



From renewable oils to functional materials: Applications, performance and industrial perspectives

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Abstract

The increasing demand for sustainable and high-performance polymeric materials has stimulated extensive research into renewable feedstocks as alternatives to petroleum-derived resources. Among various renewable resources, vegetable oils have emerged as versatile platforms for the development of functional polymeric materials because of their abundance, structural diversity, relatively low toxicity, and potential for chemical modification. Although substantial research has focused on the synthesis and functionalization of vegetable-oil-derived polymers, increasing attention is now being directed toward their practical performance and application in industrially relevant environments. This review presents an application-oriented assessment of functional polymer systems derived from vegetable oils, emphasizing their performance, technological potential, industrial relevance, and remaining challenges. Applications in protective coatings, corrosion-resistant and self-healing surfaces, polyurethane and non-isocyanate polyurethane materials, adhesives and sealants, thermosetting resins, composites, elastomers, lubricants, packaging, biomedical materials, and additive manufacturing are discussed. Particular attention is given to application-specific properties including adhesion, hardness, flexibility, thermal stability, chemical resistance, barrier performance, mechanical strength, durability, and self-healing behavior. The potential of vegetable-oil-derived polymers for multifunctional and smart materials is also highlighted. In addition, challenges associated with feedstock variability, functionalization efficiency, performance consistency, processing, scale-up, cost, long-term durability, standardization, and end-of-life management are critically considered. The transition from laboratory-scale materials to industrial products requires not only increased renewable content but also application-specific performance validation, life-cycle assessment, economic evaluation, and compatibility with existing manufacturing infrastructure. Future research should therefore focus on high-performance multifunctional materials, scalable processing, non-toxic chemistry, standardized testing, circularity, and industrial demonstration. Vegetable-oil-derived functional polymers have significant potential to contribute to sustainable material technologies when renewable feedstocks are integrated with rational molecular design and application-driven engineering.

Keywords: Vegetable oils, renewable polymers, functional polymers, bio-based materials, industrial applications, coatings, polyurethane, non-isocyanate polyurethane, self-healing, composites, sustainable materials, commercialization

Introduction

Due to an increased need for polymeric materials within coatings, adhesives, packaging, automotive, construction, electronics, medical and consumable products; there is a growing desire for sustainable alternatives to petroleum-based polymers. Vegetable oils have shown great promise due to the ability to chemically modify and convert their triglyceride structure containing variously unsaturated fatty acid chains and/or hydroxyl groups found in some vegetable oils like castor oil. The variety of chemical functionalities available allow for modification into many different types of reactive intermediates and polymer networks. Past studies demonstrated that vegetable oils can be used in free radical, cationic, ring opening metathesis, and condensation polymerizations to produce material that vary greatly in their rigidity/flexibility, and molecular weight. Recently, researchers have begun to study the preparation of polyurethanes (PU), non-isocyanate polyurethanes (NIPU), protective and self-healing coatings, nanocomposites, photocurable polymers, adhesives, biomaterials and resins for three-dimensional printing.^[1]

To successfully apply these vegetable oil derived functional polymers industrially however will depend on much more than just the incorporation of renewable resources. For

example, the functionality of these polymers will require sufficient mechanical properties (hardness, flexural modulus), adhesive properties, chemical resistance, water resistance, and thermal stability. Therefore, this review emphasizes the relationship between application properties, of vegetable-oil-derived functional polymers and discusses their technological uses, limitations based upon performance characteristics, difficulties associated with scaling up production processes, their environmental benefits (sustainability) and potential for industrial adoption.^[2]

Vegetable Oils as Platforms for Functional Materials

Chemical structures of vegetable oils influence their reactivity; the number of double bonds; the ability to form polymers; and the properties of the formed material. As a result, soybean, linseed, sunflower, rapeseed, castor, tung, palm, corn, jatropha and many other types of vegetable oils have become of interest as "renewable" sources of polymer rawmaterials.

To develop new applications, the main point to consider is how the vegetable oil chemistry (i.e., the nature of the triglyceride) will affect the desired properties of the final polymer. Unsaturated oils have multiple sites where chemicals may be attached through cross-linking reactions.

Castor oil has unique features due to the presence of natural hydroxyl groups on ricinoleic acid-containing triglycerides which make it possible to attach them directly to indirectly into polyurethane systems. This allows for generation of polymeric systems with varying glass transition temperatures; degree of flexibility; degree of cross-linking; degree of hydrophobicity; and mechanical properties based on the type(s) of fatty acids used.

Generally speaking, chemical changes made to vegetable oils involve introducing reactive groups to enable polymer formation or cross-linking. Chemical modifications include epoxidylation; hydroxylation; acrylation; methacrylation; maleination; transesterification and carbonation. In terms of an application oriented viewpoint, however, these reactions

are important primarily as a means to achieve certain final product characteristics rather than as objectives in-and-of-themselves.^[3]

Application–Property Relationship in VO-Derived Polymers

Industrial applications impose different property requirements on polymeric materials. Therefore, a single polymer formulation cannot necessarily satisfy every application. The molecular structure, functionality, crosslinking density, fillers, curing mechanism, and processing conditions must be selected according to the intended end use.

Table 1: Relationship between industrial application and important material properties ^[4]

Application	Major required properties	Typical performance parameters
Protective coatings	Adhesion, hardness, flexibility, chemical resistance	Adhesion strength, pencil hardness, flexibility
Anti-corrosion coatings	Barrier properties, water resistance, durability	EIS, polarization, salt-spray resistance
Self-healing coatings	Healing efficiency, mobility, dynamic bonding	Crack recovery, healing efficiency
Adhesives	Bond strength, toughness, moisture resistance	Lap-shear and peel strength
Sealants	Elasticity, adhesion, weather resistance	Elongation, recovery, aging
Composites	Strength, modulus, thermal stability	Tensile strength, modulus, impact strength
Elastomers	Elasticity, resilience, durability	Elongation, tensile strength
Packaging	Barrier and mechanical properties	Oxygen and water-vapor permeability
Lubricants	Lubricity, oxidation stability, wear resistance	Friction coefficient, wear rate
3D printing	Viscosity, curing rate, dimensional stability	Conversion, resolution, tensile properties
Biomedical materials	Biocompatibility, degradation, functionality	Cytotoxicity, degradation rate

This application-specific approach is particularly important because the advantages of vegetable-oil-derived polymers can differ substantially depending on the intended use.

Protective Coatings and Surface Protection

Protective coatings provide an effective method to protect surfaces from environmental conditions, such as moisture, chemicals, abrasions, ultraviolet (UV) light, corrosion and mechanical forces. Vegetable oil derived polymers are considered some of the best candidates for protective coatings due to their versatility in terms of chemistry and functionality. Vegetable oil derived polyesters, alkyls, epoxies, polyurethanes and acrylic networks have all shown potential as protective coatings. The long fatty acid chain provides both flexibility and hydrophobic characteristics; whereas the introduction of chemically reactive groups into the molecule promotes cross-linking and improves adhesion to the underlying material. Of particular interest is the use of vegetable oil based polyurethane coatings that have demonstrated the ability to produce renewable materials combined with good coating performance and flexibility. A variety of different types of polyurethane coatings have been investigated for protective coating applications including; conventional PU, water borne PU, UV curable PU, high solid PU, hyper branched PU and nano composite PU.^[5]

1. Wood Coatings

For wood coatings to effectively protect the wood against moisture related degradation, staining, chemicals, etc., it is essential to create a hydrophobic barrier between the wood and its surroundings while allowing for some degree of flexibility so as to allow for dimensional changes experienced when wood absorbs or releases moisture. Vegetable oil derived alkyl and polyurethane systems have

been studied for their application as wood coatings. Modification of the polymer network has allowed improvements to be made to the coating's hardness and chemical resistance without sacrificing the needed degree of flexibility to accommodate the dimensional changes experienced by the wood substrate.^[6]

2. Metal Coatings

Compared to wood coatings, metal coatings have higher demands placed upon them since even small imperfections within the coating layer can provide a path for corrosive substances to come into contact with the metal. As a result, vegetable oil derived polymer coatings have been investigated as possible protective/corrosion resistant layers over metals. For these coatings to perform properly in this manner, several key characteristics will need to be present. These include but are not limited to: adequate adhesion to the metal substrate, sufficient hydrophobicity to resist penetration of moisture/water vapor/ions, adequate cross-link density to prevent water/ion permeability, adequate chemical stability and/or resistance to attack by common corrosion agents (such as acids/bases), satisfactory crack resistance and long term durability. While vegetable oil derived coatings can offer beneficial hydrophobic characteristics along with improved flexibility compared to many petroleum-derived alternatives, further development/formulation efforts will likely be required to ensure that they meet the levels of performance presently achieved by commercialized industrial coatings.^[7]

3. Automotive & Industrial Coatings

Automotive and industrial coatings typically require a balance of hardness/flexibility/weather resistance/chemical resistance/surface finish/adhesion strength. Vegetable oil derived polyurethane and epoxy systems represent examples

of new technologies that can incorporate bio-renewable carbon sources into existing coatings systems while providing functional properties desired for automotive and industrial uses. However, before such technology can be used commercially in industry, extensive laboratory scale research must demonstrate consistent formulation results and reliable long-term performance under a variety of environmental exposures. Such demonstrations would involve conducting accelerated weathering tests/humidity exposure tests/chemical resistance testing/abrasion tests/thermal cycling tests/long-term adhesion studies in addition to laboratory scale characterization of basic polymer properties.^[8]

Corrosion Protection and Smart Coatings

Functional vegetable-oil-derived polymers have great potential in providing corrosion protection. Most organic coatings (coatings based on organic material) provide metal corrosion protection by creating a physical barrier between the coated surface and the environment surrounding it. Damage to this barrier provides a route for water, oxygen, and harmful substances to contact the metal surface initiating corrosion. Vegetable-oil-derived polymers have been studied as both traditional barrier coatings and advanced self-healing systems. The addition of functional fillers or molecular modifications can improve barrier performance. Carbon-based and other nanostructured fillers can improve the mechanical and barrier properties of these coatings.^[9]

1. Barrier Performance

A thick enough layer of polymer molecules will limit the diffusion of water, oxygen, and ions through a coating. Increased cross-link density generally increases barrier properties but excessive cross-linking can reduce the flexibility of the polymer network. Thus, achieving an optimal balance between stiffness and molecular motion is very important when designing a coating. While vegetable-oil-derived polymers do possess hydrophobic fatty acid segments which help limit exposure to water, simply being hydrophobic does not assure complete corrosion protection. Many factors including coating defect density, adhesion, permeability, interfacial chemistry, and long-term coating durability all impact corrosion protection.^[10]

2. Nanocomposite Anti-Corrosion Coatings

Fillers at the nanoscale can significantly enhance several properties of vegetable-oil derived polymer matrices including mechanical properties, thermal stability, barrier properties, and corrosion protection. A variety of graphene-based materials, carbon nanotubes, silicas, metal oxides, clays, and other nanostructured materials have been used as fillers to achieve these improvements. Nano-fillers can increase the length of diffusion paths through a composite reducing the ability of water and corrosive species to migrate towards the metal surface. However, effective distribution of nano-filler particles and compatible interaction between polymer chains and filler particles are necessary. Poor distribution of nano-particles can create defects which decrease coating performance.^[11]

Self-Healing and Smart Functional Coatings

Self-Healing systems based on polymers represent a progression beyond passive protective coatings toward

active smart materials. Passive protective coatings generally need to be repaired by outside forces after significant damage has occurred. Active smart Self-Healing systems are designed to restore some portion of their protective functionality after they have sustained damage. Vegetable oils have been shown to be useful as healing agents in self-help systems, especially in microcapsule-based systems. Upon rupture of the microcapsules upon mechanical damage the oil is released into the damaged area and can either become involved in forming a new film or can undergo oxidative curing. These types of Self-Healing systems have been considered as possible methods for protecting against corrosion. Active smart Self-Healing coatings can be broadly categorized into two types: extrinsic self-healing coatings, which contain a stored supply of healing agents contained within microcapsules or vascular structures separate from the rest of the system; and intrinsic self-healing coatings, which incorporate reversible interactions or dynamic covalent bonds directly into the polymer chain.^[12]

1. Extrinsic Self-Healing Coatings

Linseed and tung oils have been researched as healing agents using drying oils as examples. Microcapsules containing these oils can be incorporated into coatings made from various polymers. Mechanical damage to these coatings causes rupture of the microcapsules releasing the healing agent into the cracks. Oxidation or subsequent polymerization of the oil contributes to restoring the damaged region. There are many technical issues that need to be addressed before self-healing coatings can be implemented practically, including encapsulation costs, stability of encapsulated products, compatibility between the encapsulated product and the rest of the coating formulation, and environmental concerns.^[13]

2. Intrinsic Self-Healing Coatings

Intrinsic self-healing coatings rely on reversible interactions or dynamic covalent bonds introduced into the polymer backbone during synthesis. Examples of reversible interactions include hydrogen-bonded interactions, disulfide-exchange interactions, imine-exchange interactions, reversible Diels-Alder adducts, ionic interactions, and transesterification-reactions-based dynamic covalency. Vegetable-oil-derived polymer backbones can be synthesized so that they incorporate dynamic functional groups allowing damaged areas of the coating to undergo molecular rearrangements resulting in partial recovery of the original polymer structure. Industrial importance of self-healing coatings rests in their potential to greatly extend service-life of a coating and minimize maintenance needs. However, evaluating self-healing coatings involves much more than observing if visible cracks close up again after the healing process. Evaluation should involve measuring the extent to which the healing restores the barrier properties; mechanical integrity; adhesion properties; and corrosion-protection capabilities of the coating.^[14]

Polyurethane Applications

Vegetable oil-based polyurethanes represent one of the most studied classes of renewable polymers. The conversion of vegetable oils into polyols via chemical means and subsequent incorporation into polyurethane networks has enabled the study of numerous types of applications such as

coatings, adhesives, foams, elastomers, sealants, etc. The properties of vegetable oil-based polyurethanes depend on many factors including hydroxyl functionality, polyol molecular weight, ratio of soft to hard segments, crosslink density, isocyanate structure, curing conditions and addition of fillers. By controlling each parameter, it is possible to tailor the architectural characteristics of the polymer to its performance criteria for various applications.^[15]

1. PU coatings

Vegetable oil based PU coatings can offer excellent flexibility, adhesion and hydrophobicity. Additional modifications of the performance of vegetable oil based PU coatings can be made through the incorporation of nanoparticles, additional cross-linkers and functional polymer segments based upon the application. Additionally, there are methods that can improve the environmental performance and processing efficiency of vegetable oil derived PU coatings. Some of these methods include replacement or reduction in the amount of organic solvents used during processing by replacing them with water. Another method that can improve both the environmental performance and processing efficiency is the use of UV curable systems. Both of these methods could enable a reduction in energy required for curing and time required for curing.^[16]

2. PU foams

Vegetable oil derived polyols have also been developed for polyurethane foam production. Possible uses for this type of foam include insulation, cushioning, packaging, furniture and automotive parts. In order to develop this type of foam it will be necessary to carefully control both the density and cell structure of the foam. It is also essential that sufficient levels of compressive strength, resiliency, thermal insulating capability and dimensionally stable performance are achieved. The level at which these characteristics are balanced depends heavily on the structure of the polyol, formulation composition and blowing conditions as well as the degree of cross-linking.^[17]

Non-Iso-Cyanate Polyurethanes

In recent years non-isocyanate polyurethanes (NIPU's), which utilize alternative routes to polyurethane like materials without traditional isocyanate chemistry, have become increasingly popular due to concerns regarding health risks associated with the use of diisocyanates. Vegetable oils can be chemically converted into cyclic carbonate containing intermediates which then react with amines to produce polyhydroxyurethane networks. Application wise, vegetable oil derived NIPU's have potential as protective coatings, adhesives, sealants, elastomers and self healing materials as well as corrosion resistant surface treatments. The presence of hydroxyl groups formed during the reaction of carbonates and amines facilitate interaction between molecules and thus improve adhesion. Network architecture can be created to allow for the introduction of dynamic bonds or functional properties. However, evaluations of NIPU's must compare them with traditional polyurethane systems when using application relevant testing parameters. Parameters that need to be considered when comparing NIPU's with traditional polyurethane systems include; curing rates, viscosities, mechanical performances, thermal stabilities, resistances to

water and chemicals, processing requirements, costs as well as others.^[18]

Adhesives & Sealants

Adhesives represent an additional area of interest for vegetable oil derived polymers. Vegetable oil based polyurethane adhesives have been investigated as renewable sources for flexible building blocks within adhesive networks. Potential uses for vegetable oil based polyurethane adhesives include; construction, automotive assembly processes, packaging, textile industry and footwear industry. For an adhesive to perform adequately it needs to transfer stresses between two surfaces over time while maintaining adequate performance in environmentally exposed conditions. Evaluation parameters for adhesives include: lap shear strength, peel strengths, tensile strength, toughness, curing speed, moisture resistance, heat resistance and aging resistance. Flexible fatty acid segments from vegetable oil based polymers can increase toughness and flexibility but excess flexibility may result in decreased cohesive strength. Therefore, control over both hard segment content and crosslink density is needed to obtain optimal combinations between flexibility/strength/durability.^[19]

1. Wood Adhesives

Adhesive-wood interaction is a very significant area of study. The reason is that wood (and other cellulose products) is both highly porous and sensitive to moisture. It has been shown that vegetable oil based polyurethane formulations could provide alternative to petroleum derived materials, and at the same time, they may be capable of producing acceptable bonding properties, as well as flexible films.^[20]

2. Construction Adhesives

Construction adhesives will also need to perform over a wide range of temperatures and humidity conditions. Therefore, when considering vegetable oil derived adhesives for use in construction applications, it would be appropriate to evaluate them using long term creep testing and accelerated environmental degradation methods.^[20]

3. Packaging Adhesives

For most packaging applications, adhesives will be required to process quickly; have acceptable bonding properties; and control migration if migration is a concern. To date, water borne or solvent reduced vegetable oil base adhesives appear to be some of the best alternatives to petroleum derived materials to meet these processing requirements.^[20]

Thermosetting Resins

Thermosetting resins are commonly utilized due to the inherent properties of their cross-linked structures that include dimensional stability, chemical resistance, and durability. As such, various vegetable-oil-derived epoxy and polyester systems have been studied as either renewable alternatives or modifiers to traditional thermosetting resins. Vegetable-oil derived epoxides can act as reactive intermediates within epoxy systems. In addition to providing toughening through the introduction of flexible aliphatic structures that can help to alleviate brittleness,

these components do not appear to negatively affect the cured system's ability to maintain a high degree of cross-link density.^[21] However, excessive incorporation of flexible oil-derived intermediate components has been shown to lower the glass transition temperature (T_g) and elastic modulus (E') of the resulting cured resin. As such, there exists considerable potential for the development of a wide range of products based on vegetable-oil-derived thermosets for applications ranging from protective coatings to electrical encapsulations, adhesives, composite matrices, and molded components. Ultimately, the appropriateness of a particular product will depend upon the successful attainment of the required combination of mechanical, thermal, chemical, and dimensional properties. One of the most significant challenges associated with the development of vegetable-oil-derived thermosets lies in achieving a balance between incorporating increasing amounts of renewable content into the final product without sacrificing its physical/mechanical/thermal properties. Incorporating increasingly larger fractions of vegetable-oil-derived components into the final cured product does not necessarily result in the attainment of improved mechanical or thermal properties. Consequently, optimization of the concentration of vegetable-oil-derived components, as well as the cross-linking structure must be carried out so as to meet the requirements of a specific end-use application.^[22]

Composite Materials

Vegetable-oil-derived polymers may serve as matrix materials or modifications in composite systems. The inclusion of renewable polymer components offers a method by which dependence on fossil-derived resin systems may be reduced. Reinforcements that may be incorporated with vegetable-oil-derived matrices include natural and glass fibers, carbon fibers, cellulose, nanoclay, silica, graphene, carbon nanotubes, and metal oxide nanoparticles. Depending on the desired mechanical, thermal, barrier or functional performance, the type and quantity of reinforcement selected will vary. Composites utilizing natural fiber reinforcements are particularly desirable since both the polymer matrix and reinforcing phase can derive from renewable sources. As such, these types of composites offer a higher level of renewable component utilization than other composite systems while still retaining useful structural and functional attributes.^[23] Ultimately, the overall performance of a composite is dependent on the cumulative effect of the matrix properties, reinforcement characteristics, interfacial adhesion between phases, and processing conditions. Vegetable-oil-derived matrices can impart flexibility and toughness to composites; however, enhancements in thermal resistance, stiffness, and dimensional stability may be needed for composites destined for highly demanding structural applications.

Table 2: Application of vegetable-oil-derived polymer composites ^[24]

Matrix system	Reinforcement	Potential application
Epoxy/oil-derived	Natural fibers	Automotive interiors
PU/oil-derived	Cellulose	Flexible composites
Polyester/oil-derived	Glass fiber	Structural components
Epoxy/oil-derived	Silica	Protective materials
PU/NIPU	Nanoclay	Barrier coatings
Acrylate/oil-derived	Nanoparticles	Photocured components

Flexible Materials and Elastomers

Flexible chains of fats from oil will make a flexible framework, which has been beneficial in creating flexible materials, or elastomer. Networks created with polyurethane and polyester derived from vegetable oils can be very flexible and highly stretchy and will work well in applications where flexible deformations are needed. Some of the applications include flexible paints, gasket seals, flexible packaging, footwear, flexible polymer components (soft) and damping of vibrations. Due to the ability to use renewable feed stocks and the fact that they can produce a flexible material through molecular structures, vegetable oil derived elastomers have some excellent opportunities in areas of flexible materials. Network structure of elastomers is controlled by density of cross-linking and the ratio of rigid and flexible units. As general rule, lower levels of cross-linking promote longer lengths of stretching, elasticity and low stiffness. On the other hand, higher levels of cross-linking can improve strength, lessening deformation and improving dimensional stability. Therefore, the best possible level of cross-linking depends on desired application.^[25]

Lubricants and Tribological Applications

Vegetable oils have been researched extensively as a source of renewable lubricant due to their inherent lubricity characteristics and relatively good flash point. However, further modifications may need to be made chemically to

enhance their oxidative and thermal stability in demanding applications. In addition to lubricants themselves, vegetable-oil-based materials can be added to lubricated polymers, friction-reduction coatings, wear-resistance products, tribological composite products and functional additive products. Performance of vegetable-oil-based materials typically requires evaluation based on tribological performance factors including coefficient of friction, wear rates, and surface morphologies post-testing. While vegetable-oil-based lubricant materials have many benefits, one significant drawback is their limited oxidative stability. Unsaturated fatty acid structures within vegetable oils can oxidize at increased temperatures which may degrade lubricant performance. Thus, chemical modification of vegetable oil and/or incorporation of suitable antioxidants may be necessary to protect against oxidative degradation.^[26]

Bio-Based Packaging Products

Bio-based polymers offer a promising solution to sustainable packaging because so much polymeric material is used globally in packaging. Vegetable oil derived biopolymers can be developed for films, coatings, flexible packaging, barrier layers, polymer blends and various bio-based packaging components. Key performance attributes for packaging materials include oxygen & water vapor barrier properties, tensile strength, elongation, heat stability, clarity, & processability. Consequently, the design of the

biopolymer's composition/structure should ensure that it provides an optimal balance between mechanical performance and barrier functionality. Although the incorporation of vegetable oil derived components could help increase the amount of renewable material contained in packaging products, the performance of packaging products must remain stable throughout both manufacturing and end-use service. If you plan to utilize vegetable oil derived components in food contact applications then issues related to migration behavior, toxicity, and regulatory compliance would also require consideration prior to commercialization.^[27]

Biomedical Applications

Vegetable oil based polymers have attracted significant attention in recent years due to their potential use in a variety of biomedical applications. As such, these biomaterials could potentially serve as tissue engineering scaffolding, drug delivery agents, antimicrobial systems, tissue adhesives and biosensors. This interest has arisen primarily because of the structural variability of vegetable oil based polymers and the possibility of creating materials with desirable biological properties. In addition to providing structural support for cells during growth in culture, three dimensional scaffolds also need to possess controlled mechanical properties and provide a means for cells to interact with each other through direct cell-cell contact and indirect cell-scaffold interaction. Vegetable oil based polymer systems can be engineered to produce variable network structures and surface characteristics which would facilitate the design of scaffolding for use in tissue engineering applications. Drug delivery systems rely upon the ability to create functional polymer networks which can incorporate active molecules and control their release. The chemical structure of the polymer, its network architecture and its degradation behavior will all impact the rate and duration of drug release.^[28] As flexible adhesives for biological tissues, oil-based polymers may have potential uses. To function properly as adhesives for biological tissues, they will require a combination of good adhesion properties, sufficient mechanical strength and flexibility along with adequate biological compatibility. Polymer surfaces can be modified to act as substrates for immobilized biological recognition elements. Since the chemistry of the polymer can be adjusted, this type of approach may lead to new types of biosensor interfaces made from polymer materials. Translation of vegetable oil based polymers to medical applications requires much greater scrutiny than does their use in industrial applications. For instance, in order for a vegetable oil based polymer to be considered safe for biomedical application, it must be shown to be non-toxic to cells in vitro and in vivo. It must not degrade into toxic substances when exposed to environmental conditions such as heat, light or moisture. In addition, it must be able to withstand sterilization methods and elicit minimal or no adverse response by the host's immune system. Finally, it should exhibit long term biocompatibility. All of these issues must be addressed prior to consideration of practical biomedical application.^[29]

Additive Manufacturing and 3D Printing

Additive manufacturing is another area where vegetable oil based polymers are being explored. Vegetable oil derived acrylate and methacrylate monomers have been used as the photoinitiator and/or reactive diluents in various forms of 3-Dimensional printing (stereolithography, digital light processing etc.). To determine if a particular resin is suitable for additive manufacturing, several key parameters need to be examined; including but not limited to: viscosity, photoreactivity, cure depth, reaction rates, post-cure dimension changes/shrinkage, mechanical properties and surface finish. Control over these variables is crucial to achieve accurate prints that maintain their mechanical integrity. Vegetable oil derived photocurable materials offer opportunities for adding renewable resources to customized manufactured parts produced using 3-D printing technology. Some examples of applications where this might occur include prototype production, creation of biomedical models, custom manufacture of parts/components, soft molded parts/prototypes, lightweight components etc. While there is great promise associated with using vegetable oil based materials as part of the 3-D printing process, the development of vegetable oil based materials for 3-D printing remains relatively nascent at present. Research efforts continue to focus on the development of sustainable resins that provide optimal balances among renewable resource content, printability, curing behavior/dimensions, mechanical properties and overall performance.^[30]

Smart and Multifunctional Applications

In terms of their development as multifunctional materials (with properties not solely replacing those of existing petrochemical-based materials) vegetable oil based polymers are being developed more frequently now than ever before. Examples of multifunctional materials include those exhibiting self-healing properties, antimicrobial activity, corrosion protection capabilities, hydrophobic properties, flame retarding properties, ultraviolet resistant properties, shape memory effects, stimulus responsive behavior, conductive properties and sensing capabilities. Multifunctional vegetable oil based materials can be created by incorporating nanoparticles, dynamic covalent bonding systems, functional molecules and responsive segments into the base polymer material. By doing so, the base material structure can be optimized to meet desired application-specific requirements. Examples of multifunctional coatings prepared from vegetable oils include coatings combining renewable content with self-healing capability and corrosion protection. Functional filler incorporation combined with molecular modifications can further enhance mechanical properties/barrier characteristics/anti-corrosion/self-healing characteristics. One significant scientific issue is how to implement multifunctionality without sacrificing either processability/compatibility/cost/stability. Overly large amounts of functional component inclusion can result in increased formulation complexity/increased cost/adverse impacts on compatibility within the base polymer material. Therefore multifunctional vegetable oil based materials require precise optimization of composition/material structure/formulation/process conditions.^[31]



Fig 1: Industrial applications of vegetable-oil-derived functional polymers

Performance Comparison with Conventional Petroleum-Based Polymers

The industrial value of vegetable-oil-derived polymers should be assessed through direct comparison with existing commercial materials.

Table 3: General comparison between conventional and vegetable-oil-derived polymers [32]

Parameter	Conventional petroleum-derived polymers	Vegetable-oil-derived polymers
Feedstock	Fossil resources	Renewable biological resources
Structural diversity	Controlled synthetic chemistry	Dependent on oil composition
Renewable content	Generally low	Potentially high
Flexibility	Application dependent	Often favorable
Mechanical strength	Often highly optimized	Requires application-specific optimization
Thermal stability	Often established/high	Can require modification
Processability	Well established	Increasingly developed
Industrial standards	Extensive	Still developing for some applications
Feedstock consistency	Generally high	Can vary with source
Sustainability potential	Limited by fossil feedstock	Potentially improved
Commercial maturity	High	Variable
End-of-life options	Application dependent	Requires further development

It is important to emphasize that bio-based origin alone does not guarantee superior performance. Industrial materials must satisfy the same application requirements as conventional materials. Therefore, the appropriate objective is not simply maximum vegetable-oil content but an optimized combination of renewable content, performance, cost, safety, durability, and environmental impact.

Industrial Scale-Up and Commercialization

Laboratory-scale development of vegetable-oil-derived polymers has significant gaps in terms of commercialization. Laboratory experiments can show excellent properties as controlled systems but do not allow for large-scale reproducibility of raw materials; large-scale chemical reactions; reliable large-scale processing; regulatory compliance; and economical commercialization.

1. Feedstock variability

Raw material variability exists based on the botanical source of the vegetable oils; geographic region of origin; climate;

cultural practices related to growing the crops; methods used to extract the oils; how the oils have been stored; and level of oxidative degradation. Variability in fatty acid composition affects chemical modification, which then impacts the structure of the resulting polymers. For this reason, it is necessary to characterize the feedstocks being utilized for uniformity and standards of performance for resultant materials.^[33]

2. Process scalability

A small amount of oil can undergo a chemical reaction under laboratory conditions using an optimized reaction route that works well for a few grams of oil, however, such a process will likely not perform equally well at a kilogram or industrial scale. As size increases, so too do the effects of heat transfer, mechanical mixing, mass transfer, reaction rates, purification, solvent recovery, and waste management. Because of these issues, laboratory synthesis pathways need to be optimized prior to implementation at an industrial scale.

3. Costs

Economic viability of vegetable-oil derived polymers needs to be determined throughout the entire production chain (oil choice; functionalization; purification; polymer manufacture; formulation; processing; and manufacturing) of the end product. While vegetable oils might be cheaper than traditional petroleum-based oils, additional functionalization/purification steps could significantly increase production costs. To improve the economic viability of vegetable-oil-derived polymers, therefore, there is a need for process intensification, catalysts that function efficiently; minimizing solvents; maximizing conversion of reactants to products.

4. Compatibility with Current Facilities

Compatibility with current facilities/equipment allows for easier transition to commercially viable vegetable-oil-derived polymer systems. If viscosity, cure speed, shelf-life and other physical/chemical attributes are similar enough to those of conventional coatings/resin systems, they can be easily processed through already-established processes for applying coatings/resins.^[34]

Sustainability and Product Life Cycle Assessments

Evaluation of vegetable-oil-derived polymers should be made using a life cycle approach instead of just evaluating them based upon the percentage of "renewable" carbon incorporated into each system. Key considerations include agricultural input levels; crop land/water usage; fertilizer and pest control usage; oil extraction; chemical functionalization required for polymerization; solvent utilization; energy utilization; shipping of materials/products; fabrication process energy usage; product lifecycle duration (useful life); recyclability/dispersal post-use. Of particular importance is the source of the vegetable oil. Oils sourced from non-food/non-waste streams can help to alleviate competition with food supplies, though availability and variability in chemical composition may be greater. It would thus be beneficial to consider both resource efficiency and material consistency when selecting feedstock. In addition to performance attributes, the environmental performance of a polymer will depend on its useful lifespan and fabricating requirements. For example, a durable coating may enhance environmental performance by reducing the frequency of maintenance/replacement while a bio-based polymer with excessive energy intensive processing or with additives that cannot be recycled after use may not result in improved environmental performance relative to petroleum-based counterparts. Therefore, future research should seek to evaluate polymer performance concurrently with life cycle assessments (LCAs) and technical-economic analyses (TEAs) to better assess sustainability.^[35]

Challenges Limiting Industrial Implementation

There are several key limitations currently hindering widespread industrial adoption of vegetable-oil-derived polymers. One limitation arises due to variability inherent within different types of vegetable oils used as precursors for these polymers (botanical source variability). Such variability makes comparison/standardization difficult and influences polymer chemistry/material property characteristics. Another issue limiting mechanical properties in certain systems is that many vegetable-oil-derived

polymers possess lower mechanical properties (e.g., less stiff or less strong) compared to petroleum-based thermosets optimized over decades. Additionally, due to presence of unsaturated fatty acids, many vegetable oil-derived polymers can suffer from oxidative instability during processing/use. Oxidative instability can negatively impact long term durability/performance of materials. Finally, as mentioned above, there is a continued need for standardized performance data in order to compare vegetable-oil-derived polymers with established commercial polymers. For materials that are intended to remain in-service for extended periods of time (i.e., years), long-term durability is especially critical. Therefore, accelerated aging tests should be supplemented with realistic assessments of long-term durability.^[36]

Strategies for Improving Industrial Performance

There are several ways to achieve improvements in the performance of vegetable oil derived polymers. Molecular design, as described above, represents one of those methods. Depending upon the application area, various design parameters such as type of functional group present, molecular structure of the polymer backbone and degree of cross-linking can be controlled. Another method to increase performance of vegetable oil derived polymers is through hybridization. Vegetable oil derived polymers combined with either inorganic or carbon based fillers may significantly enhance mechanical properties, thermal properties, barrier characteristics and others. Dynamic polymer networks also provide additional advantages over traditional static polymer networks. Dynamic covalent bonding and/or reversible interactions may allow for self-healing properties; this property may potentially lead to enhanced repair ability and recyclability. Water-borne formulations will help decrease usage of organic solvents. UV-cured formulation systems will allow for rapid processing times and lower energy requirements. Using non-food grade oils (nonedible) or waste oils, will promote higher levels of resource utilization. This is due to less dependency on food-grade feedstock. Additionally, using catalytic and solvent efficient processes may further reduce energy usage, waste production and ultimately production cost which all contribute to increased industrially scalable processes.^[37]

Emerging Research Areas

Current trends indicate that vegetable-oil-derived polymers are evolving towards being multi-functional and application specific, rather than just replacing petrochemical polymers. Therefore, emerging research areas include both the use of renewable feedstocks and the incorporation of advanced functionalities and properties in the same system.^[38]

1. Self-healing coatings

Renewable polymer systems, when combined with dynamic chemical interactions, may lead to coating materials capable of restoring their original mechanical and barrier properties after damage occurs. Potential applications include extending product life and minimizing required maintenance.^[12]

2. Bio-based NIPUs

Cyclic carbonates produced from vegetable oil can react with amines to form non-isocyanate polyurethane systems.

The potential use of renewable raw materials in these systems presents a route to develop alternative polyurethane chemistries which rely less on conventional isocyanate-based routes.^[39]

3. Sustainable 3D-printing resins

Photopolymerizable acrylated vegetable oils appear to offer interesting feedstocks for photocurable additive manufacturing resins. Previous studies have explored the suitability of these materials for Stereolithography (SLA), Digital Light Processing (DLP) and similar techniques, while future work aims at finding a suitable balance among renewable content, processability, curing behavior and mechanical performance.^[40]

4. Multifunctional nanocomposites

Filler materials can provide a number of different functions in the matrix material formed from vegetable-oil-derived polymers. Examples of the functions provided by nanofiller materials include mechanical reinforcement, barrier enhancement, electrical conductivity, antibacterial properties and anticorrosive properties. To maximize the number of functions provided by each filler material, it is necessary to select the most suitable filler material(s) and ensure they are dispersed uniformly throughout the matrix material.^[41]

5. Circular polymer systems

It would be beneficial for designers to incorporate consideration of end-of-life characteristics during the material-design phase of polymer development. Characteristics such as repair, reuse, recycle, chemical recovery and longer service life can be designed-in to improve resource efficiency of vegetable-oil-derived polymer systems.^[42]

6. Data-driven material design

The integration of experimental polymer chemistry with computer simulation models and data-driven methodologies could help identify correlations between fatty acid compositions in vegetable oils used as precursors, architectures of resulting polymers, process variables affecting polymer synthesis/processing and final performances of the resulting polymers. Ultimately, such methodology could support more systematic design and optimization of vegetable oil derived functional polymers for specific applications.^[43]

Future Perspectives

If we are going to make a transition from using renewable feedstocks in the production of functionally-useful materials then the direction of our research is clearly changing from "synthesis-focused" to "application-focused material science." Rather than just studying how to synthesize new polymers based on vegetable oils, we need to think about what specific requirements an application has, and work backwards from there to determine which vegetable oil or other feedstocks would best meet those needs. Working this way could create an easier-to-see relationship between the design of the material and its actual performance.

To illustrate, when developing a coating that resists corrosion, the developer needs to consider such things as adhesion, barrier properties, whether or not the coating heals after being damaged (e.g., by cracking), at what temperature

it is cured, where it will be used during its service life, and how long it is expected to last. In similar fashion, if one is designing a bio-based adhesive to bind two substrates together, he/she should think about such things as the nature of each substrate; the amount of force needed to achieve the desired bond; under what conditions the adhesive must cure; the extent of exposure to water vapor that it may experience over time; the operating temperature range of the system where the adhesive will be used; and how long the adhesive is expected to provide good bonding characteristics.^[44]

Conclusions

The primary use of vegetable oils (VOs) is as a source of renewable feedstocks that can be transformed into different types of functional polymers. The structure of VOs based on triglycerides and the diversity of their fatty acid components allow for the creation of a wide variety of polymers that differ significantly in terms of architecture and physical-chemical properties. A large body of work exists related to the chemical transformation of VO into various forms of polymeric material; however, there is a growing trend towards characterizing the specific performance characteristics and commercial feasibility associated with each particular application. Polymers produced directly from VOs or through chemical transformations thereof have shown significant promise in various applications including but not limited to protective coatings, corrosion resistant systems, self healing materials, polyurethane (and non-isocyanate PU), adhesives, sealants, composite materials, elastomers, lubricants, packaging, biomedical materials, and 3D printed products. Of all the uses identified above, the generation of coatings and surface protection systems is one of the most critical since flexible and hydrophobic surfaces that contain self-healing and/or corrosion resistance capabilities are highly desirable. In addition to traditional applications, emerging areas such as 3D printing and biomedical technology continue to expand the technical reach of renewable materials. There appears to be a rapidly growing area of interest in using VO derived materials for sustainable coatings, self healing materials, PUs, AM processes, and biomedicine.

However, it is essential to recognize that even though many vegetable oil derived polymers have been reported to possess excellent mechanical/thermal/chemical properties they may not exhibit sufficient industrial relevance due to several factors including but not limited to: feedstock variability; low conversion efficiencies; thermal/mechanical limitations; poor oxidative stability; need for specialized processing techniques; high cost; difficulties associated with scaling up production; lack of standards for material characterization/testing; limited long term durability; and finally issues related to recycling/end-of-life management. It follows that future research efforts should focus on the performance of these materials in specific applications rather than solely focusing on how much bio-content they contain.

One possible path forward involves developing high performance multi-functional scalable and sustainable polymer systems where vegetable oils serve as molecular building blocks for advanced material design. To realize this vision additional technological developments such as self-healing chemistry, nanotechnology, water-borne formulations, UV curing, dynamic covalent networks, etc., would also enhance the practical utility of these materials.

Successful commercialization ultimately will require collaborations between polymer chemists/materials

scientists/engineering professionals/manufacturers/sustainability researchers.

Table 4: Summary of major industrial application areas

Application	Polymer systems	Key advantages	Major challenges	Industrial potential
Protective coatings	PU, epoxy, polyester, acrylate	Renewable content, flexibility	Durability, thermal resistance	High
Anti-corrosion coatings	PU, epoxy, NIPU, nanocomposites	Barrier protection, functionalization	Long-term corrosion resistance	High
Self-healing coatings	Dynamic polymers, capsules	Damage recovery	Healing efficiency, cost	Emerging
Adhesives	PU, polyester, epoxy	Flexibility, adhesion	Moisture/aging resistance	High
Sealants	PU, elastomeric systems	Elasticity	Long-term stability	Moderate–high
Composites	Epoxy, PU, polyester	Renewable matrix	Strength/thermal stability	High
Elastomers	PU, polyester	Flexibility	Mechanical durability	Moderate–high
Lubricants	Modified oils/polymer systems	Lubricity, renewability	Oxidative stability	High
Packaging	Polyester, PU, acrylate	Renewable content	Barrier properties	Emerging
Biomedical	PU, polyester, photocurable polymers	Tunable functionality	Biocompatibility	Emerging
3D printing	Acrylates/methacrylates	Renewable photocurable resins	Printability, strength	Emerging
Smart materials	Dynamic polymer networks	Multifunctionality	Complexity and cost	Emerging

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List of Abbreviations:

PU – Polyurethane **NIPU** – Non-Isocyanate Polyurethane **VO** – Vegetable Oil **SBO** – Soybean Oil **CO** – Castor Oil **LO** – Linseed Oil **TO** – Tung Oil **UV** – Ultraviolet **VOC** – Volatile Organic Compound **EIS** – Electrochemical Impedance Spectroscopy **LCA** – Life-Cycle Assessment **TEA** – Techno-Economic Analysis **DLP** – Digital Light Processing **SLA** – Stereolithography **PUA** – Polyurethane Adhesive **CNT** – Carbon Nanotube **GO** – Graphene Oxide **SEM** – Scanning Electron Microscopy **TGA** – Thermogravimetric Analysis **DSC** – Differential Scanning Calorimetry **ASTM** – American Society for Testing and Materials **ISO** – International Organization for Standardization

References

- Kathalewar M, Joshi PB, Sabnis A, Malshe VC. Non-isocyanate polyurethanes: from chemistry to applications. *RSC Advances*,2012;3:4110.
- Mo Y, Huang X, Hu C. Recent Advances in the Preparation and Application of Bio-Based Polyurethanes. *Polymers*,2024;16:2155.
- Bakkali-Hassani C, Berne D, Ladmira V, Caillol S. Transcarbamylation in Polyurethanes: Underestimated Exchange Reactions? *Macromolecules*,2022;55:7974–7991.
- Agnol LD, Dias FTG, Ornaghi HL, et al. UV-curable waterborne polyurethane coatings: A state-of-the-art and recent advances review. *Progress in Organic Coatings*,2021;154:106156.
- Yeligbayeva G, Khaldun MAA, Alfergani AA, et al. Polyurethane as a versatile polymer for coating and anti-corrosion applications: A review. *Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources*,2024;331:21–41.
- Chatterjee A, Sen S, Bhardwaj S, Maji PK. Polysilazane-Cross-Linked Acrylic Coatings for Wood: A Versatile Solution for Weather Resistance, Stain Repellence, and Fire Safety. *ACS Applied Engineering Materials*,2025;3:502–512.
- Cornille A, Auvergne R, Figovsky O, et al. A perspective approach to sustainable routes for non-isocyanate polyurethanes. *European Polymer Journal*,2016;87:535–552.
- Mantala K, Crespy D. Waterborne Polyurethane Transparent Coatings for Self-Healing at Room Temperature. *Macromolecules*,2025;58:3450–3459.
- Shen X, Zheng Q, Kim J. Rational design of two-dimensional nanofillers for polymer nanocomposites toward multifunctional applications. *Progress in Materials Science*,2020;115:100708.
- Vazirinasab E, Jafari R, Momen G. Application of superhydrophobic coatings as a corrosion barrier: A review. *Surface and Coatings Technology*,2017;341:40–56.
- Bao W, Deng Z, Zhang S, et al. Next-Generation Composite Coating System: Nanocoating. *Frontiers in Materials*,2019;6.
- Cho SH, White SR, Braun PV. Self-Healing Polymer Coatings. *Advanced Materials*,2008;21:645–649.
- Shchukina E, Wang H, Shchukin DG. Nanocontainer-based self-healing coatings: current progress and future perspectives. *Chemical Communications*,2019;55:3859–3867.
- Zhang F, Ju P, Pan M, et al. Self-healing mechanisms in smart protective coatings: A review. *Corrosion Science*,2018;144:74–88.

15. Mouren A, Avérous L. Sustainable cycloaliphatic polyurethanes: from synthesis to applications. *Chemical Society Reviews*,2022;52:277–317.
16. Chen J, Peng K, Wei-ping T. Novel waterborne UV-curable coatings based on hyperbranched polymers via electrophoretic deposition. *RSC Advances*,2019;9:11013–11025.
17. Hejna A, Kosmela P, Kirpluks M, et al. Structure, Mechanical, Thermal and Fire Behavior Assessments of Environmentally Friendly Crude Glycerol-Based Rigid Polyisocyanurate Foams. *Journal of Polymers and the Environment*,2017;26:1854–1868.
18. Delavarde A, Савин ГА, Derkenne P, et al. Sustainable polyurethanes: toward new cutting-edge opportunities. *Progress in Polymer Science*,2024;151:101805.
19. Lu Y, Larock RC. Soybean-Oil-Based Waterborne Polyurethane Dispersions: Effects of Polyol Functionality and Hard Segment Content on Properties. *Biomacromolecules*,2008;9:3332–3340.
20. Maulana S, Wibowo ES, Mardawati E, et al. Eco-Friendly and High-Performance Bio-Polyurethane Adhesives from Vegetable Oils: A Review. *Polymers*,2024;16:1613.
21. Konuray O, García-Espriu A, Morancho JM, et al. Hard epoxy thermosets obtained via two sequential epoxy-amine condensations. *European Polymer Journal*,2019;116:222–231.
22. Singh P, Rana A, Karak N, et al. Sustainable smart anti-corrosion coating materials derived from vegetable oil derivatives: a review. *RSC Advances*,2023;13:3910–3941.
23. Weyhrich CW, Petrova SP, Edgar KJ, Long TE. Renewed interest in biopolymer composites: incorporation of renewable, plant-sourced fibers. *Green Chemistry*,2022;25:106–129.
24. Khot SN, LaScala JJ, Can E, et al. Development and application of triglyceride-based polymers and composites. *Journal of Applied Polymer Science*,2001;82:703–723.
25. Diggle B, Jiang Z, Li R, Connal LA. Self-Healing Polymer Network with High Strength, Tunable Properties, and Biocompatibility. *Chemistry of Materials*,2021;33:3712–3720.
26. Murru C, Badía-Laiño R, Díaz-García ME. Oxidative Stability of Vegetal Oil-Based Lubricants. *ACS Sustainable Chemistry & Engineering*,2021;9:1459–1476.
27. García-García D, Quiles-Carrillo L, Balart R, et al. Innovative solutions and challenges to increase the use of Poly(3-hydroxybutyrate) in food packaging and disposables. *European Polymer Journal*,2022;178:111505.
28. Liu S, Maheshwari R, Kiick KL. Polymer-Based Therapeutics. *Macromolecules*,2009;42:3–13.
29. Bryers JD, Giachelli CM, Ratner BD. Engineering biomaterials to integrate and heal: The biocompatibility paradigm shifts. *Biotechnology and Bioengineering*,2012;109:1898–1911.
30. Machado TO, Stubbs CJ, Chiaradia V, et al. A renewably sourced, circular photopolymer resin for additive manufacturing. *Nature*,2024;629:1069–1074.
31. Fernandes FC, Kirwan K, Lehane D, Coles SR. Epoxy resin blends and composites from waste vegetable oil. *European Polymer Journal*,2017;89:449–460.
32. Lu Y, Larock RC. Novel Polymeric Materials from Vegetable Oils and Vinyl Monomers: Preparation, Properties, and Applications. *ChemSusChem*,2009;2:136–147.
33. Ling Z, Liang G, Liu S, et al. Non-isocyanate polyurethane from bio-based feedstocks and their interface applications. *RSC Applied Interfaces*,2025;2:1123–1142.
34. Mori R. Replacing all petroleum-based chemical products with natural biomass-based chemical products: a tutorial review. *RSC Sustainability*,2023;1:179–212.
35. Badía JD, Gil-Castell O, Ribes-Greus A. Long-term properties and end-of-life of polymers from renewable resources. *Polymer Degradation and Stability*,2017;137:35–57.
36. Zhu J, Birgisson B, Kringos N. Polymer modification of bitumen: Advances and challenges. *European Polymer Journal*,2014;54:18–38.
37. Xiong X, Yu IKM, Tsang DCW, et al. Value-added chemicals from food supply chain wastes: State-of-the-art review and future prospects. *Chemical Engineering Journal*,2019;375:121983.
38. Samuel HS, Ekpan F-DM, Ori MO. Biodegradable, Recyclable, and Renewable Polymers as Alternatives to Traditional Petroleum-based Plastics. *Asian Journal of Environmental Research*,2024;1:152–165.
39. Blattmann H, Fleischer M, Bähr M, Mülhaupt R. Isocyanate- and Phosgene-Free Routes to Polyfunctional Cyclic Carbonates and Green Polyurethanes by Fixation of Carbon Dioxide. *Macromolecular Rapid Communications*,2014;35:1238–1254.
40. Liguori A, Oliva E, Sangermano M, Hakkarainen M. Digital Light Processing 3D Printing of Isosorbide- and Vanillin-Based Ester and Ester–Imine Thermosets: Structure–Property Recyclability Relationships. *ACS Sustainable Chemistry & Engineering*,2023;11:14601–14613.
41. Zulkefli NA, Mustapha R, Jusoh SM, et al. Hybrid nanofiller reinforcement in thermoset and biothermoset applications: A review. *Nanotechnology Reviews*,2023;12.
42. Meier MAR, Metzger JO, Schubert US. Plant oil renewable resources as green alternatives in polymer science. *Chemical Society Reviews*,2007;36:1788.
43. Tremblay-Parrado K, García-Astrain C, Avérous L. Click chemistry for the synthesis of biobased polymers and networks derived from vegetable oils. *Green Chemistry*,2021;23:4296–4327.
44. Pethrick RA. Design and ageing of adhesives for structural adhesive bonding – A review. *Proceedings of the Institution of Mechanical Engineers Part L Journal of Materials Design and Applications*,2014;229:349–379.