuable in packaging production, where materials must retain form and barrier functionality under varying conditions of storage, transportation, and recycling. Transesterification-based networks, as demonstrated in experiments, remain stable at temperatures up to 250–280 °C and exhibit effective healing after damage upon heating [81].

Vitrimer composites containing lignin and nanocellulose exhibit enhanced barrier properties and maintain recyclability. Dynamic matrices ensure fixation and release of antioxidant and antimicrobial agents under humidity or heat [84]. Trials in China, the US, and EU demonstrate effectiveness in packaging for meat, dry goods, and electronics [82-85]. A crucial stage in the development of biodegradable packaging is Life Cycle Assessment (LCA). Modern LCA studies on vitrimers report a 30–60% reduction in carbon footprint compared to PET or PP counterparts, while maintaining strength and recyclability. Particularly favorable LCA profiles have been found for systems based on ELO or castor oil, sourced from non-food and rapidly renewable resources [86].

The successful use of polymers depends on disposal strategies and infrastructure. Some require industrial composting or pre-shredding. Hybrid systems, such as vitrimer–PLA composites or paper laminates, enhance degradability. Reusable and repairable packaging concepts are gaining traction. EU initiatives are promoting certification and circular bioplastics standards. Bio-based vitrimers demonstrate strong alignment with the evolving demands of the modern packaging industry—encompassing functionality, safety, recyclability, and environmental responsibility. Their full life cycle and functional circularity

are illustrated in Figure 4a and 4b, highlighting their promise in sustainable packaging.



a) b)

Figure 4 – a) Circular development cycle of bio-based vitrimers showing stages from biomass sourcing to end-of-life reuse or biodegradation; b) Functional circularity of bio-based vitrimers including synthesis, application, and sustainable material recovery.

Prospects for the Development of Bio-Based Vitrimers

Recent advances in bio-based vitrimer research highlight progress toward sustainable, reprocess able polymers, with future directions focused on raw material diversification, multifunctional architectures, industrial scalability, and circular integration, as demonstrated by catalyst-free, flame-resistant systems [87] and multifunctional vitrimers based on glycyrrhizic acid and ESO with self-healing and shape-memory properties [88].

Recyclability of fiber-reinforced composites remains a critical challenge. Researchers have developed carbon fiber composites based on ESO that can be fully reprocessed without compromising mechanical performance, opening opportunities for the transportation and aerospace sectors [89]. Such systems require a balance between structural stability and reversibility, achieved by precisely tuning the density of dynamic bonds.

Another innovative direction is the synthesis of vitrimers containing multiple types of dynamic bonds (e.g., disulfide, ester, and urethane), enabling unique property profiles. A recent review describes an epoxy vitrimer with both acetal and disulfide linkages, resulting in high strength, reprocess ability, and degradability — ideal for biodegradable packaging systems [90].

Scalability and standardization are key goals in polymer network development. A kinetic study of epoxy-based dynamic systems aids large-scale production planning. In sustainable 3D printing, a tartaric acid–based photopolymer vitrimer shows strong performance and eco-benefits over acrylates.

Life cycle analyses confirm biosystems' role in lowering energy use and ensuring safe disposal. Additionally, incorporating ESO into starch/PBAT blends boosts biodegradability to 78.5% in 120 days while enhancing strength, supporting its use in green packaging [91-94].

Growing interest in smart packaging has led to the development of bio-based vitrimer systems with adaptive properties, such as castor oil-based photo-responsive networks for self-healing and pharmaceutical applications [95], and universal soybean oil–based epoxy resins with high adhesion and film-forming capabilities for eco-friendly coatings and packaging supported by sustainability initiatives in China [96]. Future development of bio-based vitrimers lies in the creation of multifunctional, adaptive, scalable, and environmentally safe materials. Their applications extend beyond packaging to include electronics, biomedicine, transportation, and construction. However, industrialization will require continued work on property standardization, long-term durability, economic efficiency, and sustainable life-cycle performance.

Conclusion

The development of bio-based vitrimers represents a vital direction in the creation of sustainable and functional polymeric materials. Due to the presence of reversible covalent bonds, these systems combine reprocess ability, thermal stability, self-healing, weldability, and controlled biodegradability. This makes them particularly promising for applications in smart packaging, medical devices, and other areas where both environmental safety and high performance are required.

Integrating vitrimers into the framework of a circular economy necessitates an interdisciplinary approach that includes renewable-resource-based synthesis, life cycle assessment, process standardization, and compliance with environmental regulations. The use of epoxidized vegetable oils, bio-acids, and natural modifiers enables a high level of sustainability and functionality without compromising the mechanical integrity of the materials.

Overall, vitrimers represent a promising direction in sustainable materials science, and Kazakhstan holds significant potential for advancing this area in the coming years, provided there is strategic scientific and institutional support. The relevance of further research lies in the potential of these materials to be adapted to local resources, scaled up for industrial use, and aligned with international sustainable development standards.

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ОРАМАЛЫҚ МАТЕРИАЛДАРҒА АРНАЛҒАН БИОНЕГІЗДІ ВИТРИМЕРЛЕР: ТҰРАҚТЫ ДИНАМИКАЛЫҚ ПОЛИМЕРЛІК ТОРЛАРДЫ ҚҰРУ ЖӘНЕ ҚОЛДАНУ ПЕРСПЕКТИВАЛАРЫ

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Түйіндеме. *Кіріспе.* Биоыдырайтын және қайта өңдеуге жарамды полимерлі материалдарды әзірлеу – жаһандық экологиялық дағдарыс пен пластикалық қалдықтардың жиналуына байланысты өзекті мәселелердің бірі. Соңғы жылдары витримелер деп аталатын жаңа материалдар класы термореактивті полимерлерге тән механикалық беріктік пен динамикалық коваленттi байланыстар арқылы қайта өңделу қабілетінің бірегей үйлесімі арқасында үлкен қызығушылық тудыруда. *Зерттеу мақсаты.* Бұл шолу мақалада негізінен эпоксидтелген өсімдік майларынан алынған бионегізді витримерлерді синтездеу мен қолданудың қазіргі тәсілдері қарастырылады. *Нәтижелер мен талқылау.* Полимерлі торларды құруға арналған химиялық стратегиялар, соның ішінде трансэтерификация механизмдері, катализаторларды таңдау және торлану тығыздығын басқару егжей-тегжейлі талданады. Целлюлоза мен лигнин сияқты табиғи қоспаларды қолдану арқылы механикалық, барьерлік және антиоксиданттық қасиеттерді арттыру әлеуеті қарастырылады. Бұл материалдардың жылу тұрақтылығы, ылғалға төзімділігі, механикалық беріктігі, өздігінен қалпына келу қабілеті және биоыдырауы сияқты функционалдық сипаттамаларына ерекше назар аударылады. Қазіргі зерттеулер бионегізді витримерлердің тағамдық, фармацевтикалық және биофункционалды барьерлік қасиеттері бар белсенді орамалар сияқты әртүрлі мақсаттар үшін практикалық қолдану әлеуетін көрсетеді. *Қорытынды.* Бұл шолу жаңартылатын шикізатқа негізделген витримерлерді әзірлеу мен қолдану саласындағы соңғы ғылыми жетістіктерді жинақтап, тұрақты даму мен ресурс үнемдеу технологиялары контекстіндегі одан арғы зерттеу бағыттарын анықтайды.

Түйінді сөздер: бионегізді витримерлер, эпоксидтелген өсімдік майлары, динамикалық коваленттік байланыстар, трансэтерификация, биоыдырайтын орама, целлюлоза, лигнин, термореактивті полимерлер, тұрақты материалдар, қайта өңдеуге жарамдылық, функционалдық полимерлер.

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УСТОЙЧИВЫЕ ДИНАМИЧЕСКИЕ ПОЛИМЕРНЫЕ СЕТИ ДЛЯ УПАКОВКИ: РАЗРАБОТКА И ПЕРСПЕКТИВЫ БИО-ОСНОВАННЫХ ВИТРИМЕРОВ

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Резюме. *Введение.* Разработка биоразлагаемых и пригодных к переработке полимерных материалов является ключевым приоритетом в условиях глобального экологического кризиса и растущего накопления пластиковых отходов. В последние годы значительный интерес вызывает новый класс материалов — витримеры — благодаря уникальному сочетанию механической прочности, присущей термореактивным полимерам, и возможности переработки, обеспечиваемой за счёт динамических ковалентных связей. *Цель исследования.* В данной обзорной статье представлены современные подходы к синтезу и применению биоосновaнных витримеров, полученных преимущественно из эпоксидированных растительных масел. *Результаты и обсуждение.* Подробно рассмотрены химические стратегии создания полимерных сетей, включая механизмы трансэнтерификации, выбор катализаторов и контроль плотности сшивки. Обсуждается потенциал структурной модификации с использованием природных добавок, таких как целлюлоза и лигнин, с целью повышения механических, барьерных и антиоксидантных свойств. Особое внимание уделено функциональным характеристикам этих материалов, включая термическую стойкость, устойчивость к влаге, механическую прочность, способность к самовосстановлению и биоразлагаемость. Современные исследования подчеркивают потенциал биоосновaнных витримеров для практического применения в качестве упаковочных материалов для различных целей, включая пищевую, фармацевтическую и активную упаковку с биофункциональными барьерными свойствами. *Заключение.* Обзор обобщает актуальные научные достижения в области разработки и применения витримеров на основе возобновляемого сырья и определяет приоритетные направления для дальнейших исследований в контексте устойчивого развития и ресурсосберегающих технологий.

Ключевые слова: биоосновaнные витримеры, эпоксидированные растительные масла, динамические ковалентные связи, трансэнтерификация, биоразлагаемая упаковка, целлюлоза, лигнин, термореактивные полимеры, устойчивые материалы, перерабатываемость, функциональные полимеры.

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