
SMART SELF-HEALING MATERIALS: A COMPREHENSIVE REVIEW OF EMERGING TECHNOLOGIES AND FUTURE PERSPECTIVES

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DOI: <https://doi.org/10.67203/sp.ICESID.2026>

ABSTRACT

Self-healing materials represent one of the most significant paradigm shifts in modern materials engineering, offering the ability to autonomously detect and repair internal or external damage without human intervention, thereby extending service life, improving safety, and reducing maintenance costs across engineering applications. This review synthesizes recent advances in smart self-healing materials, covering the three principal design philosophies that underpin the field: capsule-based (extrinsic), vascular and intrinsic self-healing systems. It examines the healing agents, encapsulation strategies, and activation mechanisms employed across polymeric composites, cementitious materials and hydrogel-based systems, and evaluates their translation into real-world sectors including aerospace, automotive, construction, biomedicine, and flexible electronics. Particular attention is given to emerging technologies such as microencapsulated healing agents for structural and cement-based composites, dynamic covalent and supramolecular chemistries that enable repeated intrinsic healing, bio-mediated systems such as bacterially induced self-healing concrete and stimuli-responsive hydrogels for tissue engineering, wound care, and drug delivery. The review further considers how data-driven approaches, including machine learning and artificial intelligence, are beginning to accelerate the discovery, formulation optimization, and predictive modelling of healing efficiency. Despite considerable progress, the field remains constrained by challenges of production scalability, healing-agent depletion after repeated cycles, trade-offs between healing efficiency and mechanical performance, high cost, and the absence of standardized testing protocols. This review contributes to the growing body of knowledge by providing a comprehensive synthesis of emerging technologies and identifying research priorities for future development of smart self-healing materials.

Keywords: self-healing materials; smart materials; microencapsulation; vascular networks

1. INTRODUCTION

Advanced engineering materials have shifted from conventional passive systems toward smart materials that sense environmental changes and respond through controlled property alterations. Smart materials respond to stimuli including temperature, stress, pressure, moisture, pH, electric or magnetic fields, light, and chemical environments, enabling adaptive behaviour difficult to achieve with conventional materials (Mrinalini & Prasanthkumar, 2019). This broader field encompasses stimuli-responsive polymers, shape-memory materials, electroactive and magnetically responsive systems, hydrogels, nanocomposites, and self-healing materials (Srivastav et al., 2025; Jain et al., 2025).

Among these, self-healing materials (SHMs) have attracted particular interest because they introduce autonomous repair into engineering systems. A SHM restores structural integrity or functional performance following damage through autonomous or stimulus-assisted processes (El Choufi et al., 2022; Kontiza & Kartsonakis, 2024). Inspired by biological systems, where damage activates localized transport, molecular recognition, chemical reactions, and reconstruction; the engineering translation treats damage not as irreversible failure but as a trigger for programmed repair (White et al., 2001; Srivastav et al., 2025).

Material degradation often begins at microscopic scales before progressing to visible cracks, delamination, corrosion, leakage, conductivity loss, or catastrophic failure. Conventional maintenance

requires detection followed by external intervention. SHMs reduce this dependence by embedding healing mechanisms within the material architecture itself (White et al., 2001; Zhu et al., 2015). The landmark work of White et al. (2001) demonstrated an autonomic polymer composite in which crack propagation ruptured embedded microcapsules, released a healing agent, and initiated polymerization—establishing a foundational concept that stimulated extensive research into encapsulation, healing-agent chemistry, catalyst distribution, and matrix compatibility.

The field has evolved through successive generations: early extrinsic capsule-based systems (White et al., 2001), intrinsic reversible-bond polymers and advanced vascular and multi-stimuli systems inspired by biological circulatory networks (Blaiszik et al., 2010; Hager et al., 2010). Progress spans polymers, polymer-matrix composites, protective coatings, cementitious materials, metals, and soft materials. Market projections place the global SHM market in the multi-billion-USD range in the mid-2020s, with continued expansion toward 2030–2035 driven by construction, automotive, aerospace, electronics, and biomedical demand (Jose et al., 2026; Kontiza & Kartsonakis, 2024).

Reviews classify systems according to whether healing functionality is stored separately from the matrix (extrinsic: microcapsules, hollow fibres, vascular networks) or incorporated directly into the material network (intrinsic: reversible interactions or dynamic bonds) (El Choufi et al., 2022; Kontiza & Kartsonakis, 2024; Srivastav et al., 2025; Zhu et al., 2015; Jain et al., 2025). Figure 1 organizes the design space along three axes—Strategy (Intrinsic, Extrinsic, Stimuli-responsive), Mechanism (supramolecular interactions, dynamic covalent bonds, vascular/capsule architectures), and Target Functions (mechanical integrity, barrier properties, conductivity, biological compatibility)—and underpins the organization of this review.



Figure 1: Author-generated design-space map of smart self-healing materials, synthesized from the reviewed literature (Song et al., 2021; Rai et al., 2023; Dallaev, 2024; Jose et al., 2026).

2. METHODOLOGY

2.1 Review Design and Search Strategy

This study employed a structured integrative review design rather than a formal systematic review or meta-analysis. Searches spanned Web of Science, Scopus, Google Scholar, PubMed/PMC, and publisher platforms (MDPI, Elsevier, Wiley, RSC, Springer). Search strings combined terms such as “smart materials,” “self-healing materials,” “self-healing polymers,” “autonomous healing,” “microcapsule self-healing,” “vascular self-healing,” “intrinsic self-healing,” “dynamic covalent,” “supramolecular self-healing,” “self-healing concrete,” “bacteria-based self-healing,” and “stimuli-responsive hydrogels.” Emphasis was placed on 2010–2026 while retaining seminal pre-2010 studies that established foundational mechanisms.

2.2 Eligibility and Evidence Selection

Priority was given to peer-reviewed reviews and original research reporting mechanisms, healing agents, fabrication routes, healing efficiency or mechanical recovery, conditions, durability, scalability, or application evidence. Non-peer-reviewed, purely speculative, out-of-domain, or non-

English studies were excluded. Citation chaining from seminal works and recent reviews identified influential experimental and sector-specific literature.

2.3 Data Extraction and Synthesis

Extracted data included material class, healing architecture, agent or reversible interaction, activation stimulus, healing time, recovery metric, environmental conditions, repeatability, and application context. Because healing efficiency is defined differently across studies, via fracture toughness, tensile strength, modulus, crack closure, permeability, conductivity or other metrics; reported percentages are presented as representative values only and are not treated as directly equivalent. Synthesis is qualitative and comparative rather than a pooled meta-analysis (Bekas et al., 2016; Geng et al., 2023).

3. SYNTHESIZED FINDINGS AND DISCUSSION

3.1 Extrinsic Capsule-Based Self-Healing Systems

Extrinsic capsule systems remain among the most mature autonomous-repair approaches because they separate the healing agent from the host matrix until damage occurs. A propagating crack ruptures microcapsules; the liquid agent wets crack faces; polymerization or solidification restores the damaged region. Healing chemistry can be optimized independently of the structural matrix, and capsules can be distributed throughout a component (White et al., 2001; Zhu et al., 2015).

The original dicyclopentadiene/Grubbs-catalyst system recovered approximately 75% of fracture toughness (White et al., 2001). Dual-microcapsule epoxy–amine chemistry achieved about 91% average healing efficiency in an optimized formulation (Jin et al., 2012). More recent work shows strong dependence on capsule size and concentration; one study reported up to 68% load recovery while demonstrating that larger capsules can reduce unhealed-matrix mechanical performance (Mousavi et al., 2019). These results underscore the central trade-off between adequate healing-agent delivery and preservation of matrix strength.

The principal limitation of single-use capsules is finite local healing capacity: once ruptured and consumed, a location cannot generally be healed again without another reservoir. Multicore and multicapsule systems distribute this limitation, yet increased loading may introduce defects, reduce matrix continuity, and complicate manufacturing (Zhu et al., 2015; Kontiza & Kartsonakis, 2024). Capsule shell chemistry, permeability, interfacial adhesion, size distribution, core fraction, catalyst stability, and environmental compatibility therefore require simultaneous optimization.

3.2 Vascular and Microvascular Self-Healing Architectures

Vascular systems address finite healing-agent supply by embedding interconnected channels that deliver agents to multiple damage events. Toohey et al. (2007) demonstrated a microvascular network supplying reactive components to damaged regions. Subsequent architectures enable repeated healing via network refill. Early systems achieved multiple healing events; later designs using separate networks for agents and catalysts extended repeatability—reported examples include 16 cycles with ~60% fracture-toughness recovery and >30 cycles with recovery ranging from ~50% to 100%, depending on architecture and test conditions (Toohey et al., 2007; Patrick et al., 2014).

3.3 Intrinsic Self-Healing: Dynamic Covalent and Supramolecular Mechanisms

Intrinsic systems incorporate the healing mechanism directly into the material network, permitting repeated damage and repair without a separate reservoir. Healing is enabled by reversible covalent bonds (disulfide, imine, boronate ester, Diels–Alder, and related dynamic chemistries) or by reversible non-covalent interactions (hydrogen bonding, ionic association, π – π interactions, metal coordination, host–guest recognition) (El Choufi et al., 2022; Zafeer & Bhat, 2024).

A major advantage is repeatability: because healing functionality is distributed throughout the network, repair can occur at multiple locations and over multiple cycles provided network chemistry remains viable. Supramolecular polymers can heal under relatively mild conditions via reversible

intermolecular interactions that enable chain rearrangement. Optically activated supramolecular systems combine stimulus response with repair, while thermoreversible rubber-like systems established the importance of dynamic association for repeated recovery (Burnworth et al., 2011; Cordier et al., 2008).

3.4 Stimuli-Responsive and Multifunctional Self-Healing Systems

Stimuli-responsive systems extend self-healing beyond passive damage-triggered repair by coupling healing to external or environmental cues—heat, light, pH, moisture, electrical or magnetic fields, ionic conditions, and chemical environments (Mrinalini & Prasanthkumar, 2019). The stimulus can accelerate diffusion, activate reversible reactions, soften a matrix temporarily, initiate photochemical healing, or alter network association.

Value is clearest in demanding environments: heat accelerates bond exchange; light provides spatial/temporal control; pH or enzyme responsiveness suits biomedical settings. Dependence on an external stimulus, however, can reduce autonomy if the stimulus is unavailable in service. Genuinely smart materials therefore increasingly combine damage sensing with a locally available stimulus, enabling repair only where and when needed (Jain et al., 2025; Morris et al., 2025).

3.5 Cementitious and Bio-Mediated Self-Healing Materials

Self-healing cementitious materials address a different service problem: sealing cracks, reducing transport of water and aggressive agents, and preserving durability rather than restoring original fracture toughness. Autogenous healing occurs through continued hydration, calcium carbonate precipitation, or related natural processes; autonomous systems employ capsules, mineral agents, polymers, shape-memory elements, or microorganisms (Amran et al., 2022; Meraz et al., 2023; Nguyen et al., 2023).

Bacteria-based self-healing concrete offers a distinct bio-mediated route in which suitable microorganisms promote mineral precipitation—particularly calcium carbonate—within cracks. Performance depends on bacterial viability, nutrient availability, pH, temperature, moisture, crack geometry, and protection of microorganisms from the highly alkaline cementitious environment. Recent reviews emphasize that environmental conditions and crack width strongly influence outcomes, and that laboratory results under ideal conditions should not be interpreted as direct evidence of field reliability (Gruyaert & De Belie, 2023; Meraz et al., 2023).

Sustainability potential lies in extended service life and reduced repeated repair. Durability of the biological component, long-term viability, compatibility with local construction practices, encapsulation/nutrient cost, and performance under African climatic conditions require additional field-scale evidence. For Nigeria, locally available mineral precursors and biologically compatible carriers could provide lower-cost routes to autonomous crack sealing, provided structural and environmental safety are demonstrated.

3.6 Self-Healing Hydrogels for Biomedical Applications

Self-healing hydrogels combine self-repair, injectability, flexibility, biocompatibility, and controlled transport within hydrated polymer networks. Biomedical designs use dynamic covalent and reversible non-covalent associations to restore network integrity after mechanical damage, supporting wound dressings, tissue engineering, drug delivery, biosensing, and regenerative medicine (Bhuvaneswari et al., 2025; Xue et al., 2025).

Stimuli-responsive hydrogels are particularly relevant to wound care because physiological environments supply cues such as pH, temperature, ionic strength, reactive oxygen species, glucose, and enzyme activity that can control drug release, antimicrobial activity, tissue adhesion, and regeneration. Composite hydrogels can respond to pH, temperature, light, and enzyme activity while supporting controlled therapeutic delivery and tissue repair (Ding et al., 2025). Reported mechanical recovery ranges from approximately 40% to >90% depending on network chemistry and conditions, illustrating the same strength–mobility trade-off observed in structural polymers (Khan et al., 2022). High laboratory efficiency alone does not establish clinical suitability; cytocompatibility, degradation behaviour, sterilization stability, reproducibility, and long-term physiological performance must also be demonstrated (Xue et al., 2025).

3.7 Comparative Synthesis of Representative Healing Performance

Table 1 summarizes representative reported performance values. Values are intentionally not ranked because healing efficiency depends on the property measured, damage geometry, healing time, stimulus, and test protocol.

Table 1: Summary of representative reported performance values

System	Material architecture	Representative recovery	Healing condition	Key strength	Key limitation
Extrinsic capsule	DCPD/Grubbs epoxy	≈75% fracture toughness	Room-temp; seminal	Simple autonomous activation	Finite local agent supply
Extrinsic dual capsule	Epoxy–amine microcapsules	≈91% avg. efficiency	Optimized ratio; RT	High single-cycle recovery	Complexity; finite reservoir
Vascular	Microvascular epoxy	≈60% over 16 cycles	Repeated refill	Repeatable healing	Fabrication complexity
Vascular (adv.)	Advanced architecture	Up to 100% recovery	Architecture-dependent	Many cycles possible	Channel reliability
Cementitious	Microbial autonomous	/ Varies with crack/env.	Moisture, nutrients	Crack sealing; durability	Viability; field robustness
Hydrogel	Dynamic covalent supra.	Tens of % to >90%	Min–days; stimulus-dep.	Soft, injectable, multi-func.	Biocompatibility; strength

Note. Values drawn from White et al. (2001), Jin et al. (2012), Toohey et al. (2007), Patrick et al. (2014), Amran et al. (2022), Meraz et al. (2023), and Xue et al. (2025). Percentages are not directly comparable across material classes.

4. SECTOR-SPECIFIC APPLICATIONS AND TRANSLATION

4.1 Aerospace and Wind-Energy Structures

Aerospace structures demand low mass, high damage tolerance, fatigue resistance, environmental stability, and predictable certification performance. Self-healing composites are attractive because cracks and delamination can initiate below easy visual detection. Capsule-based and vascular approaches can delay damage growth; intrinsic matrices can provide repeated repair. Wind-turbine blades present a related application: large composite structures under cyclic loading with difficult maintenance access. Koralagundi Matt et al. (2015) demonstrated self-healing polymer composites for wind-turbine blade applications. Translation to flight-critical aerospace components, however, requires stringent evidence on fatigue, impact, ageing, repair repeatability, inspection compatibility, and certification.

4.2 Automotive Applications

Automotive uses include structural composites, protective coatings, sealants, interior components, and conductive materials. The principal benefit is reduced degradation from repeated mechanical, thermal, and environmental loading. Intrinsic polymers suit repeated low-level damage; extrinsic systems are useful in coatings or localized composite regions. Commercial implementation depends on cost, high-volume processing compatibility, temperature resistance, recyclability, and compatibility with existing joining and painting processes (El Choufi et al., 2022; Kontiza & Kartsonakis, 2024).

4.3 Construction and Infrastructure

Construction offers one of the strongest arguments for self-healing because inspection and repair of distributed microcracks are expensive and disruptive. Self-healing concrete can reduce water ingress and improve durability via autogenous, mineral, capsule-based, or microbial mechanisms.

Realistic exposure conditions, crack width, sustained loading, wet–dry cycling, and environmental aggressiveness can substantially alter performance; laboratory crack closure should not be the sole indicator of field effectiveness (Gruyaert & De Belie, 2023; Nguyen et al., 2023).

4.4 Biomedical and Healthcare Applications

Biomedical self-healing systems must repair while remaining biocompatible and functionally compatible with living tissue. Self-healing hydrogels support wound dressings, drug delivery, tissue engineering, biosensing, and injectable systems. Stimuli-responsive designs can exploit physiological cues to regulate drug release or healing activity; dynamic networks preserve functionality after deformation (Ding et al., 2025; Xue et al., 2025). Principal translation barriers are biocompatibility, sterilization, biodegradation control, reproducibility, long-term safety, and clinical validation.

4.5 Flexible Electronics and Bioelectronics

Flexible and stretchable electronics require recovery of both mechanical and functional properties after repeated deformation or damage. Self-healing conductive polymers, elastomers, and hydrogels can restore electrical pathways while maintaining flexibility—relevant to wearable sensors, soft interfaces, and bioelectronic devices where mechanical damage can interrupt signal transmission (He et al., 2024; Liu et al., 2024; Mashkoo et al., 2022). Future systems will need simultaneous recovery of mechanical, electrical, optical, and sensing functions rather than structural repair alone.

5. RESEARCH GAPS AND SUSTAINABILITY

5.1 Healing Efficiency versus Mechanical Performance

A central unresolved problem is simultaneous optimization of healing efficiency, strength, toughness, stiffness, environmental resistance, and processing stability. Increased molecular mobility generally improves healing but can reduce mechanical integrity; rigid crosslinked structures restrict healing kinetics (El Choufi et al., 2022; Jain et al., 2025). Future studies should report multidimensional performance rather than a single healing percentage.

5.2 Repeatability and Healing-Agent Depletion

Extrinsic capsule systems are limited by finite agent availability; vascular systems require reliable fluid transport and refillability. Intrinsic systems offer better theoretical repeatability but may suffer from fatigue of dynamic bonds or environmental sensitivity. Meaningful comparison should report number of healing cycles, retained recovery after cycling, and fraction of original functionality restored after repeated damage (Toohey et al., 2007; Patrick et al., 2014).

5.3 Standardization of Evaluation

Cross-literature comparisons remain difficult because studies vary in damage geometry, crack width, healing temperature and duration, stimulus intensity, loading configuration, environmental exposure, and definition of recovery. Future research should report both crack-level metrics and functional recovery, together with standardized damage and healing histories—particularly important when translating laboratory results into structural applications (Bekas et al., 2016; Morris et al., 2025).

5.4 Sustainability and Circular Materials Design

Self-healing can contribute to sustainability by extending service life and reducing replacement and maintenance, but healing chemistry itself must be assessed. Capsule shells, catalysts, nanoparticles, synthetic monomers, and complex processing routes may create environmental burdens. A sustainable design framework should consider embodied energy, toxicity, recyclability, end-of-life processing, local material availability, and life-cycle service extension rather than assuming inherent sustainability (Srivastav et al., 2025).

5.5 Relevance to Nigeria and Africa

For Nigeria and other African economies, the most relevant pathway is not simply to reproduce high-cost laboratory systems developed for advanced industrial markets, but to adapt self-healing principles to locally available materials, manufacturing capabilities, climate conditions, and infrastructure needs. Priorities include mineral-based healing agents for cementitious materials, bio-mediated crack sealing using locally adaptable microorganisms, natural or agricultural-derived polymer components, and low-cost encapsulation routes. Such research should be coupled with local durability testing under high temperature, humidity, wet–dry cycling, and aggressive environmental conditions. Scale-up requires affordable feedstocks, reproducible processing, quality control, skilled personnel, and standards that support local manufacturing and construction adoption.

The Nigerian context also creates opportunity for application-driven research in infrastructure, water systems, transportation, energy, and composite components. A locally grounded agenda could integrate materials characterization, design of experiments, life-cycle assessment, digital modelling, and machine learning to identify formulations that balance performance with cost and availability—aligning SHM research with broader priorities of infrastructure durability, resource efficiency, local manufacturing, and sustainable industrial development.

6. FUTURE PERSPECTIVES

6.1 Artificial Intelligence and Data-Driven Materials Design

AI and machine learning are increasingly relevant because healing performance depends on interacting formulation, processing, microstructural, and environmental variables. Data-driven models can relate polymer composition, crosslink density, capsule concentration, healing temperature, damage history, and kinetics to final performance. The most useful direction is not to replace experiments but to reduce trial-and-error and identify promising combinations for targeted validation (Jain et al., 2025).

6.2 Additive Manufacturing and Architected Healing Networks

Additive manufacturing provides spatial control over composition and architecture. Three-dimensional printing can enable controlled placement of healing reservoirs, vascular networks, dynamic polymer regions, and multifunctional structures—moving design from homogeneous formulations toward architectures tailored to predicted damage locations and load paths (Andreu et al., 2024). Remaining challenges include printability, interlayer bonding, healing-agent compatibility, scale-up, process repeatability, and long-term stability of printed architectures.

6.3 Multifunctional and Autonomous Systems

The next generation is expected to integrate sensing, actuation, repair, and communication. A truly smart material could detect damage, identify severity, trigger a suitable healing mechanism, verify recovery, and communicate condition to a monitoring system. Combining self-healing with structural health monitoring, embedded sensors, conductive networks, and digital models could create materials that participate actively in predictive maintenance rather than merely responding after damage.

6.4 Industrial Scale and Circularity

Industrial adoption will depend on reproducible manufacturing, affordable raw materials, environmental stability, standardized testing, and compatibility with existing production systems. Dynamic covalent networks may be especially important where healing and reprocessing can be combined, potentially reducing material waste (Maes et al., 2025). Claims of circularity must be validated through life-cycle assessment and end-of-life studies. For developing economies, low-cost and locally sourced healing systems deserve particular attention because economic accessibility is part of sustainability.

7. CONCLUSIONS

Smart self-healing materials have progressed from the original capsule-based concept to a broad family of extrinsic, vascular, intrinsic, stimuli-responsive, bio-mediated, and multifunctional systems.

No single architecture is universally superior. Capsule systems offer relatively simple autonomous activation but finite local healing capacity; vascular networks improve repeatability at the expense of architectural complexity; intrinsic systems offer distributed and potentially repeated repair but face the strength–mobility trade-off; stimuli-responsive systems provide additional control but may depend on environmental or external stimuli.

Comparative evidence demonstrates why healing-efficiency percentages must be interpreted within their test context. Representative polymer systems have achieved approximately 75–91% recovery in selected fracture-toughness tests; vascular architectures have demonstrated repeated healing over many cycles; hydrogel systems can achieve high mechanical recovery under selected conditions. Cementitious and bio-mediated systems are better evaluated through crack closure, permeability reduction, durability, and service-life indicators. Across all classes, standardized testing, repeatability, environmental durability, and life-cycle assessment remain critical.

For Nigeria and Africa, the strategic opportunity is to adapt self-healing principles to local materials, infrastructure needs, climate conditions, and manufacturing capacity. Research should prioritize affordable and environmentally responsible healing agents, scalable processing, realistic durability testing, and data-driven optimization. The long-term objective should be materials that do not merely heal damage but sense, respond, recover, and operate sustainably over extended service lives.

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