Recent Trends in Stereolithography Resin Formulation and Photoinitiator Systems with Sustainability Perspectives

Ismail Abiade[1]*, Moyinoluwa Oyelohunnu[1]*, O'Brien Zakumi Obed[2], Hauwau Abubakar Koaje[2]

[1]*Department of Engineering and Material Science, Meta-4 Solutions Ikeja, Lagos, Nigeria.*
[2]*Department of Chemistry, Faculty of Natural and Applied Sciences, Nile University of Nigeria, Abuja, Nigeria.*

ABSTRACT

Stereolithography (SLA) is a high-resolution additive manufacturing technique that fabricates complex structures through light induced photopolymerization of liquid resin systems. This review evaluates recent developments in SLA resin formulations, photoinitiator systems, and sustainability considerations that influence printing performance and environmental impact. Literature was sourced from Google Scholar, ScienceDirect, IEEE Xplore, Scopus, and Web of Science using keywords such as "Stereolithography" and "additive manufacturing," prioritizing studies from the past decade and following PRISMA guidelines. Previous studies report several classes of photocurable resins used in SLA, including acrylate and methacrylate resins, epoxy acrylates, urethane acrylates, poly(methyl methacrylate) systems, and emerging biobased resins derived from soybean oil, polycaprolactone, vanillin, and chitosan derivatives. These materials have been investigated for applications such as dental devices, tissue engineering scaffolds, conductive components, and reinforced composite structures. Photopolymerization efficiency in SLA is strongly governed by photoinitiators that generate reactive radicals upon light irradiation. Representative examples include Type I photoinitiators such as trimethylbenzoyl diphenylphosphine oxide and hydroxyacetophenone derivatives, and Type II photoinitiators such as benzophenone, camphorquinone, eosin Y, riboflavin, and curcumin. Recent research has also examined natural photoinitiators including chlorophyll, chalcones, coumarins, and naphthoquinone derivatives as alternatives to petroleum derived systems. This review critically examines recent SLA resin formulations and photoinitiator systems, emphasizing naturally derived photoinitiators and their effects on curing efficiency, material properties, and environmental performance. Applications across medical and non-medical sectors are evaluated to contextualize material requirements, while life cycle considerations highlight trade-offs between conventional petroleum-based and emerging bio-based resins, particularly in developing regions. Analysis indicates a growing focus on sustainable monomers, functional additives, and visible-light photoinitiators, though challenges in cost, recyclability, and long-term stability remain for broader SLA adoption.

KEYWORDS

stereolithography, resins, photoinitiators, 3D printing, photopolymerization

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INTRODUCTION

Stereolithography (SLA), one of the earliest 3D printing technologies, remains widely used for its ability to produce complex geometries and smooth surfaces due to high printing resolution.[1] Following the development of the SLA by Charles W. Hull at 3D Systems in 1980s, SLA is a widely used Additive Manufacturing (AM) technique.[2] SLA utilizes UV laser for curing and solidification of liquid photopolymer resins layer by layer based on a process known as photopolymerization to create 3D printed objects. SLA is a type of AM technique that uses laser light to trigger photopolymerization in a liquid resin, producing solid objects with high spatial resolution and layer thickness as low as 1 μm, under optimized laboratory conditions.[1] A successful stereolithographic printing process depends on precise control of several factors, including laser intensity, resin rheology and wetting properties, curing accuracy, and the chemical composition of the resin.[3]

Building upon this innovation, recent research has focused on optimizing formulation of photopolymer resin through the application of low-cost bio-acrylates. This important progress enhances the potential to achieve cost-competitiveness and support on-demand fabrication of a wide range of sustainable and renewable products and facilitate the biobased economy. [4] The majority of materials employed in SLA are conventional formulations, primarily consisting of epoxy resins, acrylate resins, and thermoplastic elastomers.[5] Most resin formulations include inert dyes that absorb incident light to enhance control over the polymerization process.[5] UV-curable resins have attracted considerable attention in the photosensitive resin industry due to their flexibility, strong adhesion, and tunable properties. [6]

Photosensitive resins cure upon exposure to light at specific wavelengths, while unexposed areas remain in liquid form, allowing for easy separation of printed parts from the resin. [7] These resins are typically composed of a initiator, an oligomer, monomer (reactive diluent), and additives. [8] Stereolithography has advanced well beyond its original role in prototyping and modeling, and is now increasingly used for manufacturing highly complex and detailed structures.[9] Researchers have developed various physical systems using different technologies to enhance the performance of stereolithography.[10]

Despite its technical advantages, SLA 3D printing remains limited by material accessibility, high resin costs, and dependence on imported photopolymer formulations, particularly in developing regions such as Africa and Nigeria. The high cost of importation and the lack of local manufacturing capacity for SLA photopolymer resins restrict widespread adoption and limit the technology's industrial impact.

This review addresses this gap by critically examining recent developments in SLA resin formulation and photoinitiator systems, with emphasis on naturally derived photoinitiator systems, their implications for curing efficiency, material properties, and environmental compatibility. The review also assesses applications of SLA across medical and non-medical sectors to contextualize material requirements within real-world use cases.

In addition, the environmental performance of SLA materials is examined through life cycle considerations, highlighting the trade-offs associated with conventional petroleum-based systems and emerging bio-based formulations. Particular attention is given to the structural and economic challenges faced by developing regions in

*To whom correspondence should be addressed
Email: ismail@createyourmeta-iv.com and moyin@createyourmeta-iv.com

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accessing and producing SLA resins. The review further discusses the future direction of SLA 3D printing, emphasizing the need for local production, material innovation, and sustainable practices to foster wider adoption and long-term growth.

This review drew literature from databases including Google Scholar, ScienceDirect, IEEE Xplore, Scopus, and Web of Science, using keywords such as "Stereolithography" and "additive manufacturing." Studies were included based on their relevance to photopolymer SLA resins and SLA advances in additive manufacturing, while works focusing solely on other vat polymerization techniques were excluded. Priority was given to research from the past decade to capture recent developments, though seminal and highly cited older studies were also considered. The review adhered to PRISMA guidelines to ensure transparency and methodological rigor.

RECENT INNOVATIONS IN STEREOLITHOGRAPHY RESIN FORMULATIONS

Recent advancements in stereolithography have focused not only on hardware improvements but also on the development of more efficient and sustainable resin formulations. Traditional SLA resins, primarily based on petroleum-derived acrylates and epoxies, often present limitations in cost, environmental impact, and mechanical performance. In response, researchers are exploring novel formulations that incorporate bio-based monomers, functional additives, and tailored photoinitiator systems to enhance curing efficiency, reduce toxicity, and expand material properties.

Hata et al.[11] developed an SLA-printable resin based on a Poly(methyl methacrylate) (PMMA) system comprising methyl methacrylate (MMA), ethylene glycol dimethacrylate (EGDMA), and PMMA powder in varying ratios. Increasing PMMA content raised viscosity, whereas higher EGDMA improved mechanical strength but reduced bond strength. The optimal formulation 30 % PMMA, 56 % EGDMA, and 14 % MMA, demonstrated strong mechanical performance and satisfactory biological and physicochemical properties, comparable to or exceeding those of commercial resins. This PMMA-based resin shows promise for application in dental SLA printing.

Romeis & Drummer[12] formulated a dual-cure resin system by blending different concentrations of an epoxy/curing agent mix with a photocurable methacrylate resin. The material was first printed via SLA to form UV-cured green parts, then thermally post-cured to enhance performance. Mechanical and dynamic mechanical tests on the fully cured specimens showed that higher epoxy content led to improved tensile strength and higher glass transition temperatures. Desai & Jagtap[13] synthesized a resorcinol-based diglycidyl ether and converted it into a resorcinol epoxy acrylate oligomer through acrylation. The resulting oligomer was used to develop photocurable resin formulations by incorporating reactive diluents and photoinitiators. Glass, nylon, and polyester fibers were then added at varying loadings to create reinforced composites. The resin–fiber composites significantly influence the final performance of SLA-printed parts, especially in structural and optical applications.

Field et al.[14] synthesized a customizable and easy-to-produce photocurable resin for stereolithography, derived from poly(caprolactone) (PCL). PCL triol was methacrylated to different extents and combined with a photoinitiator to create a UV-curable prepolymer that forms a cytocompatible material upon curing. The resulting poly(caprolactone) methacrylate (PCLMA) exhibits adjustable mechanical strength and degradation profiles depending on the degree of methacrylation. Increasing methacrylation raised the Young's modulus from 0.12 to 3.51 MPa and slowed the degradation rate from full breakdown in 17 days to minimal change over 21 days. The resin formulation provides a flexible platform for fabricating tissue engineering scaffolds with application-specific properties. Romero-Ocaña et al.[15] reported a novel incorporation of wheat and rice fibers of different sizes, derived from agricultural wastes, into a photocurable resin for composite fabrication using stereolithography. Mechanical testing showed a clear relationship between fiber size and properties like elastic modulus, tensile strength and elongation at break. The composites exhibited low thermal conductivity, making them promising candidates for use as insulating boards in construction. Tsai et al. [16] introduced a novel approach to resin formulation designed for producing conductive structures through Digital Light Processing (DLP) 3D printing. The formulated resin showed strong printability and enabled the fabrication of conductive components with electrical conductivity up to 1000 S/cm, without the need for post-processing or sintering. The authors also applied multi-material SLA to integrate conductive tracks within insulating matrices, achieving reliable interlayer connections, including blind and through-hole vias. The study highlights the potential for incorporating functional electronic features directly into SLA-printed parts.

Vetri Buratti et al.[17] synthesized a novel biobased resin suitable for stereolithography, developed by combining a photocurable poly(ester amide) (PEA) derived from renewable sources with citrate and itaconate crosslinkers, along with selected photoinitiators, terminators, and dyes. The mechanical properties and biocompatibility of the 3D printed structures were thoroughly examined to assess the potential of this resin for applications in the textile and fashion sectors. Desai & Jagtap[18] synthesized a resorcinol epoxy acrylate (REA) oligomer, formulated it with reactive diluents, and tested its suitability for SLA 3D printing. Formulations were prepared by adding 10 %, 15 %, and 20 % of reactive diluents to the REA oligomer, while maintaining a constant photoinitiator concentration. The results showed that higher diluent content improved overall performance of the resin. The 20 % formulation demonstrated optimal SLA compatibility, producing printed parts with strong dimensional stability and mechanical strength.

Rafalko et al. [19] developed a thermoset acrylate polymer resin for SLA that enables the fabrication of complex parts with high mechanical performance, showing a modulus of 1500 MPa and strain at break between 13% and 46%. The printed parts can be made fully water-soluble for use in cavity molding. While stable in neutral and acidic water, they dissolve quickly in basic conditions due to the inclusion of methacrylic anhydride, which introduces hydrolytically cleavable cross-links. By varying the monomer and cross-linker ratios, the mechanical properties can be adjusted. This resin is compatible with standard vat polymerization methods and enables fast, precise printing of detailed parts for uses like tissue scaffolds and sacrificial molds in lost-wax casting.

Celikci et al.[20] developed a composite resin for stereolithography by incorporating chitosan (CH) and its water-soluble derivatives carboxymethyl chitosan (CMCH), hydroxypropyl chitosan (HPCH), and hydroxyethyl chitosan (HECH) into acrylate resin formulations. The base resin system consisted of tripropylene glycol diacrylate (TPGDA), urethane acrylate (UA), and 1% diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide (TPO) as the photoinitiator. The optimal formulation was achieved at a 1:1 TPGDA to UA ratio, with a curing time of 60 seconds and a resin viscosity of 340–350 cP, which is suitable for SLA processing. Incorporating chitosan and its derivatives influenced the mechanical and chemical properties of the cured resins. While compressive strength declined with the addition of these biopolymers, tensile strength improved when CH, CMCH, or HECH was added up to 2.5 wt%, enhancing the flexibility of the printed parts. The cured resins exhibited high gel content (96.11 % – 97.72 %), confirming effective crosslinking. Chemical resistance tests indicated that the materials were stable in acidic and basic environments (HCl, NaOH, HF), though they showed poor resistance to organic solvents like toluene and chloroform. However, UV aging tests revealed that the inclusion of CH derivatives accelerated photooxidative degradation, reducing long-term stability.

Pitzanti et al.[21] developed photocurable resins by combining urethane dimethacrylate (UDMA) with three difunctional methacrylic diluents ethylene glycol dimethacrylate (EGDMA), di(ethylene glycol) dimethacrylate (DEGDMA), and tri(ethylene glycol) dimethacrylate

(TEGDMA). They characterized these formulations by measuring viscosity, thermal behavior, and printability. The photopolymerizable formulations showed promising attributes that support their suitability for tissue engineering and other biomedical applications. Bodor et al.[22] investigated the impact of mono- and bifunctional reactive diluents on the printability and performance of acrylated epoxidized soybean oil (AESO) based resins. Polyethylene glycol di(meth)acrylates of different molecular weights were used as diluents to modulate viscosity and mechanical properties in binary AESO mixtures. The optimized resin formulation showed a 16 % increase in modulus, a 63 % increase in tensile strength, and a 21 % increase in deformation at break compared to pure AESO. Jacobs working curves confirmed enhanced printability, and printed patterns showed better accuracy. The resin achieved a biorenewable carbon content of 67 %, indicating strong potential for applications in electronics and biomedical fields. However, expanding the range of bio-based raw materials remains a key challenge.

Sakarya et al.[23] focused on the synthesis of methacrylated polycaprolactone (PCLMA) through the reaction of polycaprolactone with methacryloyl chloride, followed by crosslinking with glycerol acrylate (GA) using Diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide (TPO) as the photoinitiator. The resulting formulation was used for stereolithographic 3D printing of biomaterials for tissue engineering. The GA-crosslinked PCLMA, particularly the PCLMA-8 formulation, exhibited good biocompatibility and is a promising candidate for tissue engineering applications.

Fuc et al.[24] recently reported the synthesis of three methacrylate monomers, vanillin methacrylate cinnamyl methacrylate, and vanillyl dimethacrylate, using methacrylic anhydride and potassium acetate as a catalyst. The catalyst used offers a more practical and efficient alternative to the commonly used 4-dimethylaminopyridine. Methacrylic acid (MA), formed as a secondary byproduct, was recovered and used to modify rapeseed oil for thermoset production. The synthesized monomers were formulated into a multicomponent resin system for SLA 3D printing. The formulated resin showed a tensile strength of 12.7 MPa, flexural strength of 16.8 MPa, storage modulus of 570 MPa at 30 °C, a glass transition temperature of 83.7 °C, and a heat resistance index of 169.5 °C while delivering superior mechanical and thermal performance.

These recent innovations in SLA resin formulations demonstrate a clear shift toward sustainable, functional, and application-specific materials. Researchers are moving away from conventional petroleum-based systems by integrating bio-based monomers like AESO, PCL, vanillin, and chitosan derivatives, and by exploring hybrid systems that combine thermal and UV curing or include functional additives such as fibers, conductive fillers, and flexible crosslinkers. These efforts are aimed at overcoming long-standing limitations in SLA resins, particularly brittleness, toxicity, and limited biodegradability. Mechanical performance and print fidelity continue to improve, with many studies reporting enhanced modulus, strength, and dimensional stability, as well as compatibility with standard SLA processes. However, challenges remain in balancing printability with mechanical robustness, ensuring long-term chemical stability, and scaling up synthesis of new resin components. Future work should focus on expanding the library of biorenewable building blocks, developing more robust and less toxic photoinitiators, and improving recyclability and end-of-life degradation profiles.

To facilitate a clearer comparison of these recent innovations in SLA resin formulations, Table 1 summarizes the key differences among the reported systems in terms of mechanical strength, degradation behavior, and printability. While individual studies emphasize specific performance targets such as high modulus, biodegradability, electrical functionality, or sustainability, a side-by-side comparison highlights the trade-offs that exist between structural robustness, environmental responsiveness, and process compatibility. This comparative overview provides a structured perspective on how formulation strategies influence final material performance and helps identify areas where further optimization is still required.

PHOTOINITIATORS FOR STEREOLITHOGRAPHY

Photoinitiators (PI) are central to resin technology. They absorb light energy and generate reactive species, usually free radicals, that initiate the polymerization of acrylates, methacrylates, or other photocurable monomers in the resin formulation. This reaction occurs when light at a specific wavelength excites electrons to higher energy states, leading to their decay and the formation of reactive species that trigger polymerization.[25] The type, concentration, and light sensitivity of the photoinitiator directly affect cure speed, resolution, mechanical performance, and biocompatibility of the printed material. Radical photoinitiators, which respond to UV or visible light, are divided into Type I and Type II based on their mechanism of active species generation as shown in Table 2.

Type I photoinitiators

Type I photoinitiators are single-component systems that, upon light excitation, undergo homolytic or heterolytic bond cleavage to generate two reactive species that initiate polymerization.[26] Examples of the Type I photoinitiators as reported in literature include trichloromethyl-S-triazine glyoxylates, acyloximino esters, phosphine oxides, hydroxyacetophenones, α-aminoalkylacetophenones, benzoin derivatives, benzylketals, oxime esters, glyoxylates, o-acyl-α-oximino ketones, hexaaryl biimidazoles (HABIs), and α-haloacetophenones.[27] Depending on their chemical structure and cleavage mechanism, they can produce radicals with varying reactivity and efficiency, influencing the polymerization rate and final properties of the cured resin.[26] When excited, the molecule enters a singlet state and may undergo intersystem crossing to a triplet state.[28] In the triplet state, bond cleavage can occur at the α-position of a carbonyl group, while β-scission may also happen if a weak bond exists between the α-carbon and a heteroatom or at the beta-position of a conjugated system.[28] This mechanism allows some molecules, like trichloromethyl triazine derivatives, to act as photoinitiators without carbonyl groups, as they generate Cl radicals through C–Cl bond cleavage.[29] An example of this, is the excitation of trimethylbenzoyl-diphenylphosphine oxide which undergoes rapid cleavage from the triplet excited state, generating two radicals: trimethylbenzoyl radical and diphenylphosphinoyl radical which can initiate polymerization at different rates.[30] This demonstrates the bond cleavage process at the α-position of a carbonyl group and the potential for β-scission when a weak bond exists between the alpha-carbon and a heteroatom. Type I initiators exhibit high cleavage rates, promoting efficient radical generation (ΦR) and polymerization initiation.[26] However, α-cleavable initiators are mainly limited by their spectral sensitivity, which is largely confined to the ultraviolet region.[26]

Type II photoinitiators

Type II photoinitiators are typically characterized by their ability to undergo a bimolecular photochemical reaction upon absorption of light, where two molecules interact to generate the active species required for polymerization. In Type II photoinitiators, the excited initiator molecule interacts with a suitable co-initiator, such as an electron donor, electron acceptor, or hydrogen donor, to generate the required radicals or radical-ions for polymerization.[31] Example of Type II photoinitiators include: Eosin-Y, Riboflavin, Camphorquinone, Benzophenone, Anthraquinones, Thioxanthones, Curcumin, Chalcones, among others.[32–38] Type II initiator performance depends on both their physicochemical properties and the choice of co-initiator.[26] The Type II is typically slower and less efficient due to competitive processes occurring during the excitation of the photoinitiator, involving the monomer, co-initiator, and atmospheric oxygen.[33]

Table 1: Comparison of recent SLA resin formulations in terms of mechanical properties, degradation behavior, and printability

Resin System	Mechanical Strength	Degradation Behavior	Printability	References
PMMA, MMA, EGDMA	High mechanical strength at 56% EGDMA, good bond strength at optimized 30% PMMA	Not degradation focused, typical thermoset stability	Good SLA compatibility at optimized viscosity	11
Epoxy/ methacrylate dual cure	Higher tensile strength and Tg with increased epoxy content	Thermally stable network, no designed degradability	Printable as green body, requires UV then thermal post cure	12
Resorcinol epoxy acrylate with fibers	Improved mechanical performance with fiber reinforcement	Not designed for biodegradation	Compatible with SLA, performance depends on filler loading	13
PCL methacrylate	Young modulus 0.12 to 3.51 MPa depending on methacrylation	Tunable degradation from 17 days full breakdown to minimal degradation over 21 days	Good UV curing, suitable for scaffold fabrication	14
Resin with wheat and rice fibers	Increased elastic modulus and tensile strength depending on fiber size	Not primarily degradable, thermal insulating behavior	Printable composites, fiber size affects resolution	15
Conductive DLP resin	Mechanical data secondary to electrical performance	Not degradation focused	High print fidelity, conductive up to 1000 S per cm without sintering	16
Biobased PEA with citrate and itaconate	Good mechanical integrity with biocompatibility	Biobased, potential hydrolytic susceptibility	Suitable for SLA textile applications	17
REA with reactive diluents	20% diluent showed optimal strength and dimensional stability	Stable thermoset network	Improved SLA compatibility at higher diluent content	18
Acrylate thermoset with cleavable links	Modulus 1500 MPa, strain at break 13 to 46%	Stable in neutral and acidic water, rapid dissolution in base	Compatible with standard vat polymerization, high precision	19
TPGDA and UA with chitosan derivatives	Increased tensile strength up to 2.5w% filler, reduced compressive strength	Accelerated photooxidative degradation with chitosan derivatives	Suitable viscosity 340 to 350 cP, 60 second curing time	20
UDMA with methacrylic diluents	Mechanical properties dependent on diluent type	Not degradation driven	Tuned viscosity and good printability	21
AESO with PEG dimethacrylates	16% modulus increase, 63% tensile strength increase	Biobased content 67% not designed for fast degradation	Improved accuracy confirmed by Jacobs working curves	22
PCLMA crosslinked with GA	Good biocompatibility and mechanical stability	Biodegradable polyester backbone	SLA compatible for biomaterial scaffolds	23
Vanillin and related methacrylates	Tensile strength 12.7 MPa, flexural 16.8 MPa, Tg 83.7 degrees C	Thermoset, not rapid degradation	Good SLA performance, multicomponent resin system	24

Table 2: Classification, mechanistic pathways, and characteristics of Type I and Type II photoinitiators

Category	Type I Photoinitiators	Type II Photoinitiators
Photochemical System	Unimolecular (single-component)	Bimolecular (requires a co-initiator)
Activation Mechanism	Light excitation induces direct bond cleavage (homolytic or heterolytic) leading to two reactive radical species	Light excitation leads to an excited state that interacts with a co-initiator (electron donor/acceptor or hydrogen donor) to generate radicals
Excited State Dynamics	Molecule transitions to singlet then triplet state; bond cleavage often occurs at the α-position of a carbonyl group; β-scission may also occur depending on bond strength and position	Excited state initiator reacts with co-initiator via electron or hydrogen transfer; radical formation depends on the co-initiator efficiency and environmental conditions
Examples	Trichloromethyl-S-triazine glyoxylates, phosphine oxides, hydroxyacetophenones, α-aminoalkylacetophenones, benzoin derivatives, oxime esters, glyoxylates, α-haloacetophenones, hexaaryl biimidazoles (HABIs), benzylketals	Eosin-Y, Riboflavin, Camphorquinone, Benzophenone, Anthraquinones, Thioxanthones, Curcumin, Chalcones
Radical Generation	High cleavage rate constants; two radicals directly produced from initiator	Radicals produced through bimolecular reaction with co-initiator; efficiency depends on both initiator and co-initiator
Photoinitiation Efficiency	Generally higher due to rapid radical generation and high ΦR	Generally lower; influenced by co-initiator type and presence of oxygen which can quench radical generation
Spectral Sensitivity	Typically absorbs in the ultraviolet region	Broader spectral range depending on initiator-co-initiator pair; some visible light activity
Advantages	High initiation efficiency; fast polymerization initiation	Allows flexibility through co-initiator tuning; enables use of visible light
Limitations	Limited spectral sensitivity; poor activity under visible light	Lower efficiency; sensitive to oxygen inhibition and co-initiator interaction dynamics
Relevance to SLA	Preferred for UV-based SLA resins where rapid polymerization is critical; limited for visible-light SLA	Suitable for visible-light SLA resins; allows tuning of cure depth and rate via co-initiator; can improve penetration in thicker layers

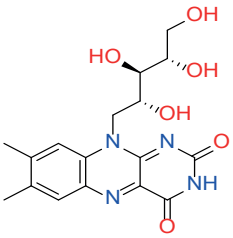
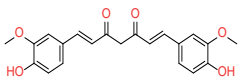
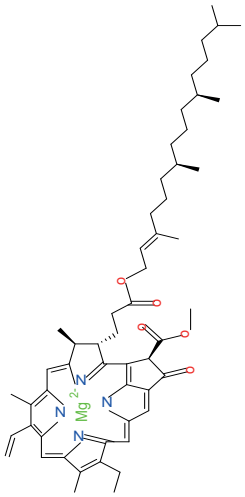
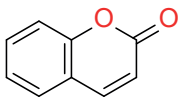
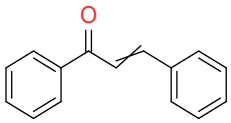
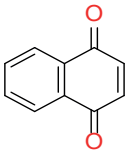
BIO-BASED PHOTOINITIATORS

Bio-based photoinitiators are gaining significant attention due to their potential for enhancing sustainability in photopolymerization processes. These initiators as shown in Table 3 are derived from renewable resources, such as natural plant extracts, oils, and other bio-based compounds, offering a more environmentally friendly alternative to traditional petrochemical-based photoinitiators. The development of bio-based photoinitiators aligns with the growing demand for greener, more sustainable chemical processes, especially in applications like SLA resin formulations, where environmental impact is a concern.

Riboflavin

Riboflavin (vitamin B2) is a water-soluble, naturally occurring compound that is both biocompatible and non-toxic.[38] Riboflavin can be sourced from plants including asparagus, broccoli, and spinach, as well as from animal organs such as kidneys and liver.[35,39] It appears orange-yellow and absorbs light across 200 to 470 nm, covering both UV and visible regions, with peak absorption at 223, 267, and 373 nm in the UV range, and at 444 nm in the visible range.[40] In the presence of oxygen, it absorbs light at wavelengths around 380 and 450 nm, leading to the generation of reactive singlet oxygen, making it an excellent photoinitiator.[38] The singlet oxygen generated functions as a photoinitiator by oxidizing biomolecules like amino acids, proteins, and nucleotides, or by initiating reactions such as the thiol-ene process and the crosslinking of tyramine and furfuryl groups.[38] Riboflavin and its derivatives have been widely studied as Type II photoinitiators in the presence of electron donors for the free radical polymerization of acrylamide.[41] Under UV irradiation, riboflavin primarily acts as a Type I initiator by generating superoxide radicals, although its mechanism can vary depending on the light source and reaction conditions.[42] In the Type I pathway, excited riboflavin transfers energy to a substrate, generating riboflavin-derived free radicals that react with molecular oxygen to produce oxidation products.[38] In the Type II pathway,

Table 3. Summary of optical characteristics and photochemical properties of selected bio-based photoinitiators

Compound name	Chemical Structure	Absorption Wavelength (nm)	Type of PI	Photochemical Behaviour
Riboflavin		223, 267, 373 (UV), 380, 444, 450 (Visible)	Type I and Type II	Functions as a Type I photoinitiator under UV light by radical generation; exhibits Type II activity via singlet oxygen under visible light.
Curcumin		200–600 (peak at 417)	Type II	Initiates radical polymerization under visible light; biocompatible, with high solubility and low toxicity.
Chlorophyll A		430–450	Type II	Absorbs violet-blue light; forms reactive oxygen species in the presence of co-initiators.
Coumarins		344, 362, 363, 423	Type II	Capable of initiating polymerization in the presence of amines; absorption properties tunable via substitution.
Chalcones		270–510 (maxima at 347, 405, 421, 480)	Type II (Type I via derivation)	Undergoes photoinduced electron transfer; derivatized forms support both free radical and cationic photopolymerizations.
Naphthoquinones		Around 420; some derivatives up to 478	Type II (some Type I)	Absorbs visible light; derivatives can generate radicals directly, depending on structure and environment.

riboflavin transfers energy directly to oxygen, forming singlet oxygen that then oxidizes the substrate; this route is more reactive but occurs predominantly under higher oxygen concentrations, while the Type I mechanism is favored when oxygen is limited.[38,43] Riboflavin has been used to fabricate photo-crosslinked membranes for guided tissue regeneration, hydrogels for bone and cartilage repair, and in UVA-induced corneal collagen cross-linking to treat keratoconus.[44–47] Riboflavin has also been employed in 3D printing polyethylene glycol diacrylate for potential tissue engineering applications.[48]

Curcumin

Curcumin is a hydrophobic phenolic compound of natural origin that has attracted attention as a potential natural photoinitiator.[37] It is a natural yellow-orange pigment derived from the rhizomes of *Curcuma longa*, is well known for its medicinal properties, including anti-inflammatory, antibacterial, antioxidant, and antiviral activities.[49] It has shown effectiveness against a range of viruses, including SARS-CoV-2, and has gained attention in the development of bio-based photoinitiators for various applications.[35,50] Due to its aromatic structure and extended π-conjugation, curcumin exhibits strong optical absorption in the blue light range (200 to 600 nm), peaking at 417 nm, making it suitable as a visible light-sensitive compound.[51] Furthermore, unlike riboflavin and flavone derivatives, curcumin exhibits high solubility in a wide range of both polar and nonpolar monomers and polymers.[37] In addition to its low toxicity, this property makes curcumin a promising candidate for photopolymerization applications.[37]

Curcumin is less dependent on oxygen. While riboflavin generates singlet oxygen to initiate reactions, curcumin can produce radicals efficiently through both Type I and Type II pathways, allowing photopolymerization to proceed even under partially oxygenated conditions.

Chlorophylls A

Chlorophyll A is a multi-component organic photoinitiator that absorbs visible light mainly in the violet–blue range (430–450 nm), giving it a green appearance.[35] Biologically, chlorophyll A plays a fundamental role in photosynthesis, acting as the primary pigment responsible for capturing light energy and converting it into chemical energy. It is ubiquitous in photosynthetic organisms, including higher plants, eukaryotic algae, and cyanobacteria, where it is embedded in the thylakoid membranes of chloroplasts and cyanobacterial cells.[41] In addition to its natural biological functions, chlorophyll A has gained attention in photopolymer chemistry. It acts as a type II photoinitiator, meaning it requires a co-initiator to generate free radicals upon light activation. Under violet-blue light irradiation, chlorophyll A can initiate the free radical polymerization of monomers such as methyl methacrylate. This process leads to the formation of crosslinked polymethyl methacrylate networks, which are relevant in biomedical and materials science applications.[52] Within the photosystems, specifically Photosystem I and Photosystem II, pairs of chlorophyll A molecules in the reaction centers participate in redox reactions that transfer electrons through the electron transport chain, ultimately driving the synthesis of ATP and NADPH.[53] The combination of natural abundance, visible light activation, and low toxicity further positions chlorophyll A as a sustainable and efficient photoinitiator in light-mediated polymer synthesis.

Chalcones

Chalcones are open-chain flavonoids consisting of two aromatic rings (A and B) connected by a three-carbon α,β-unsaturated carbonyl system. They are naturally occurring compounds widely present in edible plants, including fruits such as tomatoes, apples, and citrus, as well as nuts and vegetables such as potatoes, shallots, and bean sprouts.[54] They display a wide range of biological activities, including anti-inflammatory, antibacterial, antiviral, anticancer, and antioxidant effects.[54] Chalcones show strong optical properties and high light sensitivity due to extensive conjugation, making them promising non-linear optical materials.[41]

This enhanced conjugation enables chalcones to interact effectively with light, resulting in their potential for various photonic and optoelectronic applications. As type II photoinitiators, they absorb light mainly in the UV-blue region, with some types exhibiting absorption maxima at wavelengths of 423, 363, 362, and 344 nm.[35] However, through appropriate derivatization and substitution of the chalcone core, their photoelectric properties can be adjusted, shifting the absorption to the blue-green region.[55] Chalcones can generate free radicals through homolytic cleavage or through energy or electron transfer interactions with co-initiators. This versatility allows them to initiate polymerization of various monomers, including acrylates and methacrylates.[56]

Coumarins

Coumarins and their derivatives are naturally occurring plant compounds found in sources such as tonka beans, strawberries, cherries, apricots, cinnamon, and vanilla herbs.[41] They exhibit a wide range of biological activities, including antibacterial, antiviral, anticoagulant, and anticancer effects, which support their potential use in pharmacological applications.[57] Coumarins are typically colorless to white solids that absorb light in the near-UV-vis regions (270–510 nm), with some derivatives showing absorption maxima at 405 nm and 421 nm.[35] They act as Type II photoinitiators, initiating free-radical polymerization of methacrylate monomers such as bisphenol-A glycidyl methacrylate and triethylene glycol dimethacrylate (Bis-GMA/TEGDMA), as well as cationic polymerization of epoxy resins.[35] Coumarins have also been used in the photopolymerization of photosensitive resins for 3D printing and epoxy silicones under 405 nm laser diode irradiation, as well as in the fabrication of hydrogels for tissue engineering applications.[58–60] Coumarin-based iodonium hexafluoroantimonate is a white photoinitiator that absorbs at 347 nm in the blue-light region and has been applied in the photopolymerization of dental adhesive resins, including Bis-GMA, TEGDMA, and hydroxyethyl methacrylate.[61] Coumarin oxime esters, absorbing in the 400-480 nm range, can also initiate free radical polymerization of acrylates.[62] However, it is important to note that high concentrations of coumarin can be hepatotoxic, so precautions should be taken to use the minimum effective amount necessary to photoinitiate the polymerization reaction.[35] Coumarins have not been used directly in their natural form but are typically derivatized through synthetic functionalization pathways to enhance their properties and expand their applications.[37] Structural modification of coumarins at different positions can be used to tune their absorption spectra, enabling the design of both Type I and Type II photoinitiators.[41] Common strategies in designing coumarin-based photoinitiators include adding polyaromatic groups to increase aromaticity and introducing functional groups at the coumarin 3-position.[63]

Naphthoquinones derivatives

Naphthoquinone derivatives are naturally occurring functional metabolites produced by plants, microorganisms, marine organisms, and other sources.[64] They are generally easy to obtain and are known for their antibacterial and antitumor activities.[65,66] Naphthoquinone derivatives display yellow, red, orange, or purple colors and exhibit maximum absorption near 420 nm in the visible blue-light region.[35] Naphthoquinone derivatives were among the first compounds investigated as molecular charge separators (MCSs), leading to the identification of correlations between specific structural features and their photoinitiation performance.[67] Most naphthoquinones act as type II photoinitiators capable of initiating free radical polymerization of acrylate monomers.[67] Additionally, specific derivatives such as 1,4-naphthoquinone-2,3-dithiol can operate as type I photoinitiators,

initiating acrylate polymerization under visible light irradiation at 478 nm.[68] Compared to chlorophyll, naphthoquinone derivatives generally exhibit lower initiation efficiency. These derivatives mostly acting as Type II photoinitiators, rely on co-initiators and show slower radical production. Specific Type I derivatives of naphthoquinones can improve efficiency, but overall, they are less effective than chlorophyll in initiating polymerization under similar light conditions.

APPLICATIONS OF STEREOLITHOGRAPHY 3D PRINTING

SLA 3D printing is used in both medical and non-medical sectors as shown in Figure 1. In medicine, it supports pharmaceutical production, and biomedical applications in custom implants and tissue engineering. Outside medicine, it is used in fabricating complex building parts, food processing, and in engineering fields like aerospace and automotive.[69–71]

Medical application

SLA is widely used in medicine for its micron-scale precision and smooth finish. In pharmaceuticals, SLA enables complex dosage forms and personalized drugs. This technology has been applied to produce batches of tablets in various shapes to investigate how different factors impact drug release.[72] The findings showed that the surface-area-to-volume ratio strongly influences the release rate, which is important for designing tablets with different dosages while maintaining consistent release profiles.[72] 3D printing of tablets, capsules, and microneedle patches using SLA supports complex release profiles and combination drugs.[73] This level of control allows precise dosing and complex geometries that are difficult with conventional methods.

In tissue engineering, SLA produces biocompatible scaffolds with controlled porosity and architecture. SLA-printed bone or cartilage scaffolds can promote osteogenesis and support chondrocyte growth, aiding bone and cartilage repair.[74] Its sub-0.05 mm resolution and compatibility with bioresins allow fine microstructures and the inclusion of bioactive molecules for regenerative implants.[74] High-resolution SLA also enables patient-specific surgical guides, dental models, and implant prototypes. In dentistry and maxillofacial surgery, SLA is used to make custom crowns, aligners, and implants with very smooth surfaces.[75]

Non-Medical application

Outside medicine, fine detail and surface quality of SLA, serve diverse industrial fields. In aerospace and automotive engineering, SLA is used for lightweight functional parts and tooling. complex airfoils, ducting, and engine components can be prototyped quickly, reducing development time.[76] The aerospace/automotive industries report that 3D printing of structural parts has moved beyond prototypes to actual components, improving fuel efficiency via topology optimization.[76] Architecture and construction leverage SLA for highly detailed scale models and custom facade elements. Architects favour SLA for rapid iteration of design models with fine interior detail (thin walls, undercuts). Polymer SLA has been explored to print translucent facade panels or concrete molds, since it can create near-transparent components at building scale.[77] The ability to print complex shading and geometry into models helps evaluate environmental performance before construction. While SLA resins are not edible, research in food printing uses 3D methods for novel foods. 3D printing (mainly extrusion or sintering) has enabled customized nutrition and complex shapes (e.g. printed chocolate, pasta, plant-based meat analogues).[78] In some cases, SLA is used to make molds or texture rollers for food production. Overall, additive techniques allow digitization of recipes and personalized culinary products.[78] SLA also finds uses in consumer products, art, and electronics. Detailed jewelry and eyewear prototypes are made with SLA for its polishable finish.

In terms of performance, SLA resins generally offer moderate to high thermal stability and good chemical resistance, making them suitable for functional prototyping and some end-use parts. Mechanical strength varies with resin formulation, but reinforced or high-performance resins can achieve sufficient rigidity for structural applications. These properties combined with the high resolution of SLA make it a reliable choice for industries where both precision and material performance are important.

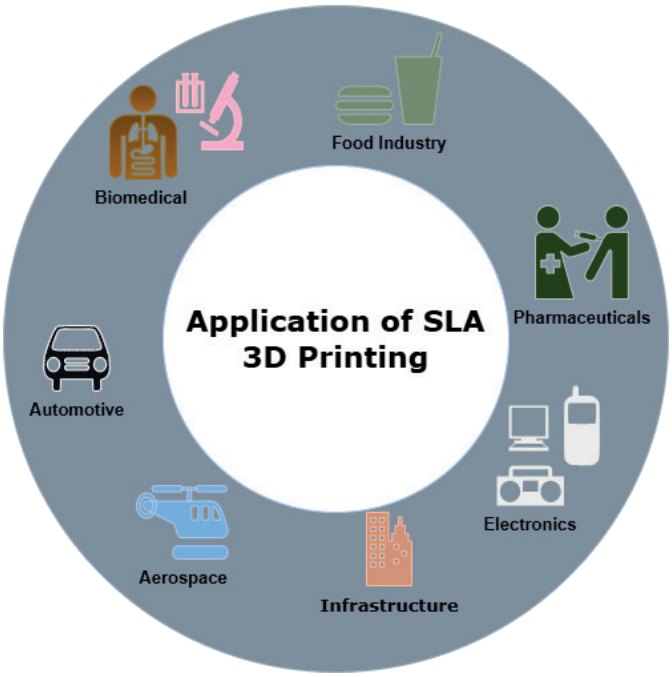


Figure 1: Various medical and non-medical applications of stereolithography 3D printing.

SUSTAINABILITY AND ENVIRONMENTAL IMPACT

The sustainability of SLA photopolymer materials hinges on both the renewable content of the resin and the environmental burdens of its life cycle. Conventional SLA resins are formulated from (meth)acrylate monomers and photoinitiators, which are mostly petroleum-derived.[79,80] The reliance on fossil feedstocks motivates the development of bio-based alternatives. Recent advances have shown that renewable feedstocks; for example, lignocellulosic biomass (e.g. lignin-derived vanillin), vegetable oils (soybean, castor, etc.), and even animal-derived fats can be converted into photopolymerizable monomers.[81] Other studies have acrylated bio-based polyesters (e.g. acrylated polycaprolactone or sebacate) or glyceryl esters to serve as multifunctional monomers.[82] These bio-derived resins have demonstrated performance comparable to petroleum analogues (e.g. vanillin-diacrylate polymers showed similar thermal and mechanical properties to commercial SLA material).[82] Bio-based compounds typically require further functionalization. Such derivatizations enable photocuring but add processing steps. Green chemistry principles (e.g. solvent minimization, benign catalysts) are increasingly applied during these syntheses to reduce upstream impacts.[81]

Life cycle environmental performance

Life-cycle assessments (LCA) have been applied to quantify the environmental performance of SLA printing. One cradle-to-gate LCA of desktop-scale SLA (bottom-up stereolithography) modeled all stages from raw material production through printing and post-processing.[83] Although, SLA has not been widely examined in life cycle assessment (LCA) studies of additive manufacturing (AM) processes.[84] This is largely attributable to the specialized composition of SLA resins, the heterogeneity of printer configurations, and the relatively limited adoption of SLA compared to filament-based AM.

The variability in photopolymer chemistry, post-processing steps, and energy requirements complicates standardized assessment, while desktop and industrial SLA systems are less common, limiting available inventory data for comprehensive cradle-to-grave analysis.

Mele et al.[83] found that the photopolymer resin production phase was the dominant contributor to most impact categories. This means that the embodied impacts of synthesizing and formulating the resin (monomer synthesis, mixing, packaging) outweighed those of the printing operation. Other significant contributors included equipment manufacturing notably the UV-curing oven (driven by energy-intensive lamps) and resin transport. For example, the production of the SLA workstation's UV oven was among the top impacts for half of the midpoint indicators.[83] By contrast, the printing process itself contributed substantially only to a few categories. Additionally, transporting resin (often from overseas suppliers) was a major factor in about half of the midpoint impacts, indicating that local sourcing of biopolymer feedstock could cut some burdens.[83]

Another recent LCA compared different 3D-printing materials (including SLA UV resin and various thermoplastics) in terms of mid-point and end-point impacts.[85] In that energy-focused analysis, the SLA UV-curable resin showed the lowest overall impacts (including GHG emissions) of all materials studied.[85] This suggests that, under certain conditions, SLA resins can be more carbon-efficient than filament-based plastics, although such results are sensitive to factors like electricity mix and inventory assumptions. In summary, existing LCAs indicate that feedstock production and resin formulation are critical drivers of resource and energy use in SLA, whereas the printing step tends to be less dominant (except for categories like GHG where energy use matters).

The impact categories most often assessed include Global Warming Potential (GWP), energy/resource depletion, and toxicity indicators.[85] Bio-based monomers can reduce fossil resource consumption (and potentially GWP) relative to petroleum monomers but the overall benefit depends on agricultural inputs, chemical conversions, and energy sources.[79] SLA resins also entail toxicity impacts: both in production (e.g. volatile organic emissions, solvent use) and use (exposure to unreacted acrylates). Photopolymer resins may include volatile or toxic elements and compounds such as antimony, acrylates, and epoxies, which can release hazardous emissions during printing.[86] These chemical hazards contribute to human and environmental toxicity categories in LCA. Studies therefore balance the trade-offs between categories: for example, a bio-acrylate might lower fossil resource use but still carry similar toxicological profiles as a petroacrylate (since both are reactive acrylate esters). Another consideration is energy and resource consumption: SLA avoids heating build plates, but requires intense UV light and post-curing, so electricity use remains non-negligible.

Trade-offs and impact categories

Replacing petro-mononers with plant-derived equivalents can cut cradle-to-gate CO_2 emissions if the bioconversion steps are efficient and renewable energy is used. For instance, an LCA showed UV-resin SLA printing generally yielded lower GWP than printed ABS parts.[85]. However, cultivating biomass has its own emissions (fertilizer, land use), and functionalizing bio-oligomers (methacrylation, acrylation) consumes reagents and energy. Regardless of origin, (meth)acrylate monomers are inherently toxic (causing irritation and posing ecological risks). Bio-based variants (e.g. vanillin acrylate) may offer modest safety improvements by avoiding petroleum impurities, but they still carry acrylate hazards. Photoinitiators (some containing antimony, phosphorus, or metal complexes) contribute to human and aquatic toxicity potentials.[86]. Thus, life-cycle toxicity impact often remains high unless formulations change (for example, replacing heavy-metal photoinitiators with organic dyes is an area of research). Bio-resins reduce demand for crude oil, however, producing the bio-feedstock can require significant land, water and chemicals.[79] Moreover, SLA printing involves other materials whose production draws on natural resources. Mele et al.[83] reported that simply transporting resin was a large fraction of impacts, so local sourcing of renewable feedstock could reduce resource use.

Emerging findings suggest that while bio-based SLA resins can decrease dependence on petroleum and potentially lower carbon footprint, they introduce new trade-offs. Bio-derived monomers may require multi-step syntheses (potentially increasing energy use and solvent waste), and they generally remain chemically similar to petro-acrylate in terms of end-of-life persistence and toxicity. These factors imply that holistic LCA (tracking GHG, human/ecotoxicity, energy and material use) is essential when evaluating sustainable SLA formulations.

CHALLENGES AND FUTURE DIRECTIONS

Despite the progress made in the development of bio-based and more environmentally responsible photopolymers for stereolithography (SLA), several significant challenges remain unresolved. These challenges span economic, chemical, and technological domains, and they must be addressed to support the transition to a more sustainable SLA ecosystem.

One of the persistent barriers to wider adoption of sustainable SLA materials is the cost-performance trade-off. Bio-derived monomers and oligomers often require multi-step syntheses, specialized catalysts, or modification processes that increase production costs compared to established petrochemical alternatives.[87,88] While some bio-based resins such as acrylated vanillin or poly(caprolactone) derivatives show mechanical and thermal performance comparable to conventional materials, they are not yet cost-competitive at scale. [14,79,82,89,90] Moreover, there is a performance gap in certain application-specific properties, such as UV stability, print resolution, or curing kinetics, which limits their applicability in demanding industrial settings.

The development of fully recyclable photopolymer networks remains an open research challenge. Traditional SLA resins form permanent thermoset networks that cannot be remelted or reshaped, preventing any conventional recycling route. Recent advances in dynamic covalent chemistry, such as vitrimers and covalent adaptable networks (CANs), offer partial reprocessability, but these systems often require high temperatures or chemical triggers that are not yet practical for widespread implementation.[79]. Closed-loop recyclable photopolymers, where printed parts can be depolymerized back to their original monomers and re-polymerized without loss of performance, remain largely experimental. Achieving chemical recyclability in SLA resins without compromising on print quality or mechanical integrity is a key research priority.[91].

Resin formulations that support circular manufacturing paradigms enabling resource recovery, material reuse, and end-of-life revalorization are still in early stages of development. Incorporating cleavable linkages or reversible cross-linking mechanisms into SLA resins holds potential, but these modifications must be balanced against requirements for shelf stability, photoreactivity, and mechanical strength. Additionally, standardization of recyclability metrics and scalable post-use processing protocols will be essential to integrate these materials into real-world additive manufacturing workflows.

The search for high-performance green alternatives also continues to face material limitations. While lignin-, soy-, and glycerol-based resins show promise, they often face compatibility issues with commercial SLA platforms or require formulation adjustments to match the rheology and curing speed of petro-based resins.[92–95] Furthermore, not all bio-based monomers are inherently environmentally benign; some still pose toxicity risks or demand energy-intensive processing. A truly green resin system must satisfy multiple constraints simultaneously derived from renewable feedstocks, synthetically efficient, non-toxic in use and disposal, and compatible with existing SLA technologies.

Future research must converge across disciplines, combining green synthetic chemistry, photopolymer science, and LCA-informed design. Investment in process intensification for bio-based monomer production, discovery of novel photocurable renewable molecules, and the development of recyclable SLA-compatible chemistries will define the next phase of innovation. Additionally, integrating circular economy principles directly into material design and 3D printing workflows could enable sustainable scaling of SLA technologies without significant environmental compromise.

CONCLUSION

The advancement of sustainable photopolymer resins for stereolithography (SLA) represents a growing yet underdeveloped area in additive manufacturing research. This review has highlighted the shift from conventional petroleum-based systems to bio-derived alternatives. These materials offer reduced environmental footprints and open new pathways for green manufacturing. However, sustainability in SLA extends beyond the origin of raw materials. A full understanding of the life cycle covering resin synthesis, processing, use, and end-of-life treatment is critical to evaluating their true environmental impact.

Current life cycle assessment (LCA) studies of SLA remain sparse, especially when compared to more established AM techniques like fused deposition modeling (FDM). The lack of consistent LCA frameworks, data availability, and resin-specific impact metrics continues to hinder robust environmental benchmarking. This knowledge gap is particularly important as SLA grows in industrial relevance and scales beyond prototyping. Although bio-based SLA resins show promise, several technical and economic challenges limit their widespread adoption. These include higher material costs, incomplete recyclability, and trade-offs in print fidelity and mechanical performance. Efforts to formulate recyclable or circular SLA resins are ongoing, but practical implementation remains limited to laboratory-scale demonstrations.

Future work must address these shortcomings through interdisciplinary approaches that combine green chemistry, photopolymer formulation, and LCA-informed design. Developing recyclable SLA photopolymer resins, lowering the environmental costs of biopolymer synthesis, and integrating circular economy principles will be key to scaling sustainable SLA technologies. To move forward, the field must prioritize not only bio-based content but also full-system sustainability balancing performance, environmental impact, and economic feasibility.

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CONFLICT OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the author/s used Grammarly to check and proofread grammatical mistakes and punctuation. Thereafter, the content of the manuscript was reviewed and edited thoroughly by the author/s as needed, as such, taking full responsibility for the content of the publication.

CREDIT AUTHORSHIP CONTRIBUTIONS STATEMENT

Ismail Abiade: Conceptualization, literature survey, writing–original draft preparation, and editing. Moyinoluwa Oyelohunnu: Investigation, formal analysis and supervision. O'Brien Zakumi Obed: Review framework design, critical analysis, writing–review and editing, and supervision. Hauwau Abubakar Koaje: Data organization, validation, and manuscript refinement.

AUTHORS ORCID

O'Brien Z Obed: https://orcid.org/0000-0002-9474-4371
Ismail Abiade: https://orcid.org/0009-0002-7301-1504

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