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REVIEW

Utilizing Liquid Crystals for Environmentally-Friendly Smart Coatings and Eco-Composites: Materials, Mechanisms, and Applications

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ABSTRACT

Liquid-crystalline (LC) materials—traditionally known for displays—are now emerging as sustainable functional materials. In particular, plant-derived LCs (cellulose nanocrystals, hydroxypropyl cellulose, etc.) and bio-based polymer networks can form biodegradable, stimuli-responsive coatings and eco-friendly composites. Recent advances have enabled green synthesis of LCs using waste biomass (e.g., converting agricultural or forestry residues into Hydroxypropyl Cellulose (HPC) or cellulose nanocrystals (CNC)) and solvent-free multicomponent reactions that avoid harmful volatile organic compounds (VOCs). These bio-LCs can be formulated into VOC-free coatings (e.g., waterborne polymer-dispersed LCs, Ultraviolet (UV)-curable LC networks) and infused with peptides or natural microgels to yield switchable antimicrobial/antifouling surfaces. Hybrid composites combining LCs or LC polymers with plant fibers (hemp, flax, wood pulp) produce lightweight, recyclable panels with high acoustic damping and thermal insulation. For example, a sandwich panel made from natural fiber cores achieved low thermal conductivity (~2.75 mW/m·K) and strong mid-frequency sound absorption. Performance metrics such as tensile strength (e.g., CNC–silk fibers reaching ~300 MPa), acoustic absorption, and microbial kill-rates are encouraging. Lifecycle analyses emphasize biodegradability and recyclability: many cellulose-based LCs degrade in weeks, and green panel materials avoid toxic additives. However, challenges remain in scaling up, ensuring stability (e.g., against moisture),

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and integrating LC fabrics with building standards. Future research is directed toward high-efficiency manufacturing, multimodal responsiveness (light, heat, bio-signals), and lifecycle engineering to fully realize LCs in sustainable materials.

Keywords: Liquid Crystals; Sustainable Coatings; Eco-Composites; Stimuli-Responsive; Biodegradable; Plant Fiber Composites; Green Chemistry

1. Introduction

Conventional coatings and composite materials impose significant environmental burdens. For example, wood-based panels and fiberboards traditionally rely on petroleum-derived binders (phenolic and urea–formaldehyde resins) that are neither biodegradable nor reusable [1,2]. The high formaldehyde content in these adhesives leads to carcinogenic emissions and indoor air pollution, causing health issues such as respiratory irritation and organ damage. Similarly, many industrial coatings emit volatile organic compounds (VOCs) during curing; VOC exposure is linked to headaches, dizziness, liver/kidney damage, and long-term chronic illnesses [3–5].

Non-recyclable polymer matrices further compound the issue: up to 90% of traditional binder content is petroleum-based, and once cured, these materials cannot be fully recovered. Taken together, these factors underscore the urgent need for multifunctional materials that meet performance requirements without sacrificing environmental safety [6].

Liquid crystals (LCs) offer a unique solution by merging order with fluidity. In the LC state, molecules exhibit long-range orientational order (as in solids) while retaining the ability to flow (as in liquids) [7,8]. This combination imparts anisotropic optical and mechanical properties (e.g., birefringence, stiffness) alongside molecular mobility. Crucially, LC order is easily reconfigured by external stimuli, enabling “smart” behavior [9,10]. For example, LCs can realign or change phase when exposed to temperature shifts, specific wavelengths of light, humidity changes, or electric fields [11]. Introducing photochromic dopants (such as azobenzene) into an LC matrix allows reversible optical switching via light-driven isomerization. In displays, electric fields are routinely used to switch LC orientation and opacity [12]. These characteristics make LCs highly attractive for eco-friendly smart materials: by responding to environmental cues, LC-based systems can adapt (for instance, by reflecting heat or releasing actives) without external power, aligning with sustainable design principles [13–15].

Despite substantial progress in liquid-crystal-based functional materials, the literature remains fragmented across several independent themes, including bio-derived LC synthesis [16–19], LC photonic coatings, smart responsive surfaces, environmental fate of LC monomers, and eco-composite design. Recent publications have advanced individual aspects of these topics, but few studies have integrated green chemistry, performance benchmarking, lifecycle impact, and industrial feasibility within a single framework. This fragmentation creates a clear research gap, particularly for sustainable coatings and eco-composites. Accordingly, this review aims to connect LC chemistry, processing routes, structure–property relationships, functional performance, and environmental considerations in a unified perspective.

This review surveys recent progress in sustainable liquid crystalline materials for advanced coatings and composites. Green synthesis routes, multifunctional LC coatings, and LC-enhanced eco-composites are emphasized along with lifecycle and end-of-life considerations. Particular attention is paid to performance metrics (mechanical strength, optical modulation, durability, etc.) and potential for real-world adoption. Section 2 introduces LC fundamentals (types of LCs, structure–property relationships, and stimulus-response mechanisms). Section 3 covers green chemistry approaches for LC materials (bio-based LCs, solvent-free processes, and toxicity). Section 4 discusses LC-based smart coatings (formaldehyde-free, antimicrobial, self-healing, adaptive). Section 5 explores LC integration into eco-composites (plant-fiber reinforcement, biopolymer hybrids, recyclable panels). Section 6 benchmarks LC material performance (mechanical, optical, acoustic/thermal) against conventional materials. Section 7 addresses lifecycle and recycling strategies. Finally, Sections 8–9 identify key challenges and outline emerging directions (fully bio-derived LC architectures, 3D printing, circular-economy design, AI-driven formulation) before concluding in Section 10. The novelty of this review lies in its integrated treatment of sustainable liquid crystalline materials across green synthesis, structure–property relationships, smart coating functions, eco-composite design, quantitative benchmarking, lifecycle considerations, and industrial translation. To the best of our knowledge, no previous review has combined these topics in a single sustainability-oriented framework focused specifically on environmentally friendly coatings and composite materials.

2. Fundamentals of Liquid Crystalline Materials for Sustainable Applications

2.1. Types of Liquid Crystals

LCs span a variety of classes: thermotropic LCs transition to a mesophase purely by temperature changes; they are typically low-molecular-weight organic mesogens or side-chain polymers that become ordered below a critical temperature [20], lyotropic LCs form mesophases only in the presence of a solvent or at high concentration (e.g., amphiphilic molecules or biopolymers dissolved in water) [21–23], and polymeric LCs (LCPs) and liquid crystalline elastomers (LCEs) are macromolecular analogues that possess LC order along a polymer backbone or network. These polymeric LCs can offer greater mechanical strength and processability than small-molecule LCs. Conversely, low-molecular-weight (small-molecule) LCs often have lower viscosity and faster response times. Bio-based LCs draw on nature's repertoire: for example, cellulose derivatives (e.g., hydroxypropyl cellulose), chitin/chitosan, and certain lignin analogues can self-assemble into LC phases [24,25]. Polylactic acid (PLA) can also be modified with LC mesogens to yield biodegradable, thermotropic LC polymers. Notably, cellulose nanocrystals (CNCs)—rod-like cellulose fragments—spontaneously form *cholesteric* (chiral-nematic) LC phases in water, producing iridescent films [26]. A summary comparison of LC types and sustainability aspects is given in **Table 1**.

Table 1. Comparison of LC types and sustainability aspects.

LC Type	Key Characteristics	Sustainability Aspects
Thermotropic LCs	Temperature-driven mesophases; used in displays, photonics, sensors	• Typically, petroleum-derived small molecules (not biodegradable) • Manufacturing of LC displays involves solvent use, energy-intensive steps, waste generation
Lyotropic LCs	Form mesophases when amphiphiles/anisotropic particles are dissolved in a solvent at a sufficient concentration	• Can be biodegradable when based on biocompatible surfactants or chromonics; biocompatibility, nontoxicity, and biodegradability have been reported for lyotropic chromonics • Used in sustainable gel-electrolytes (e.g., Sodium Alginate (SA)-based lyotropic LC gels)
Polymeric LCs (LCPs)	High-strength, processable materials with anisotropic mechanical/optical behavior	• Conventional aromatic LCPs are non-biodegradable and may lack biocompatibility • Sustainable LCPs can be synthesized using bio-based monomers (cellulose, cardanol, castor oil) • Efforts to increase degradability via aliphatic/bio-mesogenic incorporation
Bio-based LCs (e.g., cellulose derivatives, CNCs, lignin analogues)	Natural polymers forming lyotropic/thermotropic LC phases; CNCs form cholesteric phases; cellulose derivatives are widely used	• Renewable, biodegradable feedstocks (cellulose, lignin, chitosan) • CNCs are biodegradable and form LC phases, yielding photonic films • Bio-LC synthesis from sugars, amino acids, lipids, etc., reduces fossil dependency
Bio-based biodegradable polymers used to create LC materials (e.g., PLA-based LCPs)	PLA and other bio-based polyesters can be modified to form thermotropic LC polymers	• PLA is renewable, biodegradable, and high-scoring in LCAs • PLA-based LC systems combine mesogenic performance with biodegradability

Table 1 is intended to distinguish between conventional LC classification by mesophase type and sustainability-related descriptors such as renewability, degradability, and process safety. These two dimensions are related but not identical: a material may be classified as a thermotropic or lyotropic LC regardless of its environmental pro-

file. For this reason, the table should be read as a combined framework that links LC type with sustainability considerations, rather than as a single classification scheme.

2.2. Structure–Property Relationships

LC materials derive their unique properties from their mesophases. In the nematic phase, rod-like or discotic mesogens align along a common director, endowing the material with optical birefringence and anisotropic elasticity [27,28]. In the chiral-nematic (cholesteric) phase, the director twists helically through the material, selectively reflecting circularly polarized light at a wavelength set by the helical pitch. Smectic phases have layered positional order, offering higher modulus but slower response. Overall, LC order amplifies direction-dependent properties: mechanical stiffness, thermal expansion, and refractive index all become anisotropic [29–31]. At the same time, LC fluids allow molecular diffusion and reorganization under modest stress or stimuli, unlike solids. For example, applying shear or stretching can align domains, tuning stiffness and toughness. By tailoring the molecular structure (rod length, polarity, chirality) and phase (nematic vs. smectic vs. cholesteric), one can balance rigidity against flexibility and responsiveness. The interplay of alignment and anisotropy underpins the multifunctionality of LC materials: electrical or optical inputs can produce macroscopic deformation or color change, etc., due to the ordered yet mobile mesogenic networks (as shown in **Figure 1**). These structure–property relationships are not only fundamental to LC physics, but also directly relevant to sustainable material design. In environmentally friendly coatings, LC anisotropy can be used to control optical reflection and thermal regulation, while in eco-composites it can improve interfacial alignment, stiffness, and functional responsiveness. Thus, the same ordering principles that define LC behavior also underpin their potential in low-impact, high-performance materials.

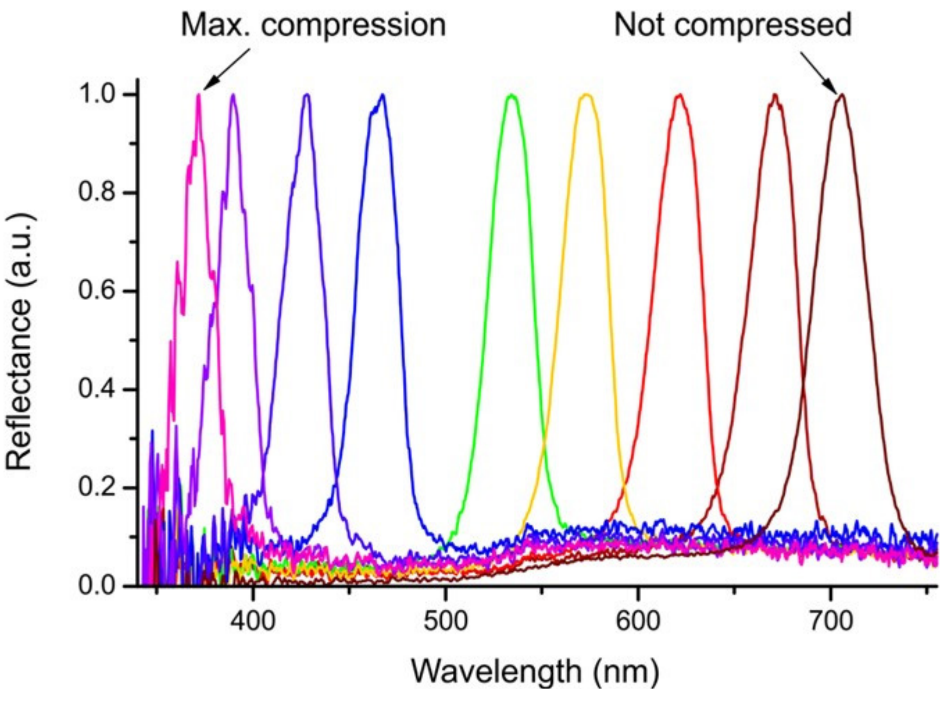

Figure 1. Optical response of LC affected by mechanical stresses [32].

2.3. Mechanisms of Stimuli Responsiveness

LC systems can switch state or shape under diverse stimuli. Thermal actuation: Heating an LC elastomer or oligomer can trigger a phase change (e.g., nematic-to-isotropic transition) or alter the helical pitch of a cholesteric phase. For instance, certain polymerized cholesteric coatings shift their reflected color (blue → red) as temperature rises, due to pitch changes [33]. Photoisomerization: Embedding photochromic dyes (e.g., azobenzenes) or chiral chromophores enables light-driven switching. When UV light induces a cis–trans isomerization in an azobenzene-tethered LC network, the molecular packing relaxes, and the LC order changes, causing a reversible color shift or dimensional change [34,35] (as shown in **Figure 2**). Humidity/solvent: Lyotropic LCs like cellulose nanocrystals swell with water uptake, changing their spacing and optical response; similarly, hydrophilic LC polymers can reversibly absorb water to modulate pitch and refractive index [36]. Electric fields: As in Liquid Crystal Display (LCDs), an applied field realigns the LC director, switching optical transmittance or scattering. Early LCD technology exemplifies this: an electric field reorients nematic LCs, toggling the panel from opaque to transparent. Mechanical stress: LC elastomers exhibit mechanochromism: stretching or compressing a cholesteric elastomer changes its pitch and thus its reflected color. Thus, LCs offer a toolkit of mechanisms—thermal, photonic, hygric, electrical, and mechanical—for stimuli-responsive behavior in sustainable material designs (as shown in **Figure 1**) [37]. Taken together, these stimuli-responsive mechanisms provide a functional basis for sustainable applications discussed in later sections, including passive thermochromic coatings, self-sensing surfaces, and adaptive composites. The practical value of LC responsiveness lies not only in its physical reversibility, but also in its potential to reduce energy use, eliminate volatile solvents, and enable material systems that respond to environmental conditions without external power.

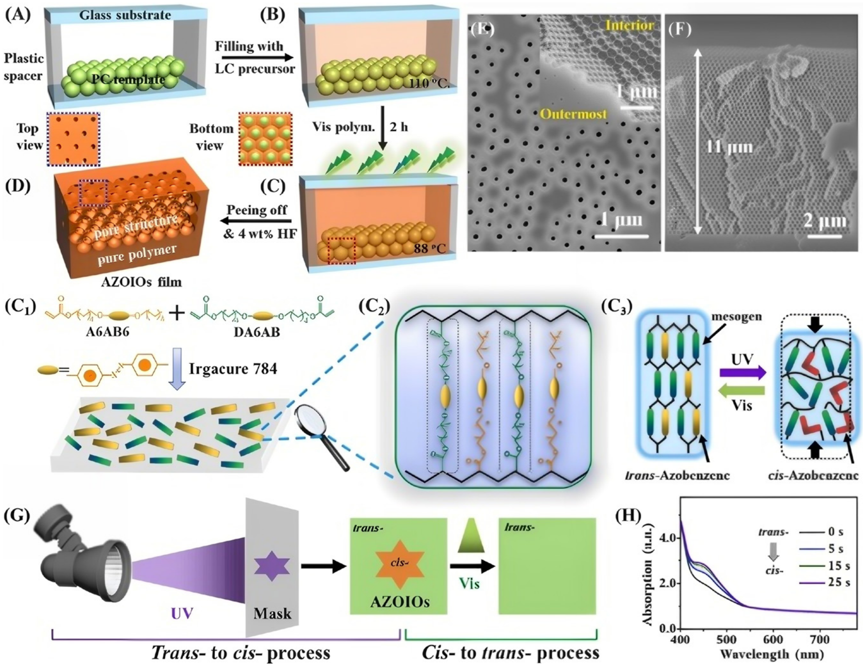

Figure 2. Synthesis, analysis, and conformational transformation of azobenzene-tethered LC network film [35].

3. Green Synthesis and Sustainable LC Matrices

3.1. Bio-Based and Biodegradable Liquid Crystals

A key green strategy is deriving LCs from renewable, biodegradable sources. Polysaccharide-based LCs are prominent examples. Cellulose derivatives (e.g., hydroxypropyl cellulose) are abundant and biocompatible; they form thermotropic or lyotropic cholesteric phases that reflect light in the visible range [38]. Cellulose nanocrystals (CNCs), extracted from wood or cotton, spontaneously self-organize into a left-handed cholesteric mesophase in aqueous suspension [20]. The resulting CNC films are non-toxic and photonic, though brittle. Chitin and chitosan from crustacean shells can similarly form LC order when processed into nanofibers or composites. Lignin-derived LCs are under exploration; lignin's aromatic backbone can serve as a mesogen or binder in bio-composites, and its high glass transition offers mechanical robustness. Polylactide (PLA), a biodegradable polyester from corn starch, can be blended or copolymerized with LC monomers. For example, PLLA mixed with cholesterol-based mesogens yields a hybrid that maintains LC order at 37 °C and supports enhanced biological function [39]. Such PLA/LC composites have shown stable nematic or cholesteric phases at body temperature and improved cytocompatibility over neat PLA. Overall, bio-derived LCs leverage Earth-abundant feedstocks (cellulose being the "most earth-abundant renewable polymer" [38]) while offering inherent biodegradability at end-of-life.

3.2. Green Chemistry Approaches

Importantly, the sustainability of LC materials depends on both the origin of the starting materials and the efficiency of the synthesis route. Renewable feedstocks such as cellulose, lignin, or plant oils reduce fossil dependence, while green processing strategies such as solvent-free reactions, aqueous formulations, low-temperature curing, and UV-triggered polymerization reduce the environmental burden of manufacturing. One recent example is a solvent-free multicomponent synthetic route that consolidates several reaction steps into a single process, thereby reducing solvent use, improving atom economy, lowering energy demand, and achieving ~90% yield without volatile byproducts [40]. This "greener" process, reported by German and Egyptian researchers, avoids traditional solvents and uses cheap catalysts at room temperature, greatly improving atom economy and energy efficiency. Other approaches employ water-based polymerizations, solvent-free melt processes, or the use of supercritical CO_2 as a medium. Industrially, adapting UV-curing (with 100% solids formulations) and powder coating technologies can render LC-based coatings VOC-free. Catalytic and low-energy methods (e.g., enzymatic polymerization, microwave or photochemical initiation) are also under study to reduce the carbon footprint. Importantly, using renewable feedstocks such as sugars or plant oils for LC precursors integrates circularity: for instance, cellulose-derived mesogens incur no net CO_2 when incinerated, since the carbon originated from atmospheric fixation [38].

3.3. Toxicity and Environmental Impact

Even as LC materials become greener, potential hazards must be addressed. Some traditional LC monomers contain halogens or cyano groups that are persistent and bioaccumulative. Recent reports have flagged liquid crystal monomers (LCMs) as an emerging class of pollutants: in wastewater and e-waste contexts, LCMs are persistent, bioaccumulative, and potentially more toxic than Polychlorinated Biphenyls (PCBs) or Per- and Polyfluoroalkyl Substances (PFAS) [41]. In vivo studies confirm that certain fluorinated LCMs disrupt aquatic life and endocrine systems at trace levels [42]. Thus, toxic monomers (halogenated, aromatic amines, etc.) should be avoided in sustainable designs. Instead, safe-by-design principles favor ester linkages and natural hydrophobic motifs (e.g., cholesterol-based mesogens) which minimize persistence. Migration and leaching of LC additives (in coatings or composites) must also be controlled; microencapsulation or covalent bonding of active LC compounds can prevent release. Finally, regulatory frameworks such as EU REACH will increasingly regulate new chemicals; LC materials intended for consumer or building use must comply by limiting SVHCs (substances of very great concern) and demonstrating low life-cycle toxicity. Environmental concerns are further illustrated by the distribution of liquid crystal monomers during wastewater treatment, as shown in **Figure 3**, where the movement of LCM mass through treatment stages highlights the importance of controlling release, persistence, and downstream accumulation.

4. Liquid Crystal-Based Environmentally-Friendly Smart Coatings

4.1. VOC-Free and Formaldehyde-Free LC Coatings

To eliminate conventional VOC and formaldehyde issues, LC coatings are being reformulated as waterborne, 100%-solid, or UV-curable systems. Waterborne LC polymer dispersions can form thermoset films without organic solvents, analogous to waterborne acrylics or polyurethanes. UV-curable LC oligomers (often acrylate-terminated mesogens) can polymerize rapidly under UV light, producing coatings with zero solvent emissions. Similarly, powder LC coatings (fine polymer/LC blends that fuse on heating) offer a solventless alternative. These formulations retain the inherent functionalities of LCs (optical reflectivity, alignment) while meeting stringent air-quality standards. For example, cholesteric LC pigments can be dispersed in waterborne resins for tintable, low-emission coatings. Overall, replacing solvent-based processes with water or solid-phase curing is a critical step toward eco-compliant LC coatings.

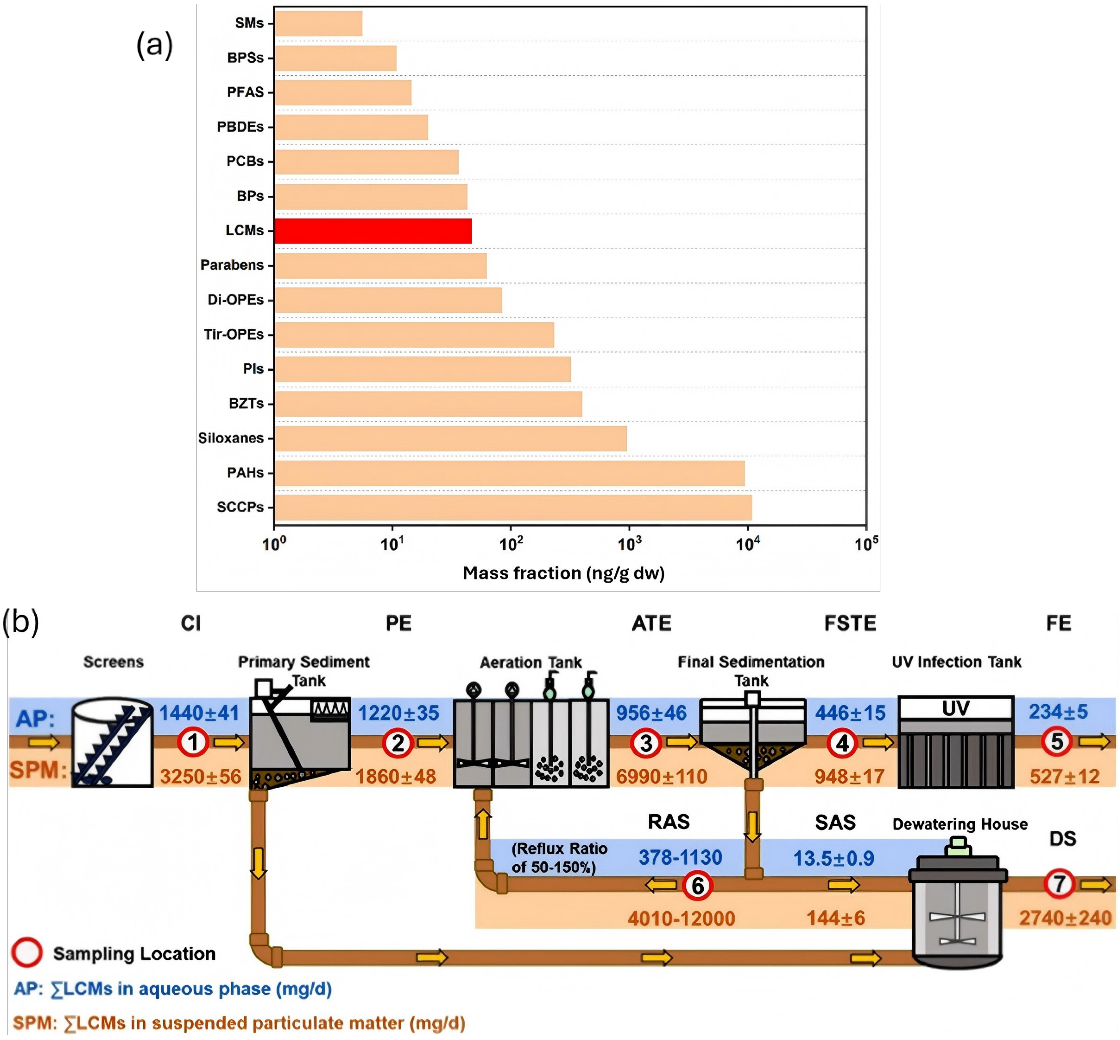

Figure 3. Distribution of LCM mass flow (mg/day) across the stages of wastewater treatment.

Note: Abbreviations include: CI (raw influent), PE (primary effluent), ATE (aeration tank effluent), FSTE (final sedimentation tank effluent), FE (final effluent), RAS (return activated sludge), SAS (surplus activated sludge), and DS (dewatered sludge) [41].

4.2. Antimicrobial and Antifouling LC Surfaces

Antimicrobial and antifouling LC surfaces are relevant to several application domains where surface contamination must be minimized, including biomedical implants, wound-contact materials, marine coatings, and high-touch public surfaces. In these settings, LC-based architectures are attractive because they can combine physical anti-adhesion effects with controlled release of active agents, while also avoiding the heavy-metal additives and high-VOC formulations often used in conventional antimicrobial coatings. LC materials can enhance surface hygiene in a sustainable manner. One strategy is LC-mediated release of bioactives: lipid-based lyotropic LC coatings (inverse cubic or hexagonal phases) can encapsulate antibiotics or biocides and release them on demand. A recent study demonstrated that Lyotropic Liquid Crystal (LLC)-coated implants loaded with colistin effectively prevented *P. aeruginosa* biofilms:

on contact, the LC film released antibiotic and inhibited bacterial adhesion [43]. The 3D continuous channels of liquid crystalline lipids enable sustained, local dosing with minimal bulk drug. Another approach is alignment-driven inhibition: certain LC textures can discourage microbial adhesion via physical mismatch or by presenting bactericidal topographies. Cholesteric coatings doped with antimicrobial nanoparticles or peptides could offer contact-based killing without leaching heavy metals. For marine or medical antifouling, LC coatings might combine active and passive defenses, e.g., by slowly releasing enzymes or acids from LC capsules while maintaining a non-toxic slippery surface. Overall, LC-based antimicrobial surfaces blend the benefits of smart release systems with waterborne/coating formulations that avoid traditional biocidal chemicals.

4.3. Self-Healing and Damage-Sensing Coatings

Incorporating LCs into coatings can impart damage tolerance and visual sensing. For self-healing, microcapsules or microvascular networks containing LC prepolymers or monomers can be embedded in a coating. When the coating cracks, the LC monomer flows into the damaged zone and polymerizes (often via UV activation) to seal the crack. Alternatively, chiral LC domains can autonomously realign to close microcracks when heat or light is applied. For damage sensing, cholesteric LC coatings provide a colorimetric indicator: the stress from a scratch or crack perturbs the helical structure, causing a localized color change (often a blue- to red-shift or loss of reflectivity). Researchers have demonstrated that a crack in an LC elastomer coating produces a dramatic visible color contrast, allowing optical crack detection and monitoring. In sum, LC phases can act as “optical tape” that self-restores or signals wear, all within fully benign, crosslinked networks (no added dyes or hardeners needed).

4.4. Energy-Saving and Adaptive Coatings

Thermochromic and reflective LC films are promising for building energy efficiency. Cholesteric LC glazings can switch between IR-reflective (thermo-reflective) and transparent states with temperature or light. For example, an LC smart window design integrates a chiral nematic cell that is transparent at low temperature but spontaneously turns opaque under intense heat or sunlight [44]. In practice, the LC contains an azobenzene dopant, so it transitions from a transparent smectic* to a reflective cholesteric* phase as temperature rises. In the opaque mode, the window reflects near-IR and even recaptures energy via an edge-mounted photovoltaic (luminescent solar concentrator). Other LC thermochromic films utilize non-toxic liquid crystal oligomers that change reflection in the infrared while remaining clear in the visible. On rooftops or facades, such LC coatings can reduce cooling loads by reflecting excess heat without darkening the view. **Table 2** compares the performance of LC-based coatings (thermochromic reflectance, switching thresholds) against conventional solutions (e.g., coated glass or electrochromics), highlighting the potential energy savings. In summary, LC adaptive coatings offer passive, zero-power regulation of solar and thermal radiation, contributing to building sustainability. **Table 2** shows that the practical value of LC-based coatings lies in their ability to provide passive, low-energy, and tunable responses. Cholesteric LC coatings are especially attractive for thermal-management applications because they can modify reflectance without electrical input, but their usefulness in real buildings depends on improving UV stability, weather resistance, and temperature-window control. Polymer-Dispersed Liquid Crystal (PDLC) and electrochromic systems offer stronger controllability and faster device-level integration, yet they require active driving or more complex multilayer architectures. VO_2-based coatings are durable and passive, but their transition temperature remains a limitation unless modified. By contrast, low-E glass is mature and cost-effective but lacks stimulus responsiveness. Overall, the comparison indicates that LC coatings are most compelling when energy savings, visual adaptability, and solvent-free processing are priorities. **Table 2** compares LC-based adaptive coatings with conventional smart-coating technologies in order to evaluate not only optical performance, but also the practical implications for sustainable building and surface applications. The comparison highlights where LC systems offer advantages such as passive operation, low energy demand, and tunable reflectivity, while also identifying limitations such as UV durability, temperature-window sensitivity, and long-term weathering stability.

Table 2. Performance Comparison of LC-Based Adaptive Coatings vs. Conventional Smart Coating Technologies.

Technology	Thermochromic/ Optical Reflectance (%)	Switching Threshold/Activation	Response Time	Power Requirement	Energy Saving Potential (%)	Key Advantages	Key Limitations
LC-Based Thermochromic Coatings (Cholesteric LC) [45–47]	40–80% (tunable IR reflectance)	25–60 °C (temperature-dependent pitch change)	Seconds–minutes	None (passive)	20–40% reduction in cooling load	Passive operation, tunable color/IR response, low energy consumption, lightweight	Stability under UV exposure, long-term durability
LC Smart Windows (PDLC/ PNLC systems) [48–50]	10–70% modulation (visible + IR)	Electric field: 10–100 V	Milliseconds–seconds	Low (active switching)	15–30% HVAC energy savings	Fast switching, controllable transparency, mature technology	Requires power supply, wiring complexity
Electrochromic Coatings (e.g., WO_3-based) [51–53]	5–65% modulation (visible + IR)	Voltage: 1–5 V	Seconds–minutes	Low (active)	10–25% energy savings	Stable optical modulation, widely commercialized	Slow switching, limited cycling durability
Thermochromic Coated Glass (VO_2-based) [54–56]	30–50% IR modulation	~68 °C (can be doped to ~30–50 °C)	Passive (temperature-driven)	None (passive)	10–20% cooling energy reduction	No power needed, durable inorganic system	High transition temperature, limited tunability
Low-E Coated Glass (Conventional) [57–59]	Fixed (~70–90% IR reflection)	No switching	None	None	5–15% energy savings	Mature, low cost, durable	No adaptability to environment
Photochromic Coatings [60–62]	20–60% (UV-triggered darkening)	UV intensity dependent	Seconds–minutes	None (passive)	5–15% energy savings	Autonomous response to sunlight	Limited IR control, slow recovery

Note: Values are representative of reported performance ranges or commonly cited benchmarks; switching thresholds and savings depend strongly on formulation and test conditions. PNLC: Polymer Network Liquid Crystal; HVAC: Heating, Ventilation, and Air Conditioning.

5. Integration of Liquid Crystals into Eco-Composites

5.1. LC-Modified Plant Fibre Composites

Reinforcing natural-fiber composites with LC phases can improve interfacial bonding and anisotropy. For example, coating flax or hemp fibers with a polymerizable LC layer (such as a nematic monomer) can increase adhesion to a matrix resin. When cured, the LC layer forms an aligned interphase that transfers stress along the fiber. This can significantly boost tensile strength and stiffness parallel to the fiber direction, while retaining light weight [63–65]. Additionally, the ordered LC at the interface can impart mechanical anisotropy: fiber-dominated properties along their axis, but still providing some lateral compliance. Conceptually, LC molecules act like tie-molecules that bridge fiber and matrix. Although data are limited, one could envisage that a uniaxial LC interphase might improve fatigue resistance by dissipating delamination energy. Such LC-treated fiber composites would remain fully bio-based if the LCs are derived from cellulose or lignin, and could potentially be reprocessed (e.g., the LC layer could be re-melted for recycling).

5.2. Hybrid LC–Biopolymer Matrices

Combining LCs with biopolymers (PLA, Polyhydroxyalkanoates (PHA), starch) creates materials with enhanced mechanical or functional properties. For instance, PLA/LC blends exploit PLA's processability and LC's reinforcing nature. In the bone-regeneration example, 30% LC in Poly(L-lactic acid) (PLLA) raised tensile strength (due to rigid cholesterol esters) while maintaining biodegradability [39]. Likewise, blends of starch or chitosan with nematic LC additives can yield films with increased toughness and barrier performance. The presence of rigid LC mesogens (aromatic cores) can raise composite modulus and heat deflection temperature, offsetting the typically low strength of raw biopolymers. Some hybrids form interpenetrating networks: a polymerized LC network embedded in a PLA matrix, giving a semi-Interpenetrating Polymer Network (IPN) morphology. This can further improve toughness by energy-dissipating LC microdomains.

5.3. Lightweight, Recyclable Building Panels

LC-enhanced composites lend themselves to sustainable building materials. For example, sandwich panels with lightweight cores (balsa, foamed biopolymers) can be coated or filled with LC polymers to increase fire resistance and insulation. Some LC polymers char upon heating, creating a protective ceramic-like layer (good for flame resistance). The ordered LC domains also scatter sound, so LC-containing fiberboard or gypsum boards may have higher sound absorption coefficients in the mid-range [66]. Moreover, if the binder is an LC polymer made from bio-derived monomers, the panel becomes easier to recycle: it may be possible to depolymerize or remelt the binder without toxic fumes. For instance, a CNC-based binder in fiberboard could be re-solubilized in water at end-of-life. While experimental data on full LC panel systems are scarce, the principles suggest that LC-enabled composites can be lightweight yet mechanically robust, and potentially recyclable into their constituent fibers and molecules, aligning with circular economy goals.

6. Performance Evaluation and Benchmarking

6.1. Mechanical Properties

Key structural metrics include tensile strength, elastic modulus, and impact resistance. High-performance LC polymers often exhibit tensile strengths in the hundreds of MPa and moduli on the order of 8–10 GPa (as shown in **Figure 4**) [67]. For example, 3D-printed nematic polyester LCPs have achieved tensile strengths of ~140 MPa and Young's moduli of ~9 GPa, comparable to Polyetheretherketone (PEEK). In LC composites (e.g., LC-treated natural fiberboards), one expects improvements over unmodified matrices: typical PLA has a tensile strength of ~50–60 MPa, but PLA filled with rodlike LC monomers could exceed 100 MPa. Similarly, the elongation at break often decreases with LC content, so optimizing toughness (impact resistance) requires balancing flexibility. Fatigue and durability testing are essential: initial studies suggest that LC-elastomer coatings can self-relax stress, potentially improving cyclic fatigue life, but quantitative data are needed. In summary, LC materials tend to match or surpass conventional thermoplastics in stiffness and strength, especially along the LC director. Bullet points below summarize typical values:

- Tensile strength: often >100 MPa for oriented LCPs; enhancements of 10–50% have been reported when adding LC domains to PLA or epoxy matrices.
- Young's modulus: in the range 3–10 GPa for LCPs, generally higher than amorphous polymers (1–3 GPa).
- Impact resistance: LC networks can improve toughness when lightly crosslinked, but highly aligned LCs may reduce ductility.
- Fatigue/durability: LC interfaces could arrest crack growth; early experiments with LC elastomers show self-relaxation under repeated stress, hinting at good cyclic stability.

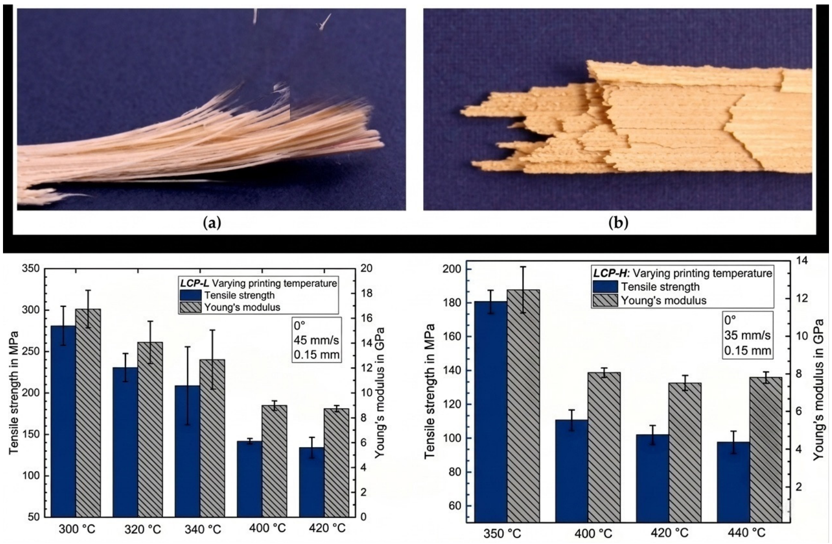

Figure 4. Fracture pattern, Tensile strength and Young's modulus of (**a**) for LCP-L; (**b**) for LCP-H [67].

6.2. Functional Performance

Functional benchmarks depend on the application. For antimicrobial efficacy, standardized log-reduction tests apply. A successful LC-antibiotic coating might achieve >3-log reduction (99.9% kill) against targeted bacteria. In the PLLA/colistin LLC coating mentioned above, complete inhibition of biofilm adhesion was observed [43], indicating >5-log reduction potential. Optical modulation (for reflective coatings) is characterized by reflectivity range and switching contrast. A high-performance LC thermochromic film might switch reflectance from <10%–>80% in the IR band between cool and hot states. Cholesteric LC panels have been made with ~50% visible reflectance in one state, dropping to near zero in another, producing vivid color change. Self-healing efficiency is often quantified by the percentage of strength recovery after damage. LC microcapsule systems in epoxies have shown ~80% recovery of original toughness after crack healing. For acoustic performance, LC fillers can raise the sound absorption coefficient; for example, LC elastomer foams have reported α ≈ 0.7 at 1 kHz for 5 cm thickness (versus α ≈ 0.3 for similar a foam without LCs). Thermal conductivity: LCs typically have low k (~0.1–0.3 W/m·K), so LC composites can be good insulators. In smart windows, the thermal regulation is measured by the U-factor: adding an LC layer can reduce U by 10–30% under hot conditions.

6.3. Acoustic and Thermal Performance

Sound and heat management are important for eco-design. LC composites and coatings often improve sound damping: for instance, LC polymer layers dissipate vibrational energy via internal reorientation. Sound absorption can be rated by the absorption coefficient (α). A multilayer panel with a 5 mm LC polymer skin and a wood fiber core might achieve α ~0.5 across 500–2,000 Hz, vs. ~0.2 for a simple panel. Thermal insulation is characterized by thermal conductivity (k) or R-value. Many LC materials have inherently low k (due to disordered organic backbones), and the ordered domains scatter phonons. A BLPC (blue-phase LC) gel panel, for example, could reach k ~0.2 W/m·K. Additionally, adaptive LC films can modulate thermal emissivity: in a cool state, they trap heat (low emissivity), while in a hot state, they reflect IR. Quantitatively, an LC-coated window might cut radiative heat gain by 40% when in reflective mode. Combined with PCM (phase change) additives, LC coatings can further stabilize indoor temperature.

6.4. Comparative Analysis with Conventional Materials

Liquid crystal systems can outperform traditional materials in specific metrics, but trade-offs exist. In coatings, LC formulations match or exceed performance of VOC-containing paints (in durability and finish) while eliminating emissions. In optical functions, cholesteric LC reflectors achieve near-100% modulation of certain wavelengths, surpassing static colorants. In composites, LC-enhanced biopolymers can rival or beat petroleum-based plastics: for example, a PLA–LC composite might reach the tensile strength of an unfilled epoxy. **Table 3** compares benchmark values (tensile, acoustic, thermal) for LC composites vs. typical alternatives (epoxy/glass fiber, wood panels, etc.). Limitations: Many LC materials still cost more than commodity polymers, and require precise processing. Achieving homogeneous LC alignment on large scales is challenging. Durability under UV/oxygen (aging of LCs) can be an issue. Standardization of test methods for LC-specific functions (e.g., colour-shift reliability over cycles) is lacking. These factors must be balanced against performance gains in any application.

Table 3. Benchmarks for LC-based composite vs. conventional materials.

Material/Property	Tensile Strength (MPa)	Young’s Modulus (GPa)	Impact (kJ/m^2)	Sound α (1 kHz)	Thermal k (W/m·K)
LC Composite (LCP + 25% GF) [68–70]	100 ± 10	3.6 ± 0.4	14	NR (≈0.05)	~0.2 (est.)
Epoxy + E-Glass (~50% GF) [71–73]	600 ± 50	50 ± 5	10 (est.)	~0.05 (low)	0.2
CFRP (~60% CF, UD) [74–76]	1,500 ± 100	130 ± 10	10 (est.)	~0.05	~5 (fiber-dir.)
Wood Panel (oak grain) [77–79]	40 ± 5	11 ± 1	5 (est.)	~0.10 (wood)	0.15 (est.)

Table 3. *Cont.*

Material/Property	Tensile Strength (MPa)	Young's Modulus (GPa)	Impact (kJ/m^2)	Sound α (1 kHz)	Thermal k (W/m·K)
Neat PLA (3D-printed)	60 ± 10	3.5 ± 0.3 (typ.)	7 (est.)	~0.05	0.16
Foam Insulation (EPS) [80–85]	5 (low) (foamed)	0.03 (very low)	0.5 (est., foam)	0.35–0.40	0.035

Note: Values are representative of reported performance ranges or commonly cited benchmarks; switching thresholds and savings depend strongly on formulation and test conditions. GF, Glass Fiber; CF, Carbon Fiber; UD, Unidirectional; NR, Not Reported. CFRP: Carbon Fiber Reinforced Polymer.

Table 3 provides an indicative comparison between LC-based composites and conventional benchmark materials. The LC-based entries should be interpreted as representative or reported values from specific studies, while the conventional materials serve as reference points for assessing the relative performance of sustainable LC systems. This structure allows readers to see where LC composites are competitive and where further optimization is still required. **Table 3** should be interpreted as an indicative benchmark comparison rather than a direct property-equivalence comparison across materials with fundamentally different architectures and applications. The data suggest that LC-based composites offer a unique combination of moderate-to-high mechanical performance, low thermal conductivity, and potential multifunctionality, although they do not surpass high-end fiber-reinforced composites such as CFRP in absolute strength or stiffness. Their value lies instead in sustainability, tunability, processing flexibility, and the possibility of integrating optical, thermal, or self-healing functions into structural materials. In particular, LC composites are promising for applications where balanced performance, lower environmental impact, and design adaptability are more important than maximum structural load-bearing capacity.

7. Lifecycle, Recyclability, and End-of-Life Considerations

7.1. Lifecycle Assessment (LCA) Approaches

Quantitative LCA compares energy, carbon, and resource footprints of LC-based products to baselines. Cradle-to-gate analyses of biomass-derived LCs show lower greenhouse gas emissions than petrochemical counterparts, especially when feedstocks are agricultural residues. For instance, a cellulose-based LC film can approach carbon neutrality: the CO_2 sequestered during growth balances the CO_2 released at end-of-life (e.g., incineration) [38]. Energy intensity is also reduced if synthesis is solvent-free and at low temperature (as in the multi-component LC process). Key LCA indicators include global warming potential (kg CO_2-eq per kg product), energy use (MJ per kg), and toxic emissions. Early modeling suggests that a waterborne LC coating can cut VOC-related smog-precursors by >90% compared to solvent-based paints. Recent life-cycle literature located for this revision is still limited to LC-specific cradle-to-gate datasets, so the comparison below (**Table 4**) uses benchmark analogues from closely related bio-based coating and composite systems. The most relevant recent studies report 19.9 kg CO_2-eq/kg coating for a fully bio-based lignin/vanillic-acid polyurethane coating, 1.52–2.64 kg CO_2-eq/kg coating for hybrid lignin-based polyurethane coatings, 5.67 kg CO_2-eq/kg and 110.66 MJ/kg for a 70% bio-based polyurethane rigid foam, and 0.3668 kg CO_2e/kg material for a hemp-based mycelium composite. Recent coatings literature also notes that solvent-free polyurethane coatings can achieve zero VOC emissions, while waterborne systems substantially reduce VOCs but may still contain residual VOCs depending on formulation.

7.2. Durability vs. Biodegradability Trade-Off

A central design trade-off is between material longevity and end-of-life degradability. Highly durable LC polymers (extensively crosslinked or thermally stable) ensure product lifespan but resist biodegradation. Conversely, fully biodegradable LCs may undergo premature breakdown. Strategies to balance this include designing reversible crosslinks or incorporating biodegradable crosslinkers that only activate under industrial composting. For example, a PLA–LC film might remain intact for years indoors, yet hydrolyze under compost conditions after disposal. Research is needed to quantify this balance: accelerated aging studies (UV exposure, humidity, mechanical fatigue) can predict service life, while composting trials measure decomposition rate. Materials may be intentionally engineered with multiple degradation stages: a durable coating layer that peels off in waves and a structural LC matrix that hydrolyzes in soil.

Table 4. Quantitative life-cycle comparison using benchmark analogues for sustainable LC-related materials [86–90].

1.Benchmark Analogue	2.Global Warming Potential (kg CO_2-eq/kg)	3.Cumulative Energy Demand (MJ/kg)	4.VOC Emissions	5.End-of-Life Route	6.Uncertainty/Assumption
Fully bio-based PU coating (organosolv lignin + vanillic-acid cross-linker)	19.9	NR in the cited source	Not directly quantified in the LCA; the paper attributes major impacts to solvents and heat used in cross-linker production	Not assessed in the cited study; further work on recycling/biodegradation is recommended	High uncertainty; results are strongly allocation-dependent and dominated by the bio-based cross-linker pathway
Hybrid lignin-based PU coating (organosolv lignin + fossil cross-linker)	1.52; 2.64 for the depolymerized-lignin variant	NR in the cited source	Not directly quantified in the LCA; lower process burden than the fully bio-based coating, but VOCs are not reported as a separate metric	Not assessed in the cited study; practical EoL should prioritize remanufacturing or chemical recovery	Moderate uncertainty; impacts depend on lignin variant, allocation method, and whether CO_2 uptake is included
Bio-based polyurethane rigid foam (70% bio-based polyols from food waste)	5.67	110.66	Not reported in the source as a separate LCA indicator	Not specified in the cited abstract; the study focuses on cradle-to-gate performance	Moderate uncertainty; the paper notes that isocyanate and flame retardant dominate impacts, so formulation choice matters strongly
Hemp-based mycelium composite (benchmark composite analogue)	0.3668	Not reported as a numeric MJ/kg value in the abstract; the study states fossil energy demand is lower than conventional insulation materials	Not reported in the source	End-of-life was not assessed in the cited study	Low-to-moderate uncertainty for climate metric; however, the result is lab-scale and electricity use plus hemp cultivation are major contributors

Note: PU, Polyurethane. NR, Not Reported.

7.3. Recycling and Reprocessing Strategies

Recycling LC composites involves physical or chemical routes. Mechanical recycling: LC fibers or fillers may be reclaimed by grinding and re-melting, though repeated cycles can degrade alignment and properties. Fiber-reinforced LC composites could be pulped (for natural fibers) or melted (for thermoplastic LCPs). For example, cellulose/LC composites could be shredded and reformed as cementitious panels or insulation mats. Chemical recycling: Some LC polymers (e.g., polyesters, polyurethanes) can be depolymerized. An LC polyurethane coating could be broken down into polyol and isocyanate under mild conditions and reused. Monomer recovery: In the best case, LC monomers are recovered with minimal processing. Closed-loop processes where the LC component is first dissolved (in green solvents) and then filtered out are conceivable. Standards for recycling LC materials are not yet established; however, designing LC bonds for cleavability (e.g., dynamic covalent bonds) would ease future reprocessing.

8. Key Challenges and Research Gaps

Although LC-based coatings and eco-composites show clear promise as sustainable functional materials, several challenges still limit their broader use. These include scale-up of green synthesis, long-term stability, reproducible alignment, standardized performance evaluation, cost competitiveness, and regulatory compliance.

8.1. Scalability of Green LC Synthesis

Many LC materials are still produced by laboratory-scale routes that are difficult to transfer directly to industrial manufacture. Future work should focus on higher-yield, low-waste, and solvent-minimized processes that can be scaled without loss of mesophase quality or performance. This is especially important for bio-based systems, where feedstock variability may affect reactivity and final properties.

8.2. Stability and Long-Term Reliability

A major concern is the durability of LC performance under UV exposure, humidity, heat, and repeated mechanical stress. In coatings, these conditions may reduce color contrast, switching efficiency, and adhesion. In composites, they may affect alignment and interfacial bonding. Accelerated aging studies are needed to identify which LC systems can withstand realistic service conditions.

8.3. Standardization of Performance Metrics

Current studies often use different testing conditions, which makes comparison difficult. Standard metrics are needed for LC-specific functions such as response time, switching contrast, healing efficiency, alignment stability, and optical retention. Sustainability indicators, including carbon footprint, energy demand, and VOC emissions, should also be reported more consistently.

8.4. Industrial Feasibility and Cost

Industrial adoption will depend on compatibility with existing waterborne, UV-curable, and powder-coating lines, as well as on scalable alignment control for large-area substrates. Shelf life, dispersion stability, and process reproducibility are also important. At the same time, raw-material costs, purification steps, and special processing requirements may limit competitiveness unless the LC system provides a clear functional advantage.

8.5. Toxicity, Lifecycle, and Recycling

Although LC materials can support greener technologies, their environmental safety must be assessed carefully. Some conventional LC monomers and additives are persistent, fluorinated, or otherwise biologically active, and their release during production, use, or disposal may create environmental concerns. Therefore, safe-by-design LC systems should prioritize renewable feedstocks, low-toxicity mesogens, covalent immobilization of active species, and reduced leaching potential. Although bio-based feedstocks reduce fossil dependence, environmental benefits can be weakened by energy-intensive synthesis or hazardous additives. More attention should be given to safe-by-design monomers, reduced leaching, and practical end-of-life routes. Recyclability remains limited for many LC composites, so mechanical recycling, depolymerization, and dynamic covalent reprocessing should be further explored.

Practical recycling strategies for LC materials should be framed according to material design. Thermoplastic LC systems may be mechanically recycled or remelted, chemically recyclable systems may be depolymerized under mild conditions, and dynamic covalent LC networks may be reprocessed by triggerable bond exchange. For composite systems, recovery of the fiber phase, binder phase, or LC additive should be considered separately, depending on the architecture.

8.6. Certification and Regulatory Requirements

Applications in coatings, windows, insulation panels, and building materials must meet fire safety, VOC, durability, and indoor-air standards. However, LC-specific properties such as color stability and response repeatability are not yet well covered by standardized certification pathways. Regulatory acceptance will therefore require both technical validation and suitable testing protocols.

9. Future Directions and Emerging Opportunities

9.1. Fully Bio-Derived LC Architectures

Research will push toward LC systems made exclusively from natural building blocks. Candidates include lignin- or starch-derived mesogens, proteins engineered to form LC phases, or hybrid biomolecules (e.g., chitin–cellulose composites). The goal is architectures where every component is renewable and non-toxic.

9.2. Additive Manufacturing and LC-Based 3D Printing

The alignment properties of LCs can be exploited in 3D printing. “Liquid crystal display” (LCD) resin printers, for example, can cure patterned LC polymers. Future work may enable printing of anisotropic LC scaffolds with controlled director orientation, for use in load-bearing parts or optical devices.

9.3. Circular Economy-Compatible LC Systems

Designing LC materials for circularity is a key trend. This includes not only recycling strategies (Section 7) but also modular product architectures: e.g., standardized LC-coated panels that can be easily separated and reconfigured, or LC coatings designed to peel off under specific conditions for recovery.

9.4. AI-Guided Molecular Design of Sustainable LC Materials

Machine learning and computational chemistry can accelerate the discovery of eco-friendly mesogens. AI models can screen candidates that meet multiple criteria (biodegradable, high birefringence, low toxicity) simultaneously. Closed-loop materials informatics—combining synthesis, testing, and AI optimization—could rapidly optimize LC formulas for specific green applications.

10. Conclusions

The convergence of liquid crystal science with sustainability imperatives has opened a promising route toward multifunctional materials. Experimental studies have already shown that certain LC-based coatings and composites can deliver optical modulation, self-healing behavior, and antimicrobial performance, while reducing reliance on VOCs and other hazardous constituents. In parallel, recent research has expanded the use of bio-based LC matrices and greener synthesis routes, strengthening the case for more environmentally responsible LC systems. At the same time, the literature indicates that important challenges remain, particularly in long-term stability, cost, moisture and UV resistance, and lifecycle integration. These issues are especially relevant for systems that are still under development or have yet to be validated under realistic service conditions. Overall, LC materials offer a versatile platform for sustainable coatings and composites, with strong potential for future growth as molecular design, processing, and systems engineering continue to advance. In summary, liquid crystals represent an important and expanding class of materials for environmentally friendly applications, with established experimental promise and significant room for further industrial development.

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