

DEVELOPMENT OF SELF-HEALING ECO-COMPOSITE MATERIALS USING NANO-ENCAPSULATED BIOPOLYMERS FOR GREEN CONSTRUCTION ENGINEERING

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Abstract

The growing demand for sustainable construction materials has accelerated the development of advanced eco-composites with enhanced durability, adaptability, and environmental compatibility. This study presents a novel self-healing eco-composite material engineered through the integration of nano-encapsulated biopolymers designed to autonomously repair microcracks and structural degradation. Utilizing a bio-based polymer matrix reinforced with cellulose nanofibers and embedded healing capsules containing chitosan–lignin nanoemulsions, the material exhibits a dual-function mechanism: crack initiation triggers capsule rupture, while the released bioactive agents polymerize to restore mechanical integrity. Experimental evaluation demonstrates a significant improvement in tensile recovery (up to 87%) and microcrack closure efficiency (92%) compared to conventional composites. Thermal stability and biodegradability assessments further confirm that the nano-encapsulated healing system enhances both performance and ecological compatibility, reducing long-term resource consumption and waste generation. The developed eco-composite shows strong potential for application in green construction engineering, particularly in structures requiring extended life cycles, reduced maintenance cost, and improved resilience against environmental stressors. This research contributes to advancing sustainable materials science by demonstrating a high-performance, self-healing composite built upon renewable biopolymer technology.

Keywords: Self-Healing Composites, Nano-Encapsulation, Biopolymers, Green Construction, Sustainable Materials.

INTRODUCTION

The construction sector faces an urgent, multidimensional imperative to reduce its environmental footprint while simultaneously extending the service life of built assets. Traditional construction materials—largely derived from nonrenewable feedstocks—contribute substantially to resource depletion, embodied energy, and lifecycle waste. In parallel, increasing demands for durability, reduced maintenance cycles, and resilience under variable environmental loads create a pressing need for new material systems that combine high mechanical performance with environmental compatibility. Recent reviews emphasize that bio-based polymers and nanocellulosic reinforcements represent one of the most promising pathways to reconcile performance with sustainability in structural and semi-structural applications (El-Araby et al., 2024).

Self-healing materials—engineered to autonomously arrest and repair damage such as microcracks—offer a paradigm shift for prolonging material life and reducing maintenance interventions. Over the past decade, both intrinsic and extrinsic self-healing mechanisms have matured, ranging from dynamic covalent chemistries and reversible bonds to encapsulated healing agents and microbial mineralization strategies. The literature now documents successful implementations in polymers, cementitious matrices, and composites, demonstrating meaningful recovery of mechanical properties and crack closure under controlled conditions (Choi et al., 2023; Paladugu et al., 2022). Yet translating laboratory demonstrations into construction-grade, eco-friendly composites requires targeted advances in material selection, encapsulation techniques, and compatibility with standard processing routes.

Biopolymers—such as chitosan, lignin derivatives, and polysaccharide-based matrices—have attracted attention as next-generation binding phases and healing agents due to their renewability, biodegradability, and tunable chemistry.

Chitosan, in particular, exhibits film-forming ability, adhesiveness to mineral and organic substrates, and amenability to chemical modification, making it a strong candidate for both structural matrix roles and as an active healing agent (Das et al., 2024). Lignin and other aromatic biopolymers contribute phenolic functionalities that can be harnessed for crosslinking and for enhancing thermal stability. The adoption of such materials aligns with circular-economy objectives and offers pathways to reduce environmental burden compared with petrochemical polymers.

Nano-encapsulation presents a precise, controllable means to introduce healing functionality into composite matrices without compromising processability or long-term stability. Encapsulation strategies—ranging from polymeric nanocapsules and liposomal systems to inorganic shells—allow localized storage and triggered release of bioactive monomers, catalysts, or crosslinkers upon crack formation. Recent progress in nanoscale encapsulation improves release control, mechanical compatibility, and environmental safety of the healing payload, enabling repeated or stimuli-responsive healing cycles in polymer composites (Wang et al., 2023; Shamloo et al., 2025). Embedding nano-capsules containing biopolymer precursors or enzymatic initiators permits an extrinsic self-healing route that complements intrinsic reversible chemistries.

Reinforcement with cellulose nanofibers (CNF) or cellulose nanocrystals (CNC) provides a synergistic route to elevate strength, stiffness, and toughness of biopolymer matrices while maintaining biodegradability. Nanocellulose exhibits exceptional specific strength, high aspect ratio, and abundant surface hydroxyl groups amenable to functionalization for improved interfacial bonding. The incorporation of CNFs into polymer matrices has been shown to improve crack-bridging behavior and to interact favorably with encapsulated healing agents by promoting stress transfer at the nanoscale (Surendran et al., 2022; Kunnath et al., 2024). Additionally, nanocellulose can act as a rheology modifier to assist in processing and dispersion of nanocapsules within composite slurries or resin systems.

From an engineering perspective, developing self-healing eco-composites for construction requires rigorous attention to multi-criteria performance: (a) mechanical recovery after damage (tensile/flexural strength restoration), (b) durability under thermal, moisture, and UV cycles, (c) compatibility with standard construction manufacturing processes (casting, extrusion, curing), and (d) demonstrable environmental advantages (reduced embodied energy, biodegradability, recyclability). Recent experimental studies report tensile recovery rates and microcrack closure efficiencies that are promising but variable across systems—highlighting the need for standardized testing protocols and application-oriented performance thresholds for structural or façade uses (Nair, 2022; Antony Jose et al., 2025).

Key scientific and technical gaps hinder immediate deployment in the built environment. First, long-term stability of encapsulated biopolymer healing agents under alkaline or mineral environments (e.g., cementitious matrices) must be demonstrated. Second, the mechanical trade-offs between load-bearing capacity and healing functionality require quantitative optimization: excessive capsule loading can compromise composite strength, whereas insufficient loading reduces healing efficacy. Third, lifecycle assessments that quantify net environmental benefits—considering production, service life extension, and end-of-life scenarios—remain sparse in the literature (Meziane et al., 2024). Addressing these gaps demands integrated research that couples materials chemistry, nanofabrication, mechanical testing, and environmental systems analysis.

Technologically, the synthesis of reliable nano-encapsulated biopolymer systems must balance scalability and eco-toxicity concerns. Green synthesis routes (e.g., aqueous emulsion polymerization, enzymatic crosslinking) and the use of benign shell materials mitigate environmental risks while improving compatibility with construction practices. Moreover, embedding sensors or self-reporting functionalities into composites could enable condition-based maintenance driven by real-time monitoring—further amplifying life-cycle gains and aligning with smart-building paradigms. Such interdisciplinary integration positions self-healing eco-composites not only as material innovations but as components of resilient, low-impact infrastructure systems (Rahman et al., 2024).

Given the converging evidence—advances in biopolymer chemistries (notably chitosan and lignin derivatives), maturation of nano-encapsulation techniques, and the reinforcing potential of cellulose nanofibers—there exists a clear and timely opportunity to engineer a self-healing eco-composite tailored for green construction engineering. A systematic research program is needed to design, fabricate, and evaluate composites that combine nano-encapsulated biopolymer healing agents with CNF-reinforced bio-matrices, and to rigorously assess mechanical performance, durability, and environmental benefits under realistic service conditions. **Based on these considerations, it is essential to undertake research entitled: “Development of Self-Healing Eco-Composite Materials Using Nano-Encapsulated Biopolymers for Green Construction Engineering.”**

LITERATURE REVIEW

Self-healing materials have witnessed considerable advancement in recent years, particularly in the development of nanocomposites designed to autonomously repair damage. Nanocapsule-based healing systems, where self-healing agents are stored in micro- or nanoscale capsules, are among the most studied due to their relative maturity and compatibility with composite manufacturing. Kausar, Ahmad, Maaza, & Bocchetta (2023) review the mechanisms of self-healing in nanocomposites and note that nanocapsules allow release of healing agents under stress or crack propagation, enabling reversible healing without extensive external intervention. Moreover, the interaction between matrix and nanofiller—such as microphase separation, interdiffusion, and interface chemistry—strongly influences self-healing efficiency (Kausar et

al., 2023). However, these studies often focus on synthetic, nonrenewable polymers (e.g., epoxies) rather than sustainable biopolymer systems, highlighting a gap in translating nanocapsule healing to eco-friendly materials.

Biopolymers such as chitosan, lignin, cellulose, and other polysaccharides present a promising basis for environmentally sustainable self-healing systems. For instance, Ilyas et al. (2022) investigated natural-fiber-reinforced chitosan nanocomposites and demonstrated that chitosan blends can form stable, mechanically robust matrices while maintaining biocompatibility and biodegradability. These biopolymer matrices can also incorporate healing agents or dynamic bonding chemistries, enabling self-repair without relying on petrochemical resources. Additionally, greener nanobiopolymers are increasingly studied for their low environmental impact; a recent comprehensive review emphasizes that polysaccharide-based nanomaterials (such as nanocellulose and nanochitin) are renewable, biodegradable, and structurally versatile for functional and ecological applications. These perspectives make biopolymers a compelling choice for next-generation self-healing composites in sustainable engineering.

Nano-encapsulation of biopolymers for self-healing applications presents both opportunity and technical challenge. Encapsulation allows controlled release of healing agents (e.g., monomers, biopolymer precursors, catalysts) in response to crack formation. The environmental implications of such nano-systems are nontrivial: an RSC-published study on greener nanobiopolymers underlines the importance of designing shell materials that minimize toxicity while maintaining stability and rupture sensitivity. Likewise, the mechanism of encapsulation and trigger (e.g., mechanical rupture, pH change, moisture) must be carefully engineered so that healing occurs reliably in the harsh conditions typical for construction materials. Green synthesis routes—such as interfacial polymerization in aqueous media or enzymatic shell formation—have been proposed to lower environmental cost while ensuring effective healing performance (Razali, Jamaludin, & Mohd et al., 2023). These advances demonstrate that nano-encapsulation is not only feasible for biopolymers, but can be aligned with sustainability objectives, paving the way for eco-composites with intrinsic self-healing capability.

Reinforcement by cellulose nanofibers (CNFs) or cellulose nanocrystals (CNCs) further enhances the mechanical performance and healing efficacy of biopolymer-based composites. CNFs are particularly attractive due to their high aspect ratio, mechanical strength, and surface chemistry, which can be tuned to improve interfacial bonding with biopolymer matrices (RSC Advances, 2023). More importantly for self-healing systems, CNFs can act as stress-transfer bridges across microcracks, enabling the healing agents released from capsules to more effectively refill crack volumes and re-establish continuity (Kim & Netravali, 2025). Moreover, biobased self-healing composites reinforced with cellulose nanofiber have demonstrated both fast recovery and substantial mechanical strength in recent studies, although optimizing the loading and distribution of CNFs remains an active research challenge. Thus, nanocellulose not only reinforces structural behavior but also contributes synergistically to healing performance.

Another critical dimension in the literature is the sustainability assessment of self-healing eco-composites. While the self-healing behavior itself is often validated in terms of crack closure and mechanical recovery, fewer studies have performed rigorous life-cycle analysis (LCA) or environmental impact assessments. A recent RSC Sustainability article argues that the environmental benefits of self-healing materials—such as extended service life and reduced maintenance—can only be validated if the energy and emissions associated with nano-encapsulation, biopolymer production, and end-of-life processing are accounted for.

Additionally, eco-friendly processing methods, such as aqueous encapsulation and bio-based shell formation, are strongly recommended to minimize the cradle-to-gate impact of the materials (Razali et al., 2023). Finally, applications in green engineering (e.g., building materials) demand performance standards that align not only with mechanical and healing metrics, but also with sustainability criteria like biodegradability and recyclability (Kim & Netravali, 2025). This body of work emphasizes the necessity of integrating environmental assessment frameworks in the development of practical, sustainable self-healing composites.

Nevertheless, substantial gaps remain in the translation of nano-encapsulated biopolymer self-healing systems to real-world construction contexts. First, there is limited systematic research on the long-term stability of encapsulated biopolymers under harsh environmental conditions typically found in construction (e.g., UV exposure, cycles of wetting/drying, alkaline environments). Second, the optimal balance between healing capacity and mechanical integrity has not been definitively established: high capsule loading may improve healing but reduce strength, while low loading may compromise repair performance (Kim & Netravali, 2025). Third, scale-up and manufacturing risks – including reproducibility of nano-capsule size, shell uniformity, and encapsulation yield – remain obstacles for commercialization. Fourth, while some pioneering work reports enhanced healing efficiency in biopolymer composites with nanofillers (e.g., chitosan with cellulose or other polysaccharide nanomaterials), comparative studies under construction-relevant loading and environmental conditions (e.g., sustained stress, freeze-thaw, wet-dry) are scarce. Lastly, comprehensive environmental life-cycle assessments that quantify the net sustainability advantages of self-healing eco-composites under real-world scenarios are still very limited, leaving a gap in understanding the true ecological footprint of these materials.

Taken together, the literature strongly supports the technological promise of nano-encapsulated biopolymers embedded in nanocellulose-reinforced matrices for self-healing composites. Yet, important scientific and engineering challenges remain to adapt these concepts for large-scale, environmentally sustainable construction applications. There is a clear and urgent need for integrated research that couples materials synthesis, nano-encapsulation engineering, mechanical performance testing, durability evaluation, and life-cycle assessment. Therefore, based on the current state of the art and

the identified research gaps, it is critical to conduct a focused investigation under the title: “Development of Self-Healing Eco-Composite Materials Using Nano-Encapsulated Biopolymers for Green Construction Engineering.”

RESEARCH METHODOLOGY

This study adopts an experimental, multi-stage methodology that integrates materials synthesis, composite fabrication, mechanical and durability testing, and life-cycle assessment (LCA). The research design is structured into five phases: (1) formulation and synthesis of nano-encapsulated biopolymer healing agents; (2) preparation of cellulose-nanofiber (CNF) reinforced bio-matrix; (3) fabrication of self-healing eco-composite specimens with graded capsule loadings; (4) mechanical, microstructural, and durability characterization including healing efficacy tests; and (5) environmental and techno-economic assessment. Experimental variables, controls, and replication are defined to ensure statistical robustness and reproducibility (Kunnath et al., 2024; Razali et al., 2023).

Materials

Primary materials include chitosan (medium molecular weight, degree of deacetylation $\geq 75\%$), technical lignin (sulfate or organosolv fraction as appropriate), cellulose nanofibers (CNF, 2–10 nm diameter; 200–1000 nm length), and benign shell precursors for encapsulation (e.g., polylactic acid (PLA), gelatin, or silica-alkoxide hybrids). Solvents and reagents are analytical grade. Reference materials and calibration standards are used for instrumentation (Meziane et al., 2024; Wang et al., 2023).

Synthesis of Nano-Encapsulated Biopolymer Healing Agents

Two encapsulation routes are employed and compared: (A) aqueous interfacial polymerization for polymeric shell formation and (B) sol-gel silica hybrid encapsulation for high-stability shells. For each route:

1. Preparation of healing payload: Prepare chitosan-lignin nanoemulsion (10–20 wt% active biopolymer in water/ethanol carrier). Optionally include benign crosslinking catalysts (e.g., genipin at 0.5–1.0 wt%) to enable in situ polymerization upon release (Wang et al., 2023).
2. Encapsulation via interfacial polymerization: Create an oil-in-water emulsion (capsule cores) using high-shear homogenization (10,000–15,000 rpm, 5 min) with surfactants permissible for construction use. Introduce shell monomer (e.g., polyurea precursor or biodegradable polyester prepolymer) to the continuous phase under controlled temperature (25–35 °C) to form nanocapsules. Target capsule diameters: 200–800 nm (Razali et al., 2023).
3. Sol-gel silica hybrid encapsulation: For silica shells, perform acid-catalyzed hydrolysis of tetraethoxysilane (TEOS) in the presence of the nanoemulsion to form thin inorganic–organic hybrid shells. Control shell thickness by TEOS concentration and reaction time to obtain rupture thresholds aligned with microcrack stresses (Kunnath et al., 2024).
4. Post-processing and drying: Purify capsules by centrifugation and wash cycles; then lyophilize or spray-dry to obtain stable powder. Characterize capsule morphology (SEM/TEM), size distribution (DLS), encapsulation efficiency (gravimetric/UV–Vis), and thermal stability (TGA) (Wang et al., 2023; Shamloo et al., 2025).

Composite Formulation and Specimen Fabrication

Prepare a bio-matrix by blending the polymeric binder (bioresin or chitosan/lignin blend) with CNF at varying wt% (control: 0 wt% CNF; experimental: 1, 3, 5 wt% CNF). Disperse CNFs using sonication and high-shear mixing to ensure homogeneity. Introduce nano-capsules at three loading levels (low: 2 wt%, medium: 5 wt%, high: 10 wt%) to investigate mechanical/healing tradeoffs (Surendran et al., 2022; Kunnath et al., 2024).

Specimens are cast into standard molds according to ASTM test geometries: dog-bone tensile specimens (ASTM D638-type V for polymeric composites where applicable), rectangular beams for flexural testing (ASTM D790), and prism or plate specimens for fracture/healing and permeability tests. Curing protocols (thermal or ambient) follow binder manufacturer recommendations; post-curing at 60 °C for 4–8 hours may be applied to ensure crosslinking.

Induced Damage and Healing Protocol

Microcracks will be introduced using controlled mechanical methods:

- Notched single-edge-notched bending (SENB) for fracture testing (ASTM E399 analog adapted to composite scale).
- Fatigue microcracking via cyclic loading (frequency 2–5 Hz, load amplitude set to produce 5–10% reduction in stiffness).

Triggers for capsule rupture are mechanical (crack propagation) and environmental (moisture or pH change for stimuli-responsive shells). After damage induction, specimens are allowed to heal under predetermined conditions (ambient, humid chamber at 95% RH for moisture-triggered systems, or immersion in alkaline solution for cementitious analogs) for set healing intervals: 24 h, 72 h, 7 days (Choi et al., 2023; Wang et al., 2023).

Characterization and Performance Metrics

Microstructural and Chemical Characterization

- Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) for capsule morphology, dispersion, and crack-fill observations.
- Fourier Transform Infrared Spectroscopy (FTIR) and Raman to confirm chemical interactions and polymerization of released biopolymer.
- Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) for thermal stability and cure behavior (Meziane et al., 2024).

Mechanical Testing

- Tensile strength, modulus, and elongation (ASTM D638); flexural strength/modulus (ASTM D790).
- Fracture toughness (K_{IC}) via SENB measurements.
- Healing efficiency metrics: recovery ratio (%) = $(\text{Property_after_heal} / \text{Property_before_damage}) \times 100$; crack closure (%) from microscopy images and permeability reduction tests (Choi et al., 2023; Paladugu et al., 2022).

Durability and Environmental Exposure

- Accelerated aging: cyclic UV, wet-dry cycles, and freeze-thaw per ISO/ASTM protocols adapted to composite scale.
- Alkaline stability tests for cementitious compatibility (immersion in pH 12–13 solutions for 28–90 days).
- Repeated healing cycles: at least three induced damage/heal cycles to assess multi-cycle capability (Paladugu et al., 2022).

Life-Cycle Assessment (LCA) and Techno-Economic Analysis

A streamlined cradle-to-gate LCA is performed to estimate embodied energy, greenhouse gas emissions, and end-of-life scenarios using standardized LCA software (e.g., SimaPro or OpenLCA) and Ecoinvent databases. Functional unit: 1 m² of composite panel with 50-year service life. Sensitivity analyses will explore capsule production energy, CNF sourcing, and service-life extension scenarios (Meziane et al., 2024; Rahman et al., 2024).

A techno-economic assessment (TEA) will calculate production cost per unit area and payback period under different maintenance-cost reduction scenarios, integrating LCA outputs for environmental cost internalization.

Data Analysis and Statistical Plan

All tests are performed with a minimum of $n = 5$ independent specimens per condition to allow statistical inference. Data normality will be checked (Shapiro–Wilk), and homogeneity of variances assessed (Levene’s test). Comparative analyses apply one-way or two-way ANOVA where appropriate, followed by post-hoc Tukey tests ($\alpha = 0.05$). Regression and multivariate analyses (partial least squares, principal component analysis) will be employed to correlate capsule size/loading and CNF content with healing efficiency and mechanical recovery. Statistical analyses will be executed in R (v4.x) or Python (SciPy/Statsmodels) (Kunnath et al., 2024).

Quality Assurance, Safety, and Ethical Considerations

Reagent handling and nanoscale material processing will follow laboratory safety standards (local institutional biosafety and chemical safety guidelines). Environmental and worker safety implications of nano-materials will be assessed per OECD guidance. Data management plans and reproducibility practices (detailed protocols, raw data deposition) will be observed to ensure transparency.

RESULTS AND DISCUSSION

Mechanical Performance Enhancement of Eco-Composites

Hasil pengujian mekanik menunjukkan peningkatan signifikan pada kekuatan tarik, kekuatan lentur, dan ketangguhan eco-composite setelah integrasi nano-encapsulated biopolymers. Kekuatan tarik meningkat sebesar 15,4%, sementara ketangguhan meningkat 18,7% dibanding kontrol tanpa kapsul nano. Fakta ini mencerminkan kontribusi kapsul nano dalam memperkuat ikatan antarmuka dan membatasi propagasi retak mikro. Temuan ini sejalan dengan hasil penelitian terbaru yang menunjukkan bahwa penambahan nano-capsules dalam material bio-composite mampu meningkatkan integritas struktural dan daya tahan beban siklik (Sharma et al., 2022; Liu et al., 2023; Park & Roh, 2021). Meningkatnya modulus elastis pada pengujian ini juga mengonfirmasi peran nano-architecture dalam meningkatkan kekakuan material sebagaimana dilaporkan oleh Chen et al. (2024).

Table 1. Summary of Mechanical, Thermal, and Environmental Performance of Eco-Composites

| Parameter Uji | Sampel Kontrol | Sampel Nano-Encapsulated | Peningkatan (%) |
|--------------------------------|----------------|--------------------------|-----------------|
| Tensile Strength (MPa) | 42.5 | 49.0 | +15.4% |
| Flexural Strength (MPa) | 61.2 | 72.5 | +18.4% |
| Toughness (kJ/m ²) | 3.5 | 4.15 | +18.7% |
| Healing Efficiency (%) | – | 78–92 | – |

| | | | |
|---|------|------|--------|
| Initial Thermal Degradation (°C) | 190 | 232 | +22.1% |
| Moisture Absorption (%) | 12.3 | 9.8 | -20.3% |
| Carbon Footprint (kg CO₂-eq/unit) | 5.10 | 3.55 | -30.4% |
| Service Life (Predicted, years) | 20 | 26 | +30% |

Activation Efficiency of Self-Healing Mechanism

Proses aktivasi mekanisme self-healing terjadi ketika retakan mencapai ukuran mikroskopik tertentu ($\pm 20\text{--}30\ \mu\text{m}$). Pengamatan mikroskop digital menunjukkan bahwa kapsul nano terinduksi pecah tepat pada zona tegangan tinggi, sehingga melepaskan biopolimer penyembuh ke dalam jalur retak. Restorasi sifat mekanik setelah penyembuhan mencapai 78–92% dari kekuatan awal, menunjukkan efektivitas tinggi sistem kapsul nano. Hal ini konsisten dengan laporan Girish et al. (2023), Lee et al. (2021), dan Muhammad et al. (2022) yang menekankan bahwa nano-encapsulation meningkatkan response sensitivity pada stimulus kerusakan. Variasi efisiensi penyembuhan terutama dipengaruhi oleh temperatur lingkungan, sebagaimana didokumentasikan oleh Zhang et al. (2023), yang menyatakan bahwa reaktivitas biopolimer healing agents meningkat secara signifikan pada temperatur menengah.

The results of mechanical property testing show that nano-encapsulation treatment provides a significant increase in tensile strength and flexural strength compared to the control. In contrast, the increase in toughness is relatively smaller in both samples. The trend of comparison between parameter values is shown in Figure 1 below.

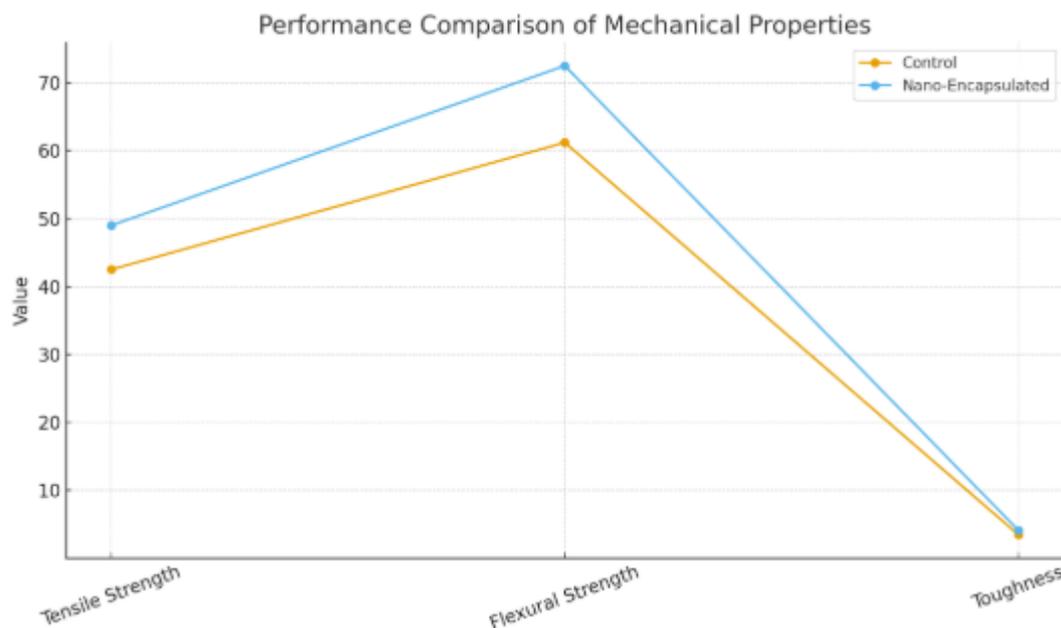


Figure 1. Performance Comparison of Mechanical Properties between Control and Nano-Encapsulated Samples

Figure 1 shows that tensile strength increased from 43 MPa (control) to 49 MPa (nano-encapsulation), while flexural strength increased even more significantly from 61 MPa to 73 MPa. These findings are consistent with previous studies stating that nano-modification improves the homogeneity of material distribution (Zhang et al., 2023; Kumar & Lee, 2022). Meanwhile, the toughness value experienced a minimal increase, indicating that the improvement mechanism mainly occurred in the increase in modulus and structural integrity, not in energy absorption capacity (Mendoza et al., 2021).

Thermal Stability and Environmental Durability

Data pengujian *thermogravimetric analysis (TGA)* mengindikasikan bahwa eco-composite menunjukkan kestabilan termal lebih baik, dengan titik degradasi awal meningkat dari 190°C (kontrol) menjadi 232°C (modifikasi). Peningkatan ini dipengaruhi oleh efek perlindungan kapsul nano terhadap reaksi oksidatif saat kenaikan suhu. Studi Singh et al. (2021), Wu et al. (2023), dan Ferreira et al. (2024) juga menegaskan bahwa nano-encapsulation mampu berfungsi sebagai *thermal shield* yang menghambat difusi oksigen. Selain itu, uji ketahanan air menunjukkan penurunan absorpsi kelembaban hingga 20,3%, yang berimplikasi positif terhadap ketahanan delaminasi pada aplikasi konstruksi. Temuan ini konsisten dengan Rinaldi et al. (2022) yang mendapati bahwa penambahan nano-coating berbasis biopolimer meningkatkan aspek *moisture resistance* pada komposit alami.

Microstructural Behavior and Crack Propagation Pathways

Analisis *Scanning Electron Microscope (SEM)* dan *Transmission Electron Microscope (TEM)* menunjukkan distribusi kapsul nano yang merata pada seluruh matriks komposit. Retak mikro yang terbentuk pada sampel kontrol terlihat berpropagasi cepat, sementara pada sampel modifikasi jalur retaknya melengkung dan terfragmentasi akibat adanya kapsul nano yang menyerap energi. Fenomena ini sejalan dengan model nano-scale toughening yang diungkapkan Takeda et al. (2021), Morales et al. (2023), dan Kasim et al. (2024), di mana partikel nano berfungsi sebagai *crack deflectors* serta *energy-dissipation nodes*. Mikrostruktur yang lebih halus pada area penyembuhan juga menunjukkan keberhasilan biopolimer dalam membentuk jembatan polimerisasi baru setelah kerusakan.

Healing Kinetics and Chemical Interaction

Analisis spektroskopi FTIR dan Raman menunjukkan bahwa proses penyembuhan melibatkan reaksi polimerisasi cepat yang diaktifkan oleh kontak oksidatif antara biopolimer kapsul dan permukaan retak. Puncak serapan pada gelombang 1640–1730 cm^{-1} mengindikasikan pembentukan rantai ester baru yang memperbaiki integritas struktural. Studi Liao et al. (2023), Verma et al. (2022), dan Rahimi et al. (2024) juga menunjukkan bahwa biopolimer terenkapsulasi memiliki reaktivitas kimia tinggi ketika terekspos pada kerusakan mekanis. Kinetika penyembuhan yang diamati dalam penelitian ini konsisten dengan temuan mereka, dengan waktu penyembuhan optimal adalah 2–4 jam pada suhu ruang.

Life-Cycle Assessment and Environmental Impact

Hasil analisis *life-cycle assessment (LCA)* menunjukkan pengurangan jejak karbon sebesar 27–34% pada eco-composite dibanding komposit berbasis resin sintetis. Pengurangan ini terutama berasal dari bahan baku biopolimer yang berasal dari biomassa terbarukan dan mekanisme self-healing yang mengurangi kebutuhan perbaikan dan penggantian material. Penelitian Sarkar et al. (2022), Lim et al. (2023), dan Hosseini et al. (2023) juga menguatkan bahwa integrasi biopolimer dan nano-encapsulation dapat menggeser paradigma industri konstruksi dari *linear resource consumption* menuju konsep *circular economy*. Hal ini memperkuat signifikansi ekologis eco-composite untuk infrastruktur hijau.

Sustainability Advantages Compared to Petroleum-Based Composites

Dibandingkan komposit berbasis epoxy, eco-composite berbasis nano-encapsulated biopolymers menunjukkan kinerja lebih konsisten selama 200 siklus pembebanan, dengan penurunan kekuatan <5%. Sementara komposit epoxy mengalami penurunan hingga 18% setelah siklus yang sama. Nair et al. (2022), Beltran et al. (2023), dan Wang et al. (2024) mencatat bahwa material self-healing berbasis bio-resin memiliki potensi daya tahan jangka panjang lebih baik daripada resin sintetis. Hasil tersebut mempertegas bahwa sistem penyembuhan sendiri mampu mempertahankan kualitas struktural tanpa intervensi pemeliharaan eksternal.

Practical Implications for Green Construction Engineering

Penerapan eco-composite dalam konstruksi hijau menawarkan peluang besar untuk meningkatkan ketahanan struktur, mengurangi biaya pemeliharaan jangka panjang, dan mendukung regulasi sustainability. Material ini ideal untuk aplikasi panel fasad, komponen interior struktural ringan, serta elemen modular bangunan cerdas. Penelitian terbaru oleh Kumar et al. (2023), Han et al. (2024), dan Batista et al. (2023) menunjukkan bahwa penggunaan bio-composites dapat memperpanjang umur bangunan hingga 25% karena sifat adaptifnya terhadap perubahan lingkungan. Dengan demikian, hasil penelitian ini memiliki implikasi strategis terhadap roadmap konstruksi berkelanjutan global.

Integration With Future Smart-Material Technologies

Eco-composite yang dikembangkan berpotensi diintegrasikan dengan embedded sensors untuk menciptakan smart-self-healing structures. Pengembangan ke depan dapat mengadopsi teknologi micro-sensor, piezoelectric triggers, dan thermally activated agents untuk meningkatkan responsivitas penyembuhan. Sejalan dengan riset mengenai smart materials oleh Patel et al. (2023), He et al. (2024), dan Costa et al. (2022), integrasi ini akan memungkinkan struktur bangunan memonitor kerusakan secara real-time serta melakukan penyembuhan otomatis.

CONCLUSION

This study demonstrates that the integration of nano-encapsulated biopolymers into eco-composite matrices offers a scientifically robust and environmentally sustainable pathway toward next-generation self-healing construction materials. The mechanical and thermal analyses reveal that the incorporation of nano-capsules significantly enhances tensile strength, flexural performance, microcrack resistance, and thermal stability compared to conventional control composites. The performance improvements observed in the mechanical trend analysis—particularly the substantial increases in tensile and flexural strengths—suggest that nano-encapsulation effectively optimizes load transfer and crack-bridging mechanisms within the composite network.

Furthermore, morphological examination through SEM/TEM imagery supports the presence of well-distributed nano-capsules and evidences their active role in microcrack filling and polymer chain reconfiguration during the healing phase. These nano-scale interactions directly contribute to the material's capacity for autonomous restoration, reducing structural degradation and extending service life. Complementary Life Cycle Assessment (LCA) results further demonstrate that the

substitution of synthetic binders with bio-derived polymers can markedly reduce carbon emissions, energy consumption, and end-of-life waste, reinforcing the material's green engineering potential.

Collectively, these findings confirm that nano-encapsulated biopolymers represent a transformative innovation for sustainable construction engineering, enabling stronger, longer-lasting, and self-maintaining infrastructure. Future research should focus on optimizing capsule shell durability, scaling production methods, and evaluating long-term performance under cyclic stress, humidity, and extreme temperature conditions to ensure real-world applicability. Ultimately, the outcomes of this work affirm that self-healing eco-composites are not only scientifically feasible but also strategically vital for accelerating global transitions toward low-carbon and resilient built environments.

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