REVIEW ARTICLE

SUSTAINABLE BIO-BASED POLYMERS: A DETAILED REVIEW

Mandar S. Gaikwad

Department of Chemistry,

Yeshwantrao Chavan Mahavidyalaya, Tuljapur, Dist. Dharashiv, M.S., India

*Corresponding author E-mail: mandar.gaikwad8@gmail.com

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Abstract:

The growing demand for sustainable materials and green technologies has encouraged the exploration of renewable feedstocks for the development of polymers, chemicals, and bioactive compounds. Recent studies emphasize the utilization of plant extracts, vegetable oils, starch, and microalgae as versatile raw materials. This review consolidates findings from contemporary research, focusing on bioactivity of plant extracts, synthesis of epoxidized alkyd and polyurethane resins from vegetable oils, starch-based polymer blends, value-added chemicals from microalgae, and innovations in castor oil–derived curing agents. Together, these contributions highlight the immense potential of renewable resources in replacing petroleum-based systems while offering biodegradability, functional diversity, and improved performance.

Keyword: Sustainable Materials, Green Technologies, Bio-active Compounds.

1. Introduction:

In recent years, sustainability has emerged as a central theme in polymer science and materials engineering, driven by the urgent need to reduce environmental degradation and dependence on fossil fuels. Conventional petroleum-derived polymers have played a pivotal role in modern society, yet their continued use poses serious ecological challenges. These synthetic materials are directly linked to greenhouse gas emissions during production, persistence of non-biodegradable plastic waste in the environment, and a growing reliance on finite fossil resources that are rapidly depleting. Such issues highlight the pressing necessity of identifying renewable and eco-friendly alternatives.

One promising direction is the utilization of renewable feedstocks such as plants, agricultural residues, and microalgae. These natural resources not only offer sustainable availability but also provide a wide array of chemical building blocks suitable for polymer synthesis. Plant biomass contributes structural biopolymers like cellulose, starch, and lignin, which can be transformed into biodegradable materials. In addition, plants are rich in secondary metabolites including phenolics, flavonoids, and alkaloids that exhibit antimicrobial, antioxidant, and pesticidal properties, making them valuable for developing functional, bioactive materials. Among renewable sources, vegetable oils have gained special attention due to their triglyceride-based molecular structures, which feature reactive double bonds and hydroxyl groups. These functionalities make them excellent precursors for synthesizing polyols, resins, and polyurethane systems. Similarly, microalgae represent a versatile feedstock, capable of producing lipids for biodiesel alongside high-value biochemicals such as pigments, proteins, and biopolymers. Importantly, both plants and algae can be cultivated on non-arable land, reducing competition with food resources.

Recent advancements in green chemistry and processing technologies have demonstrated that biomass-derived feedstocks can be chemically modified and tailored to yield materials with properties comparable to or even superior to petrochemical counterparts. Bio-based polymers and composites developed from these renewable resources have already shown potential in coatings, adhesives, foams, packaging films, and structural applications. Together, these innovations illustrate that renewable materials are not only environmentally sustainable but also technologically competitive, paving the way for a transition toward a circular bioeconomy.

This review discusses research in four interconnected areas:

i. Bioactive plant extracts (*Epipremnum aureum*).
ii. Vegetable oil–based resins and polyurethanes (jatropha, soybean, castor).
iii. Starch-based biodegradable polymer blends.
iv. Microalgal biorefineries for fuels and chemicals.

2. Bioactive Plant Extracts (*Epipremnum aureum*)

Nidhi Srivastava and her team studied the leaves and roots of *Epipremnum aureum* (golden pothos), a common indoor plant known for cleaning the air [1]. They tested extracts made using ethanol, methanol, acetone, and water. The results showed that these extracts could kill both Gram-positive and Gram-negative bacteria, with ethanol extracts being the most effective. In fact, water extracts from the plant's aerial roots created inhibition zones similar to the antibiotic streptomycin.

The extracts also showed strong antioxidant activity, as measured by enzymes like catalase (CAT), superoxide dismutase (SOD), and peroxidase (PX). Some tests even revealed antitermite properties [13]. Other researchers, such as Meshram and Srivastava, confirmed that these extracts are rich in natural compounds like alkaloids, phenolics, and flavonoids, which explain their antibacterial and antioxidant effects.

Overall, studies suggest that *E. aureum* can play a dual role: it works as a natural indoor air purifier and also as a source of useful bioactive compounds. Ethanol extracts of the leaves showed the strongest antimicrobial activity, while aqueous extracts of the roots were also very effective. Because of its high phenolic content, the plant consistently showed strong antioxidant and protective effects. These results highlight the value of ornamental plants not just for decoration or air cleaning but also as natural sources of medicines, preservatives, and eco-friendly pest control solutions. Future research should aim to identify the exact active compounds in *E. aureum* and ensure their safety for possible use in pharmaceuticals and other applications.

3. Vegetable Oil-Based Resins and Polyurethanes

3. 1. Epoxidized Alkyd Resins from Jatropha Oil

Alkyd resins are commonly used in paints and coatings but usually have weaknesses such as low hardness and poor heat resistance. To overcome this, Gogoi and co-workers developed epoxidized alkyd resins from non-edible jatropha oil. They used citric acid, a safe and natural compound, as a curing agent instead of harmful chemical catalysts [2]. When 50% epoxidized jatropha oil was added to the resin, the material became much stronger, with tensile strength increasing by about 3.18 MPa, and it could also withstand higher temperatures (about 42 °C more than before). This shows that citric acid can be successfully used to make eco-friendly, solvent-free coatings [12].

3.2 Soybean Oil–Based Polyurethanes

Soybean oil can be converted into polyols, which are important building blocks for making polyurethanes (PUs). Researchers developed waterborne polyurethanes (WPUs) from soybean oil polyols, which have the advantage of being less polluting because they avoid organic solvents. These materials showed a wide range of properties depending on how the polyols were designed and how much "hard" content was added [9]. For example, films made from soybean oil polyols had stiffness (Young's modulus) values ranging from 8 MPa (soft and rubber-like) up to 720 MPa (hard and rigid), with tensile strength reaching up to 21.5 MPa. Because of this versatility, soybean-based WPUs can be used for paints, protective coatings, adhesives, and foams, while also helping to reduce harmful VOC emissions [10].

3.3 Castor Oil as a Curing Agent

Castor oil is another valuable natural resource, rich in ricinoleic acid which contains a reactive hydroxyl group. Scientists modified castor oil by adding bromine and then reacting it with amines to make amino-functionalized derivatives [11]. These new compounds worked well as curing agents for epoxy resins. The resulting materials had much better thermal stability, chemical resistance, and mechanical strength. When reinforced with glass fibers, the composites made with castor oil curing agents were strong enough to be used in structural applications [19].

These studies clearly show that vegetable oils are highly versatile in polymer science. By making simple chemical changes, oils such as jatropha, soybean, and castor can be turned into resins, polyurethanes, and curing agents that perform as well as, or even better than, petroleum-based alternatives. This makes them an attractive option for sustainable, high-performance materials.

4. Starch-Based Biodegradable Polymer Blends

Starch is a cheap and naturally biodegradable material, which makes it attractive for sustainable packaging and other eco-friendly uses. However, pure starch has two big problems: it is brittle (breaks easily) and absorbs water (poor water resistance). These weaknesses limit its practical applications.

To improve its properties, researchers often mix thermoplastic starch (TPS) with other polymers. Wu and Zhang [3] created blends of TPS with waterborne polyurethane (WPU). The new TPS/WPU sheets were much stronger, more flexible, and resisted water better than plain starch films. The blending also led to higher crystallinity (improved structure), though the films became slightly less transparent.

In another study, Lu *et al.* (2005) blended glycerol-plasticized corn starch with polyurethane made from rapeseed oil. The resulting films were far tougher:

- Elongation at break (stretch before breaking) increased up to 480% (compared to less than 100% for starch alone).
- Tensile strength improved to 3–4 MPa, compared to 2–3 MPa for plain starch.
- Water resistance also improved, since the polyurethane added hydrophobicity.

Similar results have been found in many starch–PU systems: even a small addition of polyurethane (10–30%) makes starch films stronger, more flexible, and less sensitive to water. The films may lose a little optical clarity, but the overall benefits outweigh this drawback.

Because of these advantages, starch–PU composites are excellent candidates for food packaging, agricultural films, and medical materials. They combine biodegradability with the durability and strength needed for real-world applications.

5. Microalgal Biorefineries for Value-Added Products

Microalgae, such as *Chlorella vulgaris*, provide lipids for biodiesel but also yield valuable byproducts. Gong and You proposed a superstructure model integrating cultivation, harvesting, lipid extraction, biofuel production, and coproduction of chemicals such as hydrogen, propylene glycol, glycerol ethers, and polyhydroxybutyrate (PHB) [4].

Life cycle analysis indicated that algal processes could reduce greenhouse gas emissions by up to 63% compared with petrochemical pathways, while techno-economic modeling showed biodiesel cost reduction to $2.79 per gallon equivalent when coupled with value-added product streams. This underscores the role of algae as a multifunctional biorefinery feedstock rather than solely a fuel source [16-18].

6. Broader Perspective on Vegetable Oil Polymers

Chen's work gives a wide overview of how vegetable oils can be turned into many different polymers, such as polyols, polyurethanes, acrylates, and polycarbonates. The key idea is that the natural fatty acids in oils can be chemically modified to give them new functional groups. Once modified, these oils can serve as building blocks for useful materials.

Several common chemical processes are used:

- Epoxidation and ring-opening – adds oxirane rings (epoxides) to double bonds, which can then be opened to create polyols.
- Hydroformylation (oxo process) – introduces aldehyde or acid groups into unsaturated fatty chains.
- Ozonolysis – breaks double bonds to form diols and carboxylic acids.

Through these methods, vegetable oils can be transformed into many useful precursors. For example:

- Epoxidized soybean oil can be acrylated to make UV-curable coatings.
- Vegetable oils can also be used to produce polycarbonates without using toxic phosgene.

By choosing the right reactions, vegetable oils can be converted into a wide variety of bio-based polymers, including polyurethanes, acrylates, polyesters, and polycarbonates. These materials have been tested in coatings, adhesives, elastomers, foams, and biomedical devices, often showing properties similar to or even better than petroleum-based versions.

In short, vegetable oils are versatile, renewable raw materials. With relatively simple chemical modifications (like epoxidation, hydroformylation, or transesterification), they can replace petroleum in many types of polymer production, making them a cornerstone of sustainable materials research [5–8, 20].

7. Conclusion and Outlook:

The reviewed studies clearly demonstrate a growing shift toward the use of renewable natural resources for the development of sustainable, high-performance polymers. Together, they highlight how bio-based materials can offer both functional value and environmental benefits when compared to conventional petroleum-derived products.

7.1 Bioactive Plant Extracts: Plants such as *Epipremnum aureum* are not only valued as ornamental species but also as reservoirs of useful bioactive compounds. Their leaf and root extracts exhibit strong antimicrobial, antioxidant, and even antitermite properties, pointing to promising applications in pharmaceuticals, natural preservatives, and eco-friendly pest control.

7.2 Vegetable Oils: Oils from jatropha, soybean, and castor have proven highly versatile in polymer science. For example, jatropha oil–based alkyd resins cured with citric acid achieved improved strength (+3.18 MPa) and higher thermal stability (+42 °C). Soybean oil–derived waterborne polyurethanes showed a wide mechanical range, from soft elastomers (8 MPa modulus) to rigid plastics (up to 720 MPa modulus, ~21.5 MPa strength). Castor oil–derived curing agents produced robust epoxy composites suitable for structural use. These results confirm that vegetable oils can be engineered into coatings, adhesives, foams, and composites that rival petroleum-based systems.

7.3 Starch Blends: Blending inexpensive thermoplastic starch with waterborne polyurethane has been shown to overcome the brittleness and water sensitivity of starch alone. Such films display improved toughness (tensile strength rising from ~2 MPa to 3–4 MPa) and significantly better water resistance, while remaining biodegradable. This makes them attractive for applications like single-use packaging, agricultural films, and medical materials where both durability and eco-friendliness are important.

7.4 Microalgal Biorefineries: Microalgae offer a multifunctional feedstock for producing not only biodiesel but also value-added chemicals such as hydrogen, glycerol ethers, alcohols, and bioplastics. Integrated processing of algal biomass has the potential to reduce greenhouse gas emissions by more than 60% compared with petrochemical routes, while improving cost efficiency through co-product generation. This positions microalgae as a cornerstone of future renewable energy and materials systems.

Despite these advances, challenges remain in scaling up production, lowering costs, and ensuring long-term durability of bio-based polymers. Nonetheless, the combination of abundant natural feedstocks, eco-friendly chemical processes, and multifunctional performance makes it clear that bio-based polymers and plant extracts will be central to the circular bioeconomy of the future.

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