International Journal of
Chemical Synthesis and Chemical Reactions

ISSN: 2582-5917
Volume 11, Issue 1, 2025
Journal): 10.37628/IJCSCR

https://chemical.journalspub.info/index.php?journal=JCSCR

Research IJCSCR

Mechanisms and Applications of Self-Healing Materials: Towards Sustainable Structural

Jibrin Muhammad Yelwa[1,*], Haruna Musa[2], Kalu Michael Kalu[3], Friday Edeh[4], Francis Iyeh[5], Rufa'i Salihu[6], Mary Bernard[7], Zubairu Zulyadain[8], Abdulrahaman Mohammed[9], Alhagie Drammeh[10]

Abstract

Self-healing material is an innovative invention within material science, which possesses the ability for self-repair of damages with a view to prolong the life of various structure types. Bioinspired self-healing materials and their applications is reviewed in this study by underlining their examples and significance for infrastructure, aerospace, automotive, marine, and energy sectors. The main mechanisms are intrinsic and extrinsic self-healing processes, along with advanced fabrication techniques such as microencapsulation, 3D printing, and vascular networks integration. Though promising in potentials, the challenges of scalability, durability, compatibility, and economic viability still exist. In this review, critical gaps in research have been indicated, and future trends are discussed with emphasis on sustainable efficiency of the self-healing system. In trying to meet these challenges, self-healing materials have the potential to make significant contributions to the development of resilient and durable infrastructure, advancing the field towards practical and widespread applications.

***Author for Correspondence**
Jibrin Muhammad Yelwa
E-mail: mjyelwa@gmail.com

[1]Assistant Professor, Department of Scientific and Industrial Research, National Research Institute for Chemical Technology, Zaria, Nigeria
[2]Assistant Professor, Department of Chemistry, Bayero University, Kano State, Nigeria
[3-4]Assistant Professor, Department of Chemical Sciences, Gombe State University, Nigeria
[5]Assistant Professor, Department of Scientific and Industrial Research, National Research Institute for Chemical Technology, Zaria, Nigeria
[6]Assistant Professor, Kano Outstation, National Research Institute for Chemical Technology, Zaria, Nigeria
[7]Assistant Professor, Yola Outstation, National Research Institute for Chemical Technology, Zaria, Nigeria
[8]Assistant Professor, Department of Chemistry, Nigerian Defence Academy, Kaduna, Kaduna, State, Nigeria
[9]Assistant Professor, National Research Institute for Chemical Technology, Zaria, Nigeria
[10]Assistant Professor, Chemistry Unit, University of The Gambia, Nigeria

Received Date: January 17, 2024
Accepted Date: January 29, 2024
Published Date: January 31, 2024

Citation: Jibrin Muhammad Yelwa, Haruna Musa, Kalu Michael Kalu, Friday Edeh, Francis Iyeh, Rufa'i Salihu, Mary Bernard, Zubairu Zulyadain, Abdulrahaman Mohammed, Alhagie Drammeh. Mechanisms and Applications of Self-Healing Materials: Towards Sustainable Structural, International Journal of Chemical Synthesis and Chemical Reactions. 2025; 11(1): 01- 26p.

Keywords: Self-healing materials, bioinspired design, intrinsic healing, extrinsic healing, microencapsulation, 3D printing, structural durability, sustainable infrastructure.

INTRODUCTION

Structural materials are basically used to construct and maintain infrastructure such as buildings, bridges, roadways, and other main facilities [1]. These materials predominantly comprise of concretes, steel, and composites which provide the essential strength and durability for withstanding loads and resisting environmental stresses. In a course of time, such materials are susceptible to degradation resulting from several factors that include mechanical stresses, environmental conditions, and chemical interactions [2]. Cracking might be one of the major problems that cause material deterioration in a structure. This could be due to various causes like thermal expansion, shrinkage, and external loading [3]. Even minor cracks, due to their growth with

© JournalsPub 2025. All Rights Reserved

time, can become so serious as to cause major structural failures [4, 5]. Another issue apart from that is fracture and fatigue issues, especially in those structures that are under repetitive loading; such structures suffer from progressive and localized damage of their structure. Corrosion is another issue, especially in concrete with steel reinforcement; due to the reaction between the steel and other elements in its environment, like water and oxygen, the occurrence of rust threatens to destroy the structural integrity and life span of materials. UV radiation, moisture, and temperature fluctuations arising out of environmental factors also contribute to the degradation of structural material hence require more frequency maintenance and repair [6]. Bioinspiration has drawn inspiration from natural processes and processes and biological systems, has led to significant advancements in material science particularly in development of self-healing materials [7]. These materials mimic natural process found in biological organisms enabling autonomous repair without external intervention.

Self-healing materials offer several advantages over traditional materials. This provides advanced durability and lifetime to the structure self-sustainably, reducing frequency of repair and maintenance [8]. This capability is especially useful in structural applications, where timely detection and repair of damage are of critical importance for safety and functionality. Material with self-healing capabilities can respond to damages through various modes, including chemical reaction, physical restructuring, and release of the healing agents embedded in the material matrix [9].

This review provides an overview of some of these bioinspired self-healing materials that can be employed in different structural applications. It moreover attempts at in-depth analysis pertaining to the state of research, working mechanism, and practical application to identify the gaps in the present research and propose further investigations to provide new insights into the potentials of self-healing materials for structural applications.

FUNDAMENTALS OF BIOINSPIRED SELF-HEALING MATERIALS

Principles of Bioinspired Design

Bioinspiration involves deriving ideas from nature and biological systems to help solve some of the most complex engineering problems. It draws from the evolutionary optimizations that have equipped organisms with effective and sustainable solutions to survive and thrive in various environments [10]. Bioinspired design deals with translating such natural strategies into workable applications, fostering innovation in a wide variety of fields, including material science, robotics, and architecture [11].

Bioinspiration in material science mediates population with advanced material types that exhibit superior properties [12]. Quite a few of these materials provide improved performance and sustainability achieved by biomimicking either the structure, function, or dynamics [13]. For example, lotus leaves' superhydrophobic properties triggered the development of self-cleaning surfaces, while the structural hierarchy in nacre (mother-of-pearl), has informed the design of tough, lightweight composites [14].

Biological Systems That Inspire Self-Healing Materials

Various biological systems provide inspiration for self-healing materials. These systems have been developed mechanism to autonomously repair damages where by maintaining functionality and extending life [15]. Examples include:

PLANTS VASCULAR SYSTEMS

Plants possess complex vascular systems through which nutrients and water are circulated, allowing them to heal from injuries. Resin or latex is sometimes produced in response to an injury to seal the wound and prevent infection and further damage. This principle has inspired the development of vascular self-healing in materials where microchannels filled with healing agents can mimic the plant's ability to deliver repair substances to damaged sites [16].

ANIMALS WOUND HEALING

Animals possesses an amazing self-healing ability especially in the regeneration of skin. This complex process of wound healing may be divided, in animals, into several successive stages: hemostasis, inflammation, proliferation, and remodeling. Cell migration to the wound site, proliferation, synthesis of new components of extracellular matrix during successive stages progressively ensure the restoration of tissue’s integrity. This multi-step process has stimulated the design of synthetic materials to autonomously repair cracks and other kinds of damage through similar successive mechanisms [17].

BONE REGENERATION

Bone healing is another natural process that has inspired material scientists. Self-healing of bones is articulated through a succession of biological events that include the formation of a blood clot, callus formation, and remodeling of bones. This regeneration ability of bones has been mimicked in the development of materials with the ability to restore their mechanical properties after damage through controlled chemical reactions and structural reorganization.

MARINE ORGANISMS

Sea Cucumbers

Sea cucumbers have skins which can immediately change their stiffness for self-defense. That influence of having transition between those mechanical states has inspired materials that could switch between different rigid and flexible states, aiding in self-healing and adaptive performance under varying conditions. Self-healing mechanisms in materials are inspired by biological processes that allow organisms to recover from damage autonomously [18]. These mechanisms can be categorized into intrinsic and extrinsic mechanisms.

Intrinsic mechanisms depend on inherent material properties to execute self-repair in the event of damage, based on reversible chemical bonds, thermoplastic phases, or shape memory effects. Such a dynamic covalent bond is like, for example, Diels-Alder reactions, and it has the capability to dissociate and reform; thus, the polymers are able again and again to self-heal.

The mechanisms for extrinsic would include encapsulated healing agents, vascular networks, and nanoparticles. These are embedded within the material with an active agent. Microcapsules filled with the healing agents rupture when damaged and release their agent into the site of damage to effect repair. Such mechanisms, if well elicited, may indeed provide an insight that will always be invaluable in the design and development of systems that can self-heal upon sustaining damage to ensure better durability and longevity in service.

Figure 1 illustrates that the principles of nature-inspired self-healing systems draw from plant vascular systems and the multi-step processes of wound healing in animals. These usually are the vascular transport processes concerning resin or latex-based healing mechanisms in plants when injured. A series of similar but also largely more complex healing stages or processes characterizes animals: the process of coagulation followed by inflammation is replaced by swelling and cell migration; after proliferating cells get a structure that builds new skin tissue, maturation.

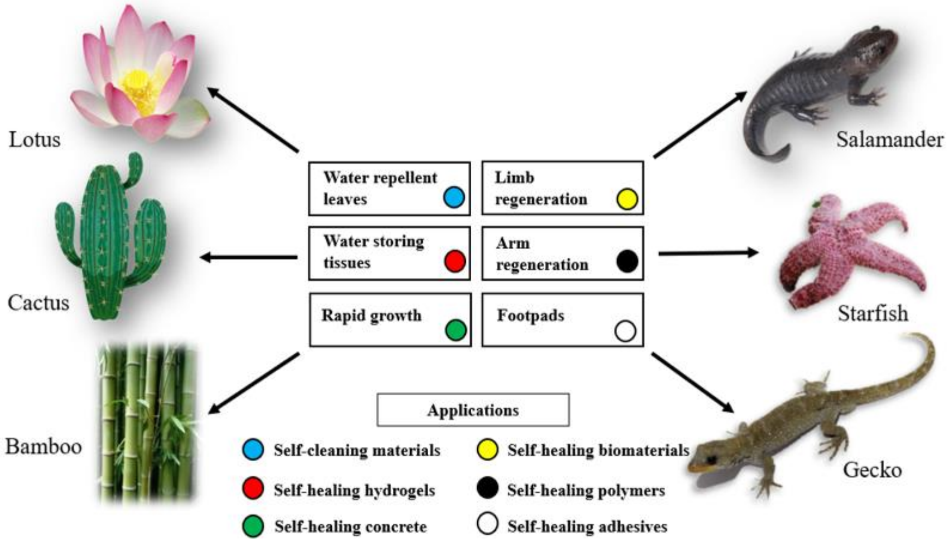

Figure 1. Nature Inspired Self-Healing: Plants and Animals.

Natural Processes of Healing in Biological Systems

Biological systems developed the various mechanisms of healing and regeneration that allowed them to survive and be functional. The study of natural biological processes brings immense insight into how synthetic self-healing material systems are designed [19].

WOUND HEALING IN ANIMALS

Hemostasis

In the case of injury, the first step toward healing is coagulation of blood to prevent excessive bleeding. Coagulation takes place by initiating aggregation of platelets, which, in turn, release a signal attracting other cells to the site of injury [20].

Inflammation

This stage serves as the invitation of immune cells to the wound site to destroy pathogens and debris. Inflammatory cells release cytokines and other growth factors responsible for initiating tissue repair during inflammation.

Proliferation

This stage has the proliferation and migration of other cell types, mostly fibroblasts, into the wound area to synthesize the material of the new extracellular matrix, which is mainly collagen, along with angiogenesis, or the formation of new vessels, enabling nutrient and oxygen supply to the healing tissue.

Remodeling

This newly formed tissue undergoes remodeling to restore its original structure and function. The collagen fibers are once again realigned, and the excess cells die off through apoptosis, a programmed cell death.

REGENERATION IN PLANTS

Callus Formation

When a plant is injured, it forms a callus, a mass of undifferentiated cells, at the wound site from which cells differentiate into whichever cell types are needed to regenerate the damaged tissue.

Sealing and Healing

The plant can synthesize substances as latex or resin, allowing them to seal wound and protection them against pathogens. This is similar to the concept of healing agents in synthetic materials under conditions of filling and repairing the cracks.

Growth and Differentiation

The matured callus cells proliferate and give rise to the plant's structure and function. This regenerative capability has inspired the development of materials that can self-repair through controlled cell-like processes.

WOUND HEALING IN ANIMALS AND REGENERATION IN PLANTS

Wound Healing in Animals:

The self-healing of skin after injury is a very complex process involving many types of cells and biochemical pathways. In case of injury to a mammal's skin, clotting of blood seals the wound in no time in order to avoid blood loss. Gradients of Inflammatory cells clean up any pathogens and debris, thereby providing a conducive environment for the growth of new tissue across the wound site. Proliferation and migration of fibroblasts and keratinocytes occur at the wound site, laying down a new extracellular matrix, hence forming new layers of skin. This concludes process of tissue remodeling, in which this newly formed tissue is organized and strengthened in such a way that it regains integrity and functionality-like skin.

This natural process has inspired the synthesis of materials that can mimic these steps. For instance, self-healing polymers can be tailored to undergo similar sequential processes, wherein a damage trigger initiates the release of healing agents that subsequently polymerize and restore material integrity.

Regeneration in Plants

Plants possess remarkable regenerative capabilities, allowing them to recover from various forms of damage. If a portion of a stem is cut through, it frequently regenerates the missing segment at the cut surface in the form of a callus, that is, a mass of undifferentiated cells, which later differentiate into new tissue. Plants also seal off injured regions with resins and gums, both hydrophobic chemicals that block the entry of water into the plant, which prevent infection of the injured site with microorganisms and additional tissue damage. This ability to regenerate has inspired materials that use embedded healing agents, such as microcapsules, to mimic the plant's healing process by releasing repair substances when damage occurs.

As such, self-healing concrete could have microencapsulated healing agents released when the occurrence of cracks happens, similarly to the plant releasing resin to seal up its wound. The agents released react with the surrounding material to fill up and repair the crack, hence restoring structural integrity to the concrete.

Bioinspiration has achieved significant development in self-healing materials by considering biomimicry of natural processes typically seen in plants and animals. In these designs, developed mechanisms in nature are advantageously used for the formation of self-repairing and regenerating material. Such understanding and replication of natural processes would provide innovative materials that enhance the durability and sustainability of structures, reducing maintenance costs apart from improving safety. The study of self-healing properties in bioinspired materials is a promising area of research, with new solutions to engineering problems and improvement of synthetic material performances.

MECHANISMS OF SELF-HEALING IN STRUCTURAL MATERIALS

Generally speaking, self-healing materials could be designed by taking inspirations from fundamental biological processes, and such processes would grant organisms the capability to independently recover from most highly specific kinds of damage [21]. Such techniques can generally be distinguished between intrinsic and extrinsic mechanisms. Intrinsic mechanisms depend on the inherent properties of the material to self-repair, such as through reversible chemical bonds, thermoplastic phases, and shape memory effects. For example, dynamic covalent bonds in Diels-Alder reactions can dissociate and reform, hence allowing multiple self-healing events in polymers [22]. Extrinsic mechanisms involve the addition of healing agents or structures to the material for self-healing, which may be encapsulated healing agents, vascular networks, and nanoparticles [23]. Microcapsules filled with healing agents, when ruptured by damage, release the agents into the damaged area to repair it. Understanding of such mechanisms provide an insight to design and development of autonomous self-healing materials that improve durability and longevity in structures and constructions of interest in various applications [24].

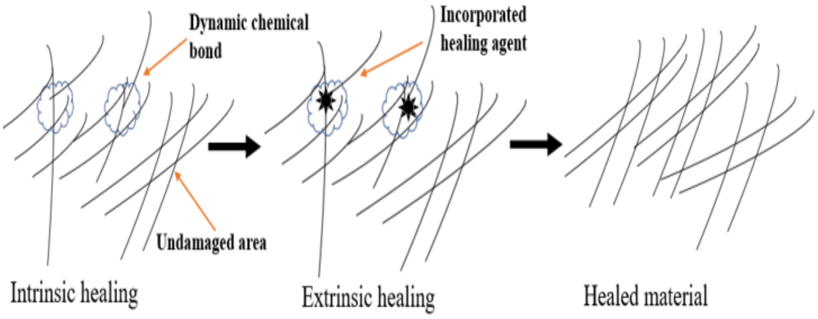

Figure 2: Intrinsic and Extrinsic Self-Healing Mechanisms

Figure 2 illustrates self-healing mechanisms in materials through intrinsic and extrinsic mechanisms. Intrinsic mechanisms take into consideration those resulting from damage-induced reversible chemical bonds, thermoplastic phases in which the crack heals via melting and resolidification, and shape memory effects in which materials resume their previous shapes upon deformation. The extrinsic mechanisms shown here include rupture-released encapsulated healing agents, vascular networks transporting healing agents to the damage sites, and nanoparticles catalyzing reactions that repair the damage. These diverse approaches demonstrate the range of strategies used to enable self-repair in advanced materials.

Intrinsic Self-Healing Mechanisms

Intrinsic self-healing describes material's capabilities for self-healing by neither external intervention nor additional healing agents. These materials can restore their structural integrity through molecular or physical processes initiated upon damage. Intrinsic self-healing is primarily achieved via mechanisms relying on reversible chemical bonds, thermoplastic phases, and shape memory effects [25].

Reversible Chemical Bonds

Reversible chemical bonds are the active ingredient of intrinsic self-healing materials that may break upon damage and then reform to heal itself. Examples include dynamic covalent bonds, hydrogen bonds, and ionic interactions [26].

Dynamic Covalent Bonds

The dynamic covalent bonds, such as those in Diels-Alder reactions, do dissociate and associate under certain conditions to enable repeated self-healing. For instance, there are those Diels-Alder bond-containing polymers that can undergo reversible cross-linking to heal cracks or breaks when subjected to heat or light [27].

Hydrogen Bonds

While hydrogen bonds are weaker than covalent bonds, they can contribute to self-healing by enabling reversible interactions between polymer chains. Polymers with high densities of hydrogen bonding groups can heal through the re-formation of these bonds, as demonstrated in materials like polyurethane and polyurea [28].

Ionic Interactions

For instance, ionic interactions involving oppositely charged ions can be used to achieve self-healing. Polymers with ionic groups can reassemble through ionic bonding, repairing damage in the process [4]. This mechanism is applicable in ionomers and other ion-containing polymers.

Thermoplastic Phases

Thermoplastic materials possess the ability to melt and re-solidify with the potential for self-healing purposes. Thermoplastics flow at a temperature above their Tg or Tm and, therefore, can fill cracks or voids at that temperature. After cooling, the material will again solidify and the damage will be healed [10].

Polyethylene (PE) and polypropylene (PP) are the most common thermoplastic polymers showing self-healing by thermal activation. In case of material damage, heating mobilizes the polymer chains to flow into the defect area. When material is cooled, it solidifies, thereby restoring structural integrity [29].

Shape Memory Effects

Shape memory materials can recover from an externally deformed temporally shape to the original one, normally internally induced either by heating or light irradiation. This could be used for self-healing purposes if it remembered an ideal configuration of the material and recovered from damage [30]. Shape memory polymers (SMPs) are a class of polymers that are known to recover into their original shape upon heating. In the case of any damage to an SMP, the application of heat higher than its transition temperature activates the shape memory effect, which forces the material into its pre-damaged state [31]. This becomes particularly useful in applications where maintaining structural integrity is critical.

Extrinsic Self-Healing Mechanisms

Where intrinsic mechanisms depend solely on inherent material properties, extrinsic mechanisms of self-healing invoke the presence of additional healing agents or structures within the material that are activated upon damage [6]. In general, this includes encapsulated approaches, vascular networks, and nanoparticles.

Encapsulated Healing Agents

Perhaps the most studied extrinsic self-healing mechanisms are encapsulated healing agents. This involves embedding microencapsulated healing agents within a material matrix and whenever any damage occurs, these capsules will rupture, thereby releasing active agents into the damaged area which then react and heal the material [32].

A typical example is the use of microcapsules filled with epoxy resin and a curing agent. In case of cracking, the capsules break and release the resin and curing agent; these, in turn, polymerize and heal the crack [8]. This method has been successfully implemented in polymeric materials and coatings to enhance their durability.

Vascular Networks

Various vascular self-healing systems mimic the circulatory system of biological organisms. These normally comprise a material-imbedded network of hollow channels or microtubes. Healing agents stored in reservoirs are transported across the vascular networks to the site of damage, where they react to repair the material [33].

Perhaps the most salient example of this mechanism is the use of a vascular network in concrete, by which a healing agent, such as a polymer or mineralizing solution, is pumped through the network into cracks forming in the concrete. The healing agent would harden in the cracks to restore integrity to the concrete [34]. This approach has shown promise in extending the lifespan of infrastructure by reducing maintenance needs.

Nanoparticles

Nanoparticles can enhance the self-healing feature of materials by acting as catalysis, filling, or as active agents. These particles can be designed in such a way that in case of damage they start chemical or physical reactions to repair the material [13]. One such example is by the use of silica nanoparticles functionalized with the healing agents. Upon material damage, these nanoparticles become exposed to the environment on account of material fracture and release the healing agent. The agent further reacts with the surrounding matrix to eventually heal the damage. This very concept has been employed in various self-improvement methodologies of polymeric materials to enhance their self-healing efficiency [35]. Very significant advance in the frontier of self-healing materials is, therefore, elicited in the pursuit of improving durability and longevity of service life for all forms of structural materials. Intrinsic self-healing depends on irreversible or reversible chemical bonds, thermoplastic phases, and shape memory effects inherent to the material for self-repair, therefore excluding any external agency in the self-healing process of the material. While extrinsic self-healing mechanisms rely on the material properties themselves, the incorporation of additional healing agents or structure extrinsically allows self-repair by means of encapsulated healing agents, vascular networks, and nanoparticles [36]. Both intrinsic and extrinsic mechanisms have advantages and outstanding challenges, and optimal research is underway concerning each methodology for specific applications.

Understanding and harnessing such self-healing mechanisms might lead to the discovery of new material techniques that could perform autonomously and sustain damage repair, reducing maintenance costs and enhancing structural safety. In some construction and infrastructure scenarios, self-healing materials will be crucial as the technology continues to be studied and developed.

TYPES OF BIOINSPIRED SELF-HEALING MATERIALS

Polymers and Polymer Composites

Polymers and polymer composites are among the most versatile materials in the development of self-healing technologies due to their ability to be engineered at the molecular level. Intrinsic self-healing polymers have inherent properties to automatically heal damage without the use of any external agents. These properties usually can be achieved by reversible chemical bonds, dynamic covalent bonds, or physical interactions that are capable of reforming material structure after damage [37].

POLYURETHANES AND EPOXIES WITH REVERSIBLE BONDING

Polyurethanes

The main reasons polyurethanes find application in self-healing are due to the combination of flexibility and toughness. Basically, these polymers are design with reversible hydrogen bonds or even disulfide linkages that enable self-healing. For example, polyurethane containing disulfide bonds can reversibly cleave and reform the bonds, thereby offering the material multiple healings under external specific stimuli like heat and light [38].

Epoxies with Reversible Bonding

Epoxy resins constitute another class of polymers that have equally been under extensive study owing to their self-healing capabilities [38]. Dynamic covalent bonds, such as Diels-Alder adducts, are introduced into the epoxy matrix to achieve reversible cross-linking. More importantly, this will result in the ability of epoxies to heal any crack by restoration of its mechanical properties through the application of heat, which can be applied reliably to high structural integrity [9].

CEMENTITIOUS MATERIALS

Self-Healing Concrete and Its Mechanisms

Concrete is a fundamental construction material; it nonetheless has a tendency to develop cracks in it due to its brittle nature. The self-healing of concrete has the objective of prolonging the service life of concrete structure by developing an autonomous crack repair [35]. Self-healing in the case of concrete may be achieved either through addition of microcapsules with healing agents, expansive mineral admixtures, or application of certain fibers that stir crack closure. Various techniques, including the microencapsulation of healing agents, expansive mineral admixtures, and application of fibers, could be employed in forming the working mechanisms of self-healing in concrete.

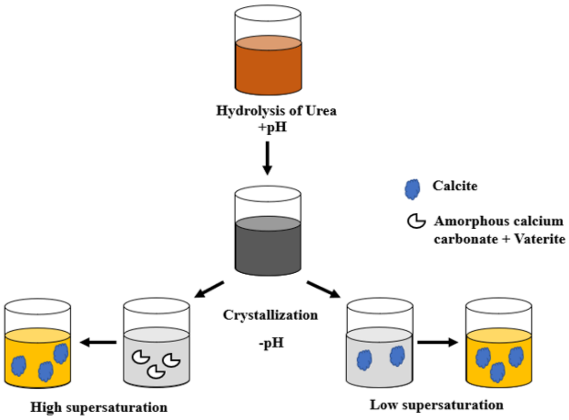

Figure 3. Self-Healing in Concrete: Microbial-Induced Calcite Precipitation

Figure 3 illustrates in detail the self-healing of concrete by means of thermal-induced calcite precipitation due to microbial activity, reflecting how bacteria can autonomously repair cracks through calcite precipitation.

Microcapsules

Microcapsules can be filled with healing agents like epoxy or polyurethane and then embedded into the concrete matrix. Once the cracks develop, the capsules will break and release the healing agent, which will eventually flow into the cracks and polymerize in order to seal it [39].

Microbial-Induced Calcite Precipitation

The microbial-induced calcite precipitation technique is a bio-inspired new frontier in the self-healing concrete discipline. In this system, bacteria are used to precipitate calcium carbonate-or better known, calcite-within the cracks in concrete and therefore self-heal them [40].

Conventional concrete is mixed with appropriate bacteria, such as *Bacillus* species, along with nutrient sources. When cracks develop, then water ingress will activate the bacteria, which metabolize the nutrients to produce calcite. This calcite will fill the crack and restore the integrity of the concrete structure.

METALLIC MATERIALS

Self-Healing Metals and Alloys

In recent years, self-healing metals and their alloys were developed to be one of the trends in research that pursues capacity for repair of this material after being under mechanical damage or corrosion [29]. These materials are able either to heal by mechanisms like oxidation or by reversible phase transformations.

Oxidation

Some metals will form an inert oxide layer after exposure to air or water that can heal minor cracks in the surface. For instance, both aluminum and titanium alloys will spontaneously form a passivating oxide layer excluding further oxidation and corrosion [29]. This becomes even more critical in high-temperature applications as metals will be prone to oxidative attack.

Reversible Phase Transformations

Other classes of alloys, including SMAs, have this reversible phase transformation, which enables self-healing. For instance, SMAs will go back to their original shape upon heating above some critical temperature; not only are cracks closed, but mechanical properties are restored [41]. This property is driven by the martensitic transformation: a change in the crystal structure of the alloy with temperature.

CERAMICS AND GLASSES

Self-Healing Ceramics and Their Applications

Although ceramics have high hardness, thermal stability, but they are also brittle and prone to cracking [42]. Developing self-healing ceramics can address this limitation and make them suitable for application in severe environmental usage such as aerospace to defense.

CRACK HEALING AT HIGH TEMPERATURES

Crack Healing

In general, the self-healing mechanism in ceramics is mainly dependent on high-temperature processes for crack healing, involving mechanisms such as diffusion or sintering. Ceramics with a dispersed particulate healing agent, for example, silicon carbide (SiC), could be self-healed under conditions of high temperature. The healing agent melts or undergoes a phase transformation, filling the cracks and restoring the material's integrity [42].

SiC ceramics used in high-temperature applications can self-heal through the oxidation of SiC particles, forming a silica (SiO_2) layer that fills the cracks. This mechanism described above repairs the cracks in such a way that material resistance against further oxidation increases, which is actually one prime requirement for using these materials in turbine blades and other high-temperature components [29].

Bioinspired self-healing materials provide enormous potential for enhancing durability and longevity of structural materials in a wide variety of applications [35]. Polymers and polymer composites, such as polyurethanes and epoxies with reversible bonding, provide flexible and robust solutions for autonomous repair. Cementitious materials, such as self-healing concretes and microbial-induced calcite precipitation, respond to the pervasive problem of infrastructure cracking [38]. Mechanisms like oxidation and reversible phase transformations provides self-healing in metallic materials for high-performance applications. Ceramics and glasses, with their high-temperature crack healing properties, provide solutions for extreme environments [42]. As research continues to advance, these bioinspired materials will no doubt be integral to the future of sustainable resilient infrastructure.

Table 1. Comparison of Self-Healing Materials.

Material Type	**Advantages**	**Disadvantages**	**Common Applications**
Polymer Composites	Flexible, durable, repeatable healing	Limited by mechanical properties	Coatings, structural components
Cementitious Materials	Autonomous crack repair, long lifespan	Slow healing process, environmental limitations	Infrastructure, bridges, buildings
Metals & Alloys	High strength, temperature resistant	Complex healing processes, limited scalability	Aerospace, automotive, marine structures
Ceramics & Glasses	High hardness, thermal stability	Brittle, requires high temperatures for healing	High-temperature environments, aerospace

Table 1 presents a comparison of different types of self-healing materials, including respective advantages, disadvantages, and typical applications.

FABRICATION TECHNIQUES FOR BIOINSPIRED SELF-HEALING MATERIALS

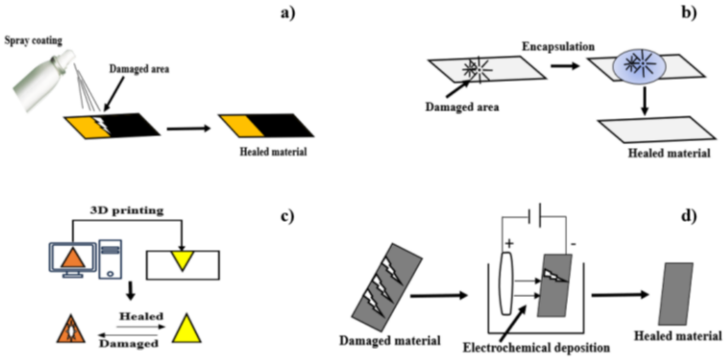

Figure 4. Advanced Fabrication Techniques for Self-Healing Materials: (a) Spray coating, (b) Microencapsulation, (c) 3D printing, (d) Electrochemical deposition.

Figure 4 shows various fabrication techniques adopted for the development of self-healing material including techniques microencapsulation, where the incorporation of microcapsule-containing active healing agents can be performed with any one of the following methods such as solvent evaporation, interfacial polymerization, and spray drying. It mentions the 3D printing and additive manufacturing techniques like Fused Deposition Modelling (FDM), Stereolithography (SLA), and Direct Ink Writing (DIW) to fabricate complex self-healing structures. This figure describes the integration techniques related to vascular network integration, such as microfluidic templating and direct ink writing, and techniques for the functionalization of the surface and coating, such as Layer-by-Layer (LbL) assembly, sol-gel coating, electrochemical deposition, and spray coating, involved in imparting self-healing properties to structural material.

MICROENCAPSULATION TECHNIQUES

Methods for Encapsulating Healing Agents in Polymers and Composites

Microencapsulation is one of the most practiced methods for fabrication used in self-healing materials where the healing agents are encapsulated within microsized capsules and then embedded into a polymer or composite matrix. When damage occurs in the material, these capsules rupture due to a crush event, thus releasing the healing agents that subsequently repair the damage [39].

Solvent Evaporation

The most common technique for microencapsulation consists of evaporation of a volatile solvent of both polymer and healing agent followed by emulsification in an aqueous phase containing a stabilizer [41]. Microcapsules form upon the evaporation of the solvent with encapsulation of the healing agent in a polymer shell. This method is commonly use because it is easy and the capsule size can be controlled by adjusting the emulsification parameters [39].

Interfacial Polymerization

For interfacial polymerization, another approach is to make the monomers react at the interface of the two immiscible phases in order to form the polymer shell around the core of the healing agent. With this method, it's possible to prepare well-defined core-shell capsules and is particularly useful for encapsulating liquid healing agents. Compared with this, through choosing the appropriate types of monomers for reaction conditions, it is possible to precisely control the properties of resultant microcapsules for shell thickness and permeability [43].

Spray Drying

Spray drying is another technique in the preparation of microcapsules. In this technique, a solution or suspension of the healing agent and polymer is subsequently atomized into a hot chamber. Because the temperature rises upward, the solvent evaporates rather quickly, with the result of being solid microcapsules [1]. Spray-dried microcapsules can be produced on a large scale with consistent size distribution, which is quite advantageous. However, its application can be greatly limited by core healing agents that cannot withstand the temperature of treatment [4].

3D PRINTING AND ADDITIVE MANUFACTURING

Advanced Fabrication Techniques for Creating Complex Structures with Self-Healing Properties

Recently, 3D printing and additive manufacturing, in general, have completely revolutionized fabrications with complicated structures possessing self-healing properties. These techniques enable the control of material architecture with precision by introducing mechanisms for self-healing at different scales [44].

Fused Deposition Modeling (FDM)

In FDM, one of the popular techniques in 3D printing, thermoplastic material is extruded through a heated nozzle and then laid down layer by layer to build up a three-dimensional structure. Micro-capsules or vascular networks could be embedded into the filament to enable the FDM to fabricate self-healing material with healing agents. The layer-by-layer construction allows precise placement of the healing agents to ensure they are evenly distributed throughout the material.

Stereolithography (SLA)

Stereolithography uses a laser for the curing of photopolymer resins, layer by layer, with striking structural detail. This may also be used in incorporating self-healing agents by simply mixing with the resin before printing. The SLA process is high-resolution and pretty accurate; hence, it is useful in such applications that require complex geometries and details. Besides this, SLA is able to fabricate parts with imbedded microcapsules or vascular networks that are responsible for autonomous healing.

Direct Ink Writing (DIW)

In the case of DIW, the paste-like ink is extruded via nozzles that enable it to fabricate 3D structures. This offers very convenient methods for embedding all kinds of functional components such as microcapsules, fibers, and nanoparticles within the materials being processed. DIW will be able to fabricate self-healing materials with tailored properties by adjusting the composition and rheology of ink. Hence, the method can be applied to the fabrication of multi-functional materials with complicated architecture and integrated healing ability.

VASCULAR NETWORK INTEGRATION

Techniques for Embedding Vascular Networks in Materials

Biological systems are inspiring vascular networks that have been used to deliver healing agents to the damaged areas in a material [34]. These vascular networks can be imbedded within materials to provide a continual supply of healing agents and offer the potential for unlimited cycles of self-healing.

Microfluidic Templating

Microfluidic templating can be stocked in one of the techniques in which material matrix is introduced by a sacrificial template. After embedding into the material matrix, the sacrificial template is usually removed, thus leaving behind a network of hollow channels [45]. These channels can be filled with healing agents that can flow to the damaged area upon requirement. This technique can achieve precision in control over the size and distribution of these channels to enable optimization of delivery accordingly for a healing agent.

Direct Ink Writing (DIW) of Vascular Networks

DIW can also be used for the direct printing of vascular networks in a material. DIW produces complex three-dimensional networks of microchannels with various inking materials that rapidly solidify from the moment of deposition. These networks only need to be encased within structural components during printing processes with limited perturbation in order to assure effortless integration of the self-healing function. The flexibility of DIW allows for the design of customized vascular networks for particular applications [46].

Hybrid Approaches

Hybrid methodologies then combine several fabrication techniques for the introduction of vascular networks within the material. For example, the fabrication of larger-scale materials can be realized with the help of 3D printing techniques, while microfluidic templating can be used to embed the vascular network [40]. In these hybrid methods, the advantages of each technique are utilized to realize material with superior self-healing performance and structural integrity.

SURFACE FUNCTIONALIZATION AND COATING TECHNIQUES

Methods for Applying Self-Healing Coatings to Structural Materials

Surface functionalization and coating represent the two main procedures that are considered important in enhancing self-healing properties in structural material. Both procedures comprise a layer of self-healing material deposited on the surface of a substrate for protection against deterioration with the aim of autonomous repair [47].

Layer-by-Layer (LbL) Assembly

One of the versatile methods for self-healing coatings is layer-by-layer assembly, which has been offering, in succession, multi-layered coatings of oppositely charged polyelectrolytes deposited onto a substrate. To allow controlled release update damage, healing agents of self-healing can be loaded within specific layers. Due to the possibility of control over coating thickness and precise distribution of composition, various applications might easily be fulfilled by LbL assembly.

Sol-Gel Coating

In the case of sol-gel coating, the liquid precursor is usually processed into a gel-like network that is applied to the substrate. Through this technique, the thin coating with uniformity and the embedded healing agent can effectively be obtained [47]. All these activities allow the integration of functional nanoparticles along with other additives that improve the self-healing properties in the material for coating. These coating techniques are employed where properties like corrosion resistance and mechanical durability are involved.

Electrochemical Deposition

The self-healing coatings are applied by the method of electrochemical deposition, where a material from the solution gets deposited onto a conductive substrate. This technique allows one to fabricate a coating with microcapsules or nanoparticles embedded into it and releasing the healing agent upon its damage [48]. This current technique, which enables precise control in thickness and composition, normally finds its applications in protection coatings and electronics.

Spray Coating

The key advantages of spray coating are that it is a relatively straightforward, scalable method for the application of self-healing coatings. The process simply involves spraying a solution or suspension containing the self-healing material onto a substrate to create a uniform layer. Coatings with embedded microcapsules, nanoparticles, or other healing agents can be applied by means of spray coating. Because the application is easy and the head is versatile, this head has broad applications in automotive, aerospace, and industrial uses.

Advanced techniques have been developed for the fabrication of bioinspired self-healing material and can embed various healing agents and structures in polymers, composites, and other materials. Some of the most important processes by which self-contained healing agents are introduced within materials include various microencapsulation techniques involving solvent evaporation, interfacial polymerization, and spray drying. 3D printing and additive manufacturing allow for precise control over material architecture and hence permit the fabrication of complex geometrical structures embedded with self-healing capabilities [49]. In vascular network integration techniques, such as microfluidic templating and DIW, provide routes toward continuous delivery of healing agents thereby improving the self-healing performance. Surface functionalization and coating techniques comprising LbL assembly, sol-gel coating, electrochemical deposition, and spray coating offer protective layers capable of autonomous repair of damage [31]. As research continues to advance, these fabrication techniques will definitely play important role in the development of the various advanced self-healing materials for a wide range of applications.

APPLICATION IN STRUCTURAL ENGINEERING

Self-healing materials are increasingly integrated within different structural applications to improve long-term durability in essential infrastructures such as bridges, buildings, and roadways [50]. Self-healing materials has been successfully used in bridge construction projects to autonomously repair cracks, reducing the need for maintenance and prolonging the structure's lifespan. Self-healing composites are used in aircraft and vehicle components to maintain structural integrity after damage, thereby improving safety and reducing maintenance requirements. Self-healing materials prevent corrosion in marine and offshore structures, extending the service life of ships and platforms. Integrating these materials into the processes of building and maintenance would lead engineers to develop more resistant and sustainable infrastructure [51].

Use of Self-Healing Materials in Bridges, Buildings, and Roads

The application in infrastructure and construction is increasingly signifying incorporation with self-healing material, giving more durability to structures like bridges, buildings, and roads by mitigating the common issues of cracking, corrosion, and general wear and tear, thereby reducing maintenance cost and prolongs the service life of the structures [50].

Bridges

The main purpose that the bridges have to serve is to carry almost constant stress from traffic loads and environmental conditions, thus leading to the development of cracks and other deterioration modes. Self-healing concrete, comprising microcapsules of healing agents or bacteria that precipitate calcium carbonate, is able to autonomously heal such cracks over time [52]. This will provide significant enhancement in structural integrity of the bridge and will make it more resistant to harsh environmental conditions.

Buildings

The applications of self-healing materials in building construction include those in concrete, coating applications, and sealants. Self-healing concrete is particularly useful for detection and repair of cracks, as this process is usually very complicated and costly [52]. Integration of self-healing into the concrete mixture will protect the structural health of the building by preventing the ingress of water and harmful chemicals that can cause further degradation.

Roads

Roads and pavements are always subjected to mechanical stress and attack by environmental

© JournalsPub 2025. All Rights Reserved

elements that will inevitably lead to formation of potholes and cracks. In self-healing asphalt, added capsules containing rejuvenators or healing agents can autonomously repair these cracks. When a crack appeared, it would rupture the capsules, releasing the healing agents into the crack to restore integrity to the material [51]. This technology greatly diminishes the need for constant repair and maintenance, hence elongating service life on road surfaces.

AEROSPACE AND AUTOMOTIVE INDUSTRIES

Applications in Aircraft and Vehicle Structures

The aerospace and automotive industries have always been among the leading ones to embrace such self-healing materials due to the vital need for the material to be reliable and durable enough to withstand extreme conditions [53].

Aircraft

The applications of self-healing materials are endless, from aircraft fuselage to wing and fuel systems. They can repair the damages autonomously caused by impacts, fatigue, or environmental factors. For example, composite embedding of microcapsules filled with healing agents may restore structural integrity through the release of active agents upon damage. This capability is important for airlines because it helps to maintain aircraft safety and performance during long periods when repairs may be impossible to make.

Vehicles

Self-healing materials in automotive industries find their application in both interior and exterior parts of the vehicles. From aesthetic appeal to anti-corrosion protection, one can develop self-healing paints and coatings with scratch-repairing possibilities in minor damages on the surface of a vehicle. Meanwhile, in the manufacturing process of different parts, including bumpers and dashboards, self-healing polymers can autonomously heal minor damages to improve durability and prolong the life spans of components.

MARINE AND OFFSHORE STRUCTURES

Use in Ships, Offshore Platforms, and Coastal Infrastructure

Marine and offshore structures continuously face extreme environmental conditions of saltwater, waves, and fluctuating temperatures that could lead to very serious material degradation over time. Thus, self-healing materials are one very promising answer to enhancing durability and resilience in those structures.

Ships

Saltwater corrosion with mechanical stresses is an inherent feature in the normal operation environment of ships and sea vessels. Self-healing coatings with entrapped microcapsules or vascular networks containing active corrosion inhibitors or healing agents maintain scratches and damages on the hull of a ship autonomously without human intervention. This prevent initiation of corrosion, maintain structural integrity and reduce the maintenance cost to extend the service life of the vessels.

Offshore Platforms

Offshore oil and gas platforms suffer mechanical impacts of very high pressure and corrosive environmental factors. Self-healing materials used in these structures can repair cracks and damages caused by such conditions to ensure the platform operational safety and reduce downtimes. For instance, self-healing concrete and coatings can be applied to underwater components to prevent corrosion and structural failures.

Coastal Infrastructure

Coastal infrastructure, such as seawalls, piers, and docks, are also prime candidates for self-healing materials. These are structures that hover in constant contact with tidal forces and saline water, leading to rapid deterioration. An inbuilt self-healing potential in the construction material can enable the infrastructures to self-repair the cracks and damages autonomously. Consequently, this will enhance its resilience and reduce the frequency of repairs quite significantly.

ENERGY SECTOR

Applications in Wind Turbines, Pipelines, and Power Plants

The benefit of self-healing materials within the energy sector is immense, as this application enhances the durability or reliability of individual parts applied in wind turbines, pipelines, and power plants [54].

Wind Turbines

Large and cyclic loading, as well as environmental stressors, may cause fatigue and material degradation in wind turbine blades. Self-healing composites used in the blades can repair microcracks that develop over time, thereby maintaining structural integrity and efficiency of the turbine. This reduces maintenance costs and extends the life of the turbines, making wind energy more sustainable and cost-effective [55].

Pipelines

Pipelines carrying oil, gas, and water are particularly prone to corrosion and to mechanical damage. To delay major failures and contamination of the environment, pipelines can be coated by materials or coatings that can repair small leaks and cracks. Pipelines coated with self-healing materials containing microencapsulated corrosion inhibitors can extend service life without forming any corrosion.

Power Plants

In power plants, especially those with high-temperature applications, self-healing materials can play an important role. The boiler tubes, turbines, and reactor vessels are always under extreme conditions of temperature and pressure, which always result in the degradation of materials. Self-healing ceramic and alloy materials can repair themselves at high temperatures to ensure the reliability and safety of these critical components [56]. This reduces the possibility of catastrophic failures and improves the total efficiency of power generation systems as a whole. For structural engineering, self-healing materials represent a transformative and contemporary developments, allowing considerable improvements in durability, reliability, and lifetime of various constructions in infrastructure, construction, aerospace, automotive, marine, offshore, and energy industries [57].

Table 2. Self-Healing Materials in Structural Applications.

Application	**Material Used**	**Benefits Observed**
Bridge Construction	Self-Healing Concrete	Reduced crack maintenance
Aircraft Wings	Self-Healing Polymers	Improved safety, reduced maintenance
Ship Hulls	Self-Healing Coatings	Prevention of corrosion
Pipeline Coatings	Self-Healing Paints	Prevention of leaks, extended service life

Besides performance and safety, the integration of self-healing technologies into applications has the added value of sustainability through reduced frequency of repairs and/or replacements

[58]. As research and development within this field continues to progress, the adoption of self-healing materials into structural engineering will increase, thus delivering more resilient and sustainable infrastructure.

Table 2 gave examples of practical applications that were made from each self-healing material and its associated benefit.

PERFORMANCE EVALUATION AND TESTING

Standard Testing Methods

Mechanical Testing

Mechanical testing plays an important role in evaluating the performance of the self-healing materials under specified loads and stresses. This will ensure that materials fit into requirements within structural applications [59].

Tensile Testing

Tensile tests measure the response to tension of a material and provide data on strength, elasticity, and ductility of the material. In tensile tests, a sample is stretched up to a point of break, mostly recording a stress-strain curve that enables the identification of ultimate tensile strength, the yield strength, and elongation at break. Tensile testing before and after self-healing could pictorially present the material's ability to recover its mechanical properties [60].

Compression Testing

Compression tests investigate the behavior of a material under compressive loads. A test specimen is subjected to an axially applied compressive force until it deforms or fractures. This test is especially important for materials that are applied in load-carrying structures. For self-healing materials, the ability to recover compressive strength after damage is critical. Compression tests can only partly assess how well the material restores its original properties after healing [34].

Fatigue Testing

Fatigue tests impose cyclic loading on material for durability and lifespan estimations under repeated stress. This test is very important for materials in applications where they experience fluctuating loads such as bridges and aircraft. In fatigue testing of self-healing materials, cyclic loads are applied until cracks form, allowing the material to heal, and reapplying the load to measure the improvement in fatigue life. Successful self-healing materials should indicate more extended fatigue lives after the healing cycles [35].

Environmental Testing

Environmental testing determines the performance of the material in various environmental conditions, ensuring its durability and life span during practical applications.

UV Exposure

UV radiation can degrade polymers and other materials by breaking of chemical bonds, resulting in discoloration, embrittlement, and mechanical properties loss. UV exposure tests involve samples exposed to UV light for extended periods and assessing changes in properties. For self-healing materials, the retention or recovery of properties after UV exposure is one of the key features for applications in outdoor environments [61].

Moisture Resistance

Moisture causes material swelling, weakening, and even corrosion. Moisture resistance tests involve samples being exposed to high humidity or direct contact with water and measure any change in weight, dimensions, and mechanical properties. Self-healing materials should show their ability to heal and retain performance after exposure to moisture, this would make the materials suitable for use in either humid conditions or wet environments [62].

Temperature Variations

Temperature variation can induce thermal expansion and contraction, thereby causing development of stresses and eventually cracks. Temperature variation tests involve cycling samples over high to low temperatures and measuring its response [63]. For self-healing materials intended for use under extremely variable-temperature environments, resistance toward temperature change and self-healing ability against thermal-induced damage is required.

NOVEL TESTING TECHNIQUES

Real-Time Monitoring of Healing Processes

Real-time monitoring techniques continuously deliver data on the process of healing and give insight into dynamic processes of self-healing materials.

Digital Image Correlation (DIC)

DIC is a non-contact optical technique to measure deformation, strain, and crack propagation on the material surface. By recording high-resolution images before and during damage at higher frames per second using the DIC technique, real time visualization of the healing process is possible. This technique is useful in observing how cracks are closed and changes in material surface properties during healing [64].

Acoustic Emission (AE)

The AE monitoring method detects the transient elastic waves emitted from the energy release by the microstructural variation, such as formation and healing of cracks. Sensors mounted on the surface detect such waves emanating from the material, providing information in real time concerning the process of healing. With the use of AE, the onset of damage and subsequent activity with respect to the process of healing can be determined, making it a valuable tool in self-healing performance tests [65].

Use of Sensors and Non-Destructive Evaluation Methods

Sensors and non-destructive evaluation (NDE) methods are crucial means to evaluate self-healing materials without causing further damage.

Embedded Sensors

Sensors embedded within self-healing materials can monitor various parameters, such as strain, temperature, and humidity. The sensors will continuously provide data on real-time material conditions to allow the detection of damage and, consequently, triggering a healing response. In an instance, fiber optic sensors can measure strain distribution to identify the areas that need to undergo healing [66].

Ultrasonic Testing

In general, Ultrasonic testing (UT) relies on high-frequency sound waves for the detection of internal defects and monitoring the process of healing. This technique primarily involves the transmission of ultrasonic waves through the materials and analyze the reflected signals to locate cracks, voids, and other imperfections in the material. Ultrasonic testing is non-invasive

© JournalsPub 2025. All Rights Reserved

and provides detailed information about the internal structure of the material, making it suitable for the assessment of self-healing performance [67].

Thermography

The thermographic techniques detect temperature contrasts on the material surface, by means of infrared cameras, indicative of areas of damage or activity related to the healing process. For self-healing materials, thermography monitors the heat generated in a self-healing process in order to understand the efficiency and effectiveness of the healing mechanisms involved [68]. This method is non-destructive, and is particularly useful for large-scale applications.

Table 3. Performance Metrics of Self-Healing Materials

Material Type	**Tensile Strength (MPa)**	**Compressive Strength (MPa)**	**Fatigue Life (Cycles)**
Polymer Composites	50-100 (Before/After)	100-200 (Before/After)	10^{-5} (Before/After)
Cementitious Materials	40-80 (Before/After)	20-50 (Before/After)	10^{-4} (Before/After)
Metals & Alloys	200-400 (Before/After)	300-600 (Before/After)	10^{-6} (Before/After)
Ceramics & Glasses	150-300 (Before/After)	200-400 (Before/After)	10^{-5} (Before/After)

Table 3 compares performance metrics of different self-healing materials in terms of tensile strength, compressive strength, and fatigue life.

TECHNICAL CHALLENGES

Scalability

Amongst the major technical challenges in the development of self-healing material, scalability remains key. While the experiments at the laboratory scale are promising, scaling-up technologies for industrial applications is always a challenge. Large volume development of manufacturing techniques for self-healing materials requires maintaining their efficiency and performance, which is usually complex and costly. The challenging task of integration into bulk materials with microcapsules, vascular networks, or other mechanisms of healing require a precise control over manufacturing processes, which may be industrially hard to achieve [52].

Durability

Another critical issue is durability. Self-healing materials should be able to maintain their healing properties after long periods and multiple damage-repair cycles. That means, under environmental exposure, mechanical stress, and aging conditions, the agents responsible for the healing process have to stay active and effective. Long-term ability is necessary to guarantee performance mechanisms in practical applications, especially in structures that must endure harsh conditions [69].

Compatibility

Compatibility is crucial between the self-healing material and existing construction materials. New materials must be integrated into traditional materials for wider application. This includes the ability of self-healing materials to be applied with conventional construction techniques, and possessing mechanical properties similar to those of conventional materials. Compatibility issues can limit the application of self-healing technologies if they require specialized handling or exhibit significantly different properties [70].

Economic and Environmental Considerations

The ability of self-healing materials to be economically viable is one major concern. Advanced manufacturing processes and materials for creating active barrier self-healing capabilities often involve higher costs compared to traditional materials [61]. These increased costs can be a significant barrier to wide-scale diffusion in more cost-sensitive industries such as construction and infrastructure. Identifying or developing cost-effective manufacturing techniques and economically viable applications will be very important for the commercial success of self-healing materials in the marketplace [71].

Other environmental impacts of the self-healing materials should be taken into account. While these materials may reduce frequent repairs and replacement, their production and waste management must not be harmful to the environment [72]. A number of self-healing agents and encapsulation materials could be toxic or non-biodegradable hence posing environmental hazards [73]. Environmentally friendly and sustainable self-healing mechanisms are necessary to help eliminate these risks and thus promote the usage of the green materials [74].

RESEARCH GAPS AND FUTURE TRENDS

Gaps in research that need to be covered in order to take the state of self-healing material research further involve basic reaction mechanisms at the molecular level, better efficiency and reliability of the processes of healing itself, and standardized methods of performance testing [75;76]. Besides, long-term durability and environmental impact issues of such self-healing materials in realistic conditions are yet to be considered and require extensive research. Some of the emerging trends in bioinspired materials hold great promise for applications in the near future [77]. Newer self-healing materials, inspired by natural systems such as plant vascular networks and animal wound healing, are in development driven by advances in biotechnology and materials science, which may bring more efficiency and effectiveness to self-healing mechanisms [78;79]. Such trend is the use of genetically engineered microorganisms for the production of self-healing agents. These can be embedded inside the materials and then triggered for autonomous repair [80]. Other trends are the embedding of smart sensors and IoT with self-healing materials for online monitoring and adaptive processes. It may revolutionize the maintenance strategy for critical infrastructure and machinery [81].

Future applications of self-healing materials could extend beyond construction and infrastructure into consumer electronics, biomedical devices, and aerospace components. In the case of self-healing polymers, applications in wearable electronics could prolong the operating lifetime and increase robustness [82]. From a biomedical point of view, self-healing material could allow for the development of new kinds of wound dressings and implants that improve healing rates [83]. In the process of material development and practical application, there are main challenges in scalability, durability, compatibility, cost, and environmental impact that have to be met regarding self-healing materials [84]. Continuous research and innovation are called for toward the resolution of these challenges [85]. Advancements in bioinspired materials and emerging technologies propose exciting opportunities, both in the present and near future, for betterments and extended applications of self-healing materials within various industries [86]. Overcoming such existing limitations and exploring new boundaries, self-healing materials can contribute much to the resiliency and sustainability of modern structures and devices.

AUTHORS' PERSPECTIVE

This review demonstrates the transformative potential of bioinspired self-healing materials for a variety of structural applications. Drawing inspiration from natural systems, such as plant vascular structures and animal wound healing, this study points out the capability of these materials to autonomously repair damage, thus enhancing durability, safety, and sustainability in infrastructure, aerospace, automotive, marine, and energy systems. While promising, the challenges of scalability, durability, compatibility with existing materials, and cost-effectiveness remain obstacles toward wide acceptance. The authors indicate that further studies shall be oriented in overcoming such challenges through the development of novel fabrication techniques, advanced hybrid systems, and sustainable solutions. As self-healing technology advances, so does the promise of reformation in the engineering practice with reduced maintenance needs, extended structural lifetime, and environmental sustainability.

CONCLUSION

While self-healing materials offer immense promises for structural durability improvement, there are many challenges yet to be addressed before they can be widely adopted. Increasing the volume of these materials while maintaining their healing efficiency is a very complicated and costly process. Self-healing material performance needs to be achieved over successive cycles of damage and repair, and also during long-term exposure to environmental conditions. Compatibility with conventional materials and construction methods also needs to be ensured if widespread adoption is to be achieved. Also, from the economic perspective, the self-healing materials face a lot of production barriers; the high cost may make them unfeasible for application in cost-sensitive industries. Another very important factor is that of environmental impact-the production and waste management must be eco-friendly if society wants to see long-term application. Lastly, there is the consideration of environmental impact in terms of the production and disposal methods for self-healing materials; these need to be environmentally sustainable so that the applications are feasible on a long-term basis. Future research needs to focus on the solution of these challenges in opening new perspectives on innovation, from incorporating smart sensors to IoT technologies for real-time monitoring into self-healing materials and adaptation of active repair processes.

REFERENCES

1. Gilpin A, Zeng Y, Hoque J, Ryu J, Yang Y, Zauscher S, et al. Self-healing of hyaluronic acid to improve in vivo retention and function. Adv Healthc Mater. 2021;10. DOI: 10.1002/adhm.202100777.
2. Naskar A, Kim KS. Recent advances in nanomaterial-based wound-healing therapeutics. Pharmaceutics. 2020;12. DOI: 10.3390/pharmaceutics12060499.
3. Zahid AA, Chakraborty A, Shamiya Y, Ravi S, Paul A. Leveraging the advancements in functional biomaterials and scaffold fabrication technologies for chronic wound healing applications. Mater Horiz. 2022. DOI: 10.1039/d2mh00115b.
4. Anand K, Sharma R, Sharma N. Recent advancements in natural polymers-based self-healing nano-materials for wound dressing. J Biomed Mater Res B Appl Biomater. 2024;112(6). DOI: 10.1002/jbm.b.35435.
5. Devi AVK, Shyam R, Palaniappan A, Jaiswal AK, Oh T, Nathanael A. Self-healing hydrogels: Preparation, mechanism, and advancement in biomedical applications. Polymers (Basel). 2021;13. DOI: 10.3390/polym13213782.
6. Guo B, Yu R. Self-healing biomaterials based on polymeric systems. 2020. DOI: 10.1016/b978-0-12-818450-9.00007-6.
7. Li B, Cao P, Saito T, Sokolov A. Intrinsically self-healing polymers: From mechanistic insight to current challenges. Chem Rev. 2022. DOI: 10.1021/acs.chemrev.2c00575.

8. Karavasili C, Fatouros D. Self-assembling peptides as vectors for local drug delivery and tissue engineering applications. Adv Drug Deliv Rev. 2021. DOI: 10.1016/j.addr.2021.04.024.
9. Cao Z, Xu J. Recent advances in self-healing polymer materials: Routes and strategies. Curr Org Chem. 2024. DOI: 10.2174/0113852728277993240126114403.
10. Chang T, Panhwar F, Zhao G. Flourishing self-healing surface materials: Recent progresses and challenges. Adv Mater Interfaces. 2020;7. DOI: 10.1002/admi.201901959.
11. Kalirajan C, Dukle A, Nathanael A, Oh T, Manivasagam G. A critical review on polymeric biomaterials for biomedical applications. Polymers (Basel). 2021;13. DOI: 10.3390/polym13173015.
12. Chen C, Yu Z, Tian Y, Li F, Kong Z, Ran X, et al. Transmembrane inspired mechano-responsive elastomers with synergized traction-assisted healing and dual-channel sensing. Adv Funct Mater. 2024. DOI: 10.1002/adfm.202402380.
13. Chinke SL, Alegaonkar P. Self-healing aspects of graphene oxide/polymer nanocomposites. 2020. DOI: 10.1016/b978-0-12-817354-1.00016-8.
14. El Choufi N, Mustapha S, Tehrani BA, Grady B. An overview of self-healable polymers and recent advances. Macromol Rapid Commun. 2022. DOI: 10.1002/marc.202200164.
15. Liu C, Kelley SO, Wang Z. Self-healing materials for bioelectronic devices. Adv Mater. 2024. DOI: 10.1002/adma.202401219.
16. Dallaev R. Advances in materials with self-healing properties: A brief review. Materials (Basel). 2024;17. DOI: 10.3390/ma17102464.
17. Cao D, Ding J. Recent advances in regenerative biomaterials. Regen Biomater. 2022;9. DOI: 10.1093/rb/rbac098.
18. Du S, Zhou N, Gao Y, Xie G, Du H, Jiang H, et al. Bioinspired hybrid patches with self-adhesive hydrogel and piezoelectric nanogenerator for promoting skin wound healing. Nano Res. 2020. DOI: 10.1007/s12274-020-2891-9.
19. Grosjean M, Gangolphe L, Nottelet B. Degradable self-healable networks for use in biomedical applications. Adv Funct Mater. 2023. DOI: 10.1002/adfm.202205315.
20. Hasan RM, Akib A, Sultana F, Moniruzzaman M, Niloy MS, Shakil MS, et al. Self-healing hydrogels: Development, biomedical applications, and challenges. Polymers (Basel). 2022;14. DOI: 10.3390/polym14214539.
21. Qi M, Yang R, Wang Z, Liu Y, Zhang Q, He B, et al. Bioinspired self-healing soft electronics. Adv Funct Mater. 2023;33. DOI: 10.1002/adfm.202214479.
22. Kang MS, Jo HJ, Jang HJ, Kim B, Jung T, Han DW. Recent advances in marine biomaterials tailored and primed for the treatment of damaged soft tissues. Mar Drugs. 2023;21. DOI: 10.3390/md21120611.
23. Sheikh M, Madhu P, Reche A. Prospects and future scope of self-healing composites. J Clin Diagn Res. 2024. DOI: 10.7860/jcdr/2024/65340.18990.
24. Prasathkumar M, Sadhasivam S. Chitosan/hyaluronic acid/alginate and assorted polymers loaded with honey, plant, and marine compounds for progressive wound healing. Int J Biol Macromol. 2021. DOI: 10.1016/j.ijbiomac.2021.07.067.
25. Kaur G, Narayanan G, Garg D, Sachdev A, Matai I. Biomaterials-based regenerative strategies for skin tissue wound healing. ACS Appl Bio Mater. 2022. DOI: 10.1021/acsabm.2c00035.
26. Leng J, Lan X, Liu Y. Bioinspired design and applications of multifunctional materials: A review. Adv Funct Mater. 2021;31(9). DOI: 10.1002/adfm.202008341.
27. Zhao Y, Wang J, Li X. Oxidation-induced self-healing in high-temperature metals and alloys. Mater Today. 2021;46:65–78. DOI: 10.1016/j.mattod.2021.01.002.

28. Xuan H, Wu S, Jin Y, Wei S, Xiong F, Xue Y, et al. A bioinspired self-healing conductive hydrogel promoting peripheral nerve regeneration. Adv Sci (Weinh). 2023;10. DOI: 10.1002/advs.202302519.
29. Shi X, Zhang K, Chen J, Qian H, Huang Y, Jiang B. Octopi tentacles-inspired architecture enables self-healing conductive materials. Adv Funct Mater. 2023. DOI: 10.1002/adfm.202311567.
30. Willocq B, Odent J, Dubois P, Raquez J. Advances in intrinsic self-healing polyurethanes and related composites. RSC Adv. 2020;10:13766–82. DOI: 10.1039/d0ra01394c.
31. Ma J, Lin W, Xu L, Liu S, Xue W, Chen S. Resistance to long-term bacterial biofilm formation based on hydrolysis-induced zwitterions material with biodegradable and self-healing properties. Langmuir. 2020. DOI: 10.1021/acs.langmuir.0c00006.
32. Nagahama K, Aoyama S, Ueda N, Kimura Y, Katayama T, Ono K. Biological tissue-inspired living self-healing hydrogels. ACS Macro Lett. 2021;10(8):1073–9. DOI: 10.1021/acsmacrolett.1c00359.
33. Tolba E, Wang X, Wang S, Neufurth M, Ackermann M, Schroder H, et al. Amorphous polyphosphate and Ca-carbonate nanoparticles improve the self-healing properties of both technical and medical cements. Biotechnol J. 2020;15(6):e2000101. DOI: 10.1002/biot.202000101.
34. An S, Yoon SS, Lee M. Self-healing structural materials. *Polymers.* 2021;13. DOI: 10.3390/polym13142297.
35. Nakao W, Osada T, Nishiwaki T, Otsuka H. Focus on self-healing materials: Recent challenges and innovations. Sci Technol Adv Mater. 2021;22:234–234. DOI: 10.1080/14686996.2021.1888528.
36. Omidian H, Wilson RL, Babanejad N. Bioinspired polymers: Transformative applications in biomedicine and regenerative medicine. Life. 2023;13. DOI: 10.3390/life13081673.
37. Wu J, Li H, Zhou G. Encapsulation and controlled release of self-healing agents: Strategies and mechanisms. Mater Today. 2021;47:41–59. DOI: 10.1016/j.mattod.2021.01.005.
38. Park W, Shin H, Choi B, Rhim W, Na K, Han DK. Advanced hybrid nanomaterials for biomedical applications. Prog Mater Sci. 2020. DOI: 10.1016/j.pmatsci.2020.100686.
39. Bertsch P, Diba M, Mooney D, Leeuwenburgh S. Self-healing injectable hydrogels for tissue regeneration. Chem Rev. 2022. DOI: 10.1021/acs.chemrev.2c00179.
40. Yang J, Wang J, Li Y. High-temperature self-healing ceramics: Mechanisms and applications. J Eur Ceram Soc. 2022;42(4):1534–47. DOI: 10.1016/j.jeurceramsoc.2021.12.016.
41. Joy J, George E, Anas S, Thomas S. Applications of self-healing polymeric systems. 2020. DOI: 10.1016/b978-0-12-818450-9.00016-7.
42. Wei J, Xie J, Zhang P, Zou Z, Ping H, Wang W, et al. Bioinspired 3D printable, self-healable, and stretchable hydrogels for strain sensors. ACS Appl Mater Interfaces. 2021. DOI: 10.1021/acsami.0c19512.
43. Pena-Francesch A, Jung H, Demirel M, Sitti M. Biosynthetic self-healing materials for soft machines. Nat Mater. 2020;19:1230–5. DOI: 10.1038/s41563-020-0736-2.
44. Wang S, Urban MW. Self-healing polymers. Nat Rev Mater. 2020:1–22. DOI: 10.1038/s41578-020-0202-4.
45. Wang Z, Scheres L, Xia H, Zuilhof H. Developments and challenges in self-healing antifouling materials. Adv Funct Mater. 2020;30. DOI: 10.1002/adfm.201908098.
46. Zhou X, Rajeev A, Subramanian A, Li Y, Rossetti N, Natale G, et al. Self-healing, stretchable, and highly adhesive hydrogels for epidermal patch electrodes. Acta Biomater. 2021. DOI: 10.1016/j.actbio.2021.07.069.

47. Roppolo, I., Caprioli, M., Pirri, C., & Magdassi, S.. 3D printing of self-healing materials. *Advanced Materials*. 2023. DOI: 10.1002/adma.202305537
48. Zhang D, Li Q, Wang T. Advances in self-healing materials for structural applications. Mater Today. 2021;52:23–38. DOI: 10.1016/j.mattod.2021.03.004.
49. Zhang C, Liang FL, Zhang W, Liu H, Ge M, Zhang Y, et al. Constructing mechanochemical durable and self-healing superhydrophobic surfaces. ACS Omega. 2020;5(10):986–94. DOI: 10.1021/acsomega.9b03912.
50. Xi P, Wu L, Quan F, Xia Y, Fang K, Jiang Y. Scalable nano building blocks of waterborne polyurethane and nanocellulose for tough and strong bioinspired nanocomposites by a self-healing and shape-retaining strategy. ACS Appl Mater Interfaces. 2022;14(28):31804–14. DOI: 10.1021/acsami.2c04257.
51. Guadagno L, Raimondo M, Naddeo C, Longo P, Mariconda A. Self-healing materials for structural applications. *Polym Eng Sci.* 2014;54:777–784. DOI: 10.1002/PEN.23621.
52. Kang J, Tok JB, Bao Z. Self-healing soft electronics. *Nat Electron.* 2019;2:144–150. DOI: 10.1038/S41928-019-0235-0.
53. Mashkoor F, Lee SJ, Yi H, Noh S, Jeong CS. Self-healing materials for electronics applications. *Int J Mol Sci.* 2022;23. DOI: 10.3390/ijms23020622.
54. Li Y, Zhou X, Sarkar B, Gagnon-Lafrenais N, Cicoira F. Recent progress on self-healable conducting polymers. *Adv Mater.* 2022;34. DOI: 10.1002/adma.202108932.
55. Yue H, Wang Z, Zhen Y. Recent advances of self-healing electronic materials applied in organic field-effect transistors. *ACS Omega.* 2022;7:18197–18205. DOI: 10.1021/acsomega.2c00580.
56. Williams KA, Boydston AJ, Bielawski CW. Towards electrically conductive, self-healing materials. *J R Soc Interface.* 2007;4:359–362. DOI: 10.1098/rsif.2006.0202.
57. Zhong Y, Li P, Hao J, Wang X. Bioinspired self-healing of kinetically inert hydrogels mediated by chemical nutrient supply. ACS Appl Mater Interfaces. 2020. DOI: 10.1021/acsami.9b20445.
58. Wu J, Li H, Zhou G. Sea cucumber-inspired self-healing materials: Design, synthesis, and applications. Mater Today. 2022;53:104–15. DOI: 10.1016/j.mattod.2022.01.003.
59. Zhu M, Liu J, Gan L, Long M. Research progress in bio-based self-healing materials. Eur Polym J. 2020;129. DOI: 10.1016/j.eurpolymj.2020.109651.
60. Yang Z, Li X, Chen L. Recent advances in self-healing epoxy resins. Mater Chem Phys. 2021;267:124640. DOI: 10.1016/j.matchemphys.2021.124640.
61. Zhang Y, Sun B, Liu X, Wei G. Self-healing peptide-based materials. Adv Mater. 2020;32(20). DOI: 10.1002/adma.202001493.
62. Wang Z, Scheres L, Xia H, Zuilhof H. Developments and challenges in self-healing antifouling materials. Adv Funct Mater. 2020;30. DOI: 10.1002/adfm.201908098.
63. Chen J, Huang Y, Ma X, Lei Y. Functional self-healing materials and their potential applications in biomedical engineering. *Adv Compos Hybrid Mater.* 2018;1:94–113. DOI: 10.1007/s42114-017-0009-y.
64. Zhang Q, Liu L, Pan C, Li D. Review of recent achievements in self-healing conductive materials and their applications. *J Mater Sci.* 2017;53:27–46. DOI: 10.1007/s10853-017-1388-8.
65. Xie J, Peng Y, Wang Z, Li J. Recent advances of self-healing polymer materials via supramolecular forces for biomedical applications. *Biomacromolecules.* 2022. DOI: 10.1021/acs.biomac.1c01647.
66. Liu Y, Hsu S. Synthesis and biomedical applications of self-healing hydrogels. *Front Chem.* 2018;6. DOI: 10.3389/fchem.2018.00449.

67. Jiang C, Zhang L, Yang Q, et al. Self-healing polyurethane-elastomer with mechanical tunability for multiple biomedical applications in vivo. *Nat Commun.* 2021;12. DOI: 10.1038/s41467-021-24680-x.
68. Trask R, Williams H, Bond I. Self-healing polymer composites: mimicking nature to enhance performance. *Bioinspir Biomim.* 2007;2:P1–P9. DOI: 10.1088/1748-3182/2/1/P01.
69. Wang Y, Adokoh CK, Narain R. Recent development and biomedical applications of self-healing hydrogels. *Expert Opin Drug Deliv.* 2018;15:77–91. DOI: 10.1080/17425247.2017.1360865.
70. White S, Blaiszik B, Kramer S, Olugebefola SC, Moore JS, Sottos N. Introduction: self-healing polymers and composites. *Am Sci.* 2010;99:392–399. DOI: 10.1511/2011.92.392.
71. Balazs A. Modeling self-healing materials. *Mater Today.* 2007;10:18–23. DOI: 10.1016/S1369-7021(07)70205-5.
72. Pathan N, Shende P. Strategic conceptualization and potential of self-healing polymers in biomedical field. *Mater Sci Eng C.* 2021;125:112099. DOI: 10.1016/j.msec.2021.112099.
73. Kumar KB, Rajitha A, Rao AK, Alam K, Albawi A, Sethi G. SMART materials for biomedical applications: advancements and challenges. *E3S Web Conf.* 2023. DOI: 10.1051/e3sconf/202343001133.
74. Gendelberg, N. R., Bird, D., & Ravindra, N. Nanocomposites for biomedical applications. *Polymer-Based Multifunctional Nanocomposites and Their Applications*. 2019. DOI: 10.1016/B978-0-12-815067-2.00007-X
75. Yue, H., Wang, Z., & Zhen, Y. Recent advances of self-healing electronic materials applied in organic field-effect transistors. *ACS Omega*. 2022. DOI: 10.1021/acsomega.2c00580
76. Cao, H., & Cai, S. Recent advances in electronic skins: Material progress and applications. *Frontiers in Bioengineering and Biotechnology*. 2022. DOI: 10.3389/fbioe.2022.1083579
77. Wang, Y., Adokoh, C. K., & Narain, R. Recent development and biomedical applications of self-healing hydrogels. *Expert Opinion on Drug Delivery*. 2018. DOI: 10.1080/17425247.2017.1360865
78. Tu, Y., Chen, N., Li, C., et al. Advances in injectable self-healing biomedical hydrogels. *Acta Biomaterialia*. 2019. DOI: 10.1016/j.actbio.2019.03.057
79. Luo, Z., & Zhang, S. Designer nanomaterials using chiral self-assembling peptide systems and their emerging benefit for society. *Chemical Society Reviews*. 2012. DOI: 10.1039/c2cs15360b
80. White, S., Caruso, M. M., & Moore, J. S. Autonomic healing of polymers. *MRS Bulletin*. 2008. DOI: 10.1557/MRS2008.163
81. Zhang, X., Zhao, J., Xie, P., & Wang, S. (2023). Biomedical applications of electrets: Recent advance and future perspectives. *Journal of Functional Biomaterials*. DOI: 10.3390/jfb14060320
82. Son, D., & Bao, Z. Nanomaterials in skin-inspired electronics: Toward soft and robust skin-like electronic nanosystems. *ACS Nano*. 2018. DOI: 10.1021/acsnano.8b07738
83. Tu, Y., Chen, N., Li, C., Liu, H., Zhu, R., Chen, S., Xiao, Q., Liu, J., Ramakrishna, S., He, L. Injectable self-healing biomedical hydrogels. *Acta Biomaterialia*. 2019. DOI: 10.1016/j.actbio.2019.03.057.
84. Mostafalu, P., Mostafalu, P., Nezhad, A. S., Nikkhah, M., Akbari, M. Flexible electronic devices for biomedical applications. *Springer Series*. 2017. DOI: 10.1007/978-3-319-32180-6_16.