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Polymers and others Advance Materials: A State-of-the-Art Review

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Abstract

Developing emerging technologies requires pushing the boundaries of material science. Right now, conventional neat polymers simply do not last long enough in the field. They suffer from sudden mechanical failure, struggle with thermal instability, and throwaway disposal methods have created a massive environmental crisis. To tackle these exact issues, this review provides a critical evaluation of two rapidly growing solutions: sustainable bio-composites and self-healing polymer systems. Rather than offering a basic summary, we break down the actual mechanical trade-offs and healing efficiencies of both intrinsic and autonomic repair mechanisms (such as hollow fiber networks and microencapsulation). We also examine whether bio-based matrices like PHA, PCL, and PLA—alongside natural fiber reinforcements—are practically viable for real-world manufacturing. The paper evaluates the performance of these advanced materials across several demanding industries. Specific applications discussed include lightweight carbon-fiber parts for aerospace, bioresorbable medical stents, and the design of asymmetric supercapacitors for advanced electronics. Ultimately, getting these materials out of the lab and into the market remains incredibly difficult. By identifying the primary barriers to commercialization—like high production costs, emerging nanotoxicity concerns, and a total lack of unified testing standards—this review highlights the specific research gaps that engineers must close to achieve widespread industrial use.

Keywords: Advanced materials, self-healing polymers, sustainable composites, bio-based polymers, nanocomposites

INTRODUCTION

As cutting-edge technologies advance, engineers are constantly developing new materials to meet highly specific demands. Tailored composites provide excellent mechanical, thermal, and conductive properties, making them ideal for high-performance applications. However, modern engineering must also address growing ecological concerns. Because of this, next-generation materials must be sustainable and environmentally friendly [1–2]. Thanks to their excellent cost-to-performance ratio, polymers have already replaced traditional materials like metal, glass, and wood in many industries. Unlike other materials, which may be light in weight, they have little tendency to corrode. Furthermore, they have the inherent ability to resist bacteria and other microbial contaminants. Biological contamination prevention helps prevent premature degradation of the material [3–4]; in other words, the components have greater longevity once placed outside.

What we have today is a drastic transformation in industry based on nanotechnology, flexible electronics, and additive manufacturing [5–6]. It is impossible to apply traditional materials for these purposes, because the new processes place a heavy toll on their structure.

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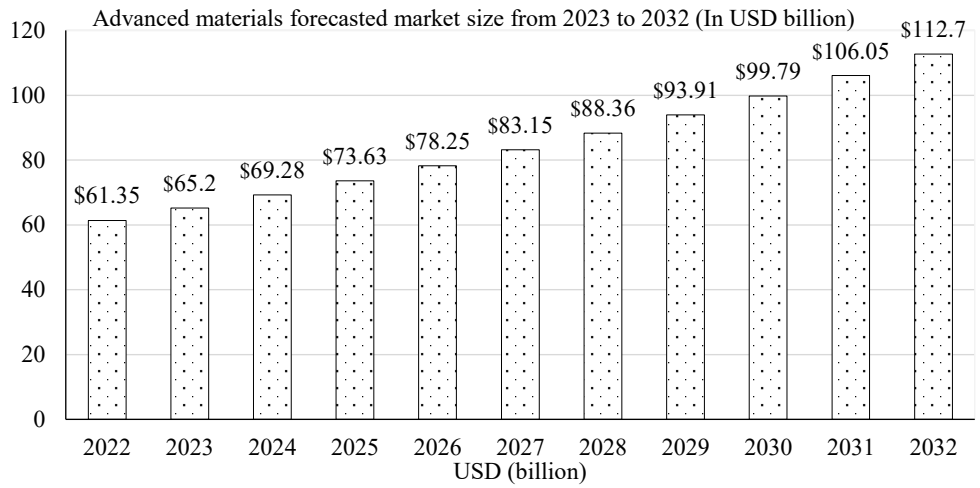


Figure 1. Advanced materials forecasted market size from 2023 to 2032 (In USD billion) [9].

This is why specialists emphasize the need for advanced materials, whose structure must provide additional benefits [7–8]. Looking at Figure 1 below, one can see the estimated economic effect, which illustrates the expected size of the market of advanced materials globally (USD billions) until 2032 [9].

While it is very tempting to enumerate every place where such materials are currently employed, such an approach would not bring any benefit in terms of breaking engineering limitations. In this case, however, the aim is to present a rather sharp critique of two areas that currently suffer from serious problems. Currently, two largest revolutions within materials science take place: Self-Healing Polymer Systems [10] and Sustainable/Bio-Based Polymer Composites [11].

Quite a large amount of efforts are currently being put into smart polymers due to their ability to autonomously self-repair after getting damaged, exposed to light, and/or heated. This results in much higher operational life and reliability of the parts made of these materials [10]. However, one should not forget about growing ecological issues. The new generation of components must be absolutely safe for environment and biodegradable if we still want to use them [1, 11].

The presentation of textbook material summaries cannot take the materials out of laboratory settings and into industrial factories. In order to close this gap, the present paper was composed in a structured format of a comparison analysis, which includes classification of various types of advanced polymers; then, the limitations and potentialities of self-healing and bio-derived systems are discussed in depth, in regard to their effectiveness when applied to challenging tasks in the aerospace, biomedical, and electronic industries. Finally, the paper presents an overview of factors limiting their commercial applications. Determining current limitations in technology and research can help future scientists to find answers to further issues.

CLASSIFICATION OF ADVANCED POLYMER MATERIALS

In contrast to traditional approaches, where the goal is to select natural materials appropriate for an assigned engineering task, nowadays scientists tend to design novel synthetic compounds according to desired functions of materials. The majority of advanced polymers can be classified depending on their structure into several categories, such as hybrid materials, nanocomposites, intrinsically conducting polymers (ICPs), and biomimetic composites [12–13].

Bio-Inspired Composites

From sea shells to bones and spider silk, the natural world has come up with some of the most effective engineering models ever known. As a result, bio-inspired composites have achieved a

remarkable combination of low weight and high strength. Their unparalleled strength-to-weight ratio is what makes them ideal for harsh conditions. Currently, they are widely employed in aerospace parts, body armor, and biomedical devices [9, 14–15].

Intrinsically Conducting Polymers (ICPs)

Until 1977, industry had largely relied on polymers for insulation purposes only. In that year, however, structural innovations resulted in the emergence of intrinsically conducting polymers (ICPs), which are quite unique materials. These polymers not only conduct electricity but also function as artificial muscles and respond to changes in the environment. The actuator made from an ICP outperforms human muscles in terms of physical endurance by enduring much greater stress. Based on external stimuli, their electrical resistance can increase or decrease dynamically. To create ordinary types such as polyacetylene, polyaniline, and polypyrrole, researchers generally oxidize monomers using electrochemical vapor methods [16]. Various types of intrinsically conducting polymers (ICPs) are illustrated in Figure 2.

Nanocomposites & Hybrid Polymers

Nanomaterials can be extremely delicate, and for that reason, they are often embedded in polymer structures as protection measures. Quantum dots provide an excellent example. Given that quantum dots are extremely fragile structures, engineers have no choice but to embed them within hyper-branched, co-, and homo-polymers in order to protect them. Hybridization of such materials allows them to be used for interacting with living tissues. Modern medicine is highly reliant on such nanocomposites in biosensors and internal imagers [17–18].

Comparative Analysis of Polymer Materials

While it may seem sufficient to know what properties an object possesses, knowing its practical drawbacks can make all the difference. In order to make the comparison of our polymer classes more critical, we have created Table 1.

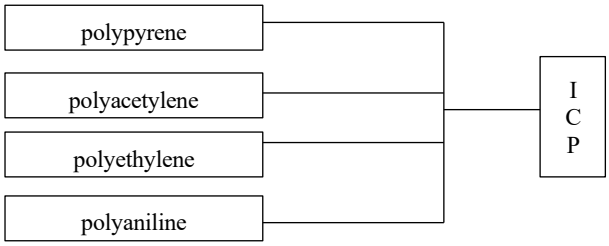


Figure 2. Various types of ICPs (source: *www.sciencdirect.com*; keyword used: inherently conducting polymer) [16].

Table 1. Comparative analysis of advanced polymer classifications.

Polymer classification	Primary functional properties	Typical applications	Current technological limitations
Bio-Inspired Composites	High strength-to-weight ratio, hierarchical toughness, impact resistance	Structural armor, load-bearing biomedical implants	Extremely complex and expensive to manufacture at an industrial scale; difficult to perfectly replicate nanoscale natural architectures.
Intrinsically Conducting Polymers (ICPs)	Stimuli-responsive electrical conductivity, actuation capabilities	Sensors, artificial muscles, flexible electronics	Poor long-term environmental stability; mechanical degradation over repeated actuation cycles.
Polymer Nanocomposites	Enhanced thermal, electrical, and optical properties at low filler loadings	Biosensors, targeted drug delivery, advanced packaging	Agglomeration of nanoparticles during processing; emerging concerns regarding long-term nanotoxicity.
Hybrid Polymer Materials	Synergistic integration of organic flexibility and inorganic durability	Energy storage (supercapacitors), high-performance coatings	Interfacial adhesion issues between disparate phases; complex and multi-step synthesis processes.

The focus of the table lies not only on the description of physical features of such materials, but also on the obstacles which prevent commercial and technological applications from being possible. Identifying such weaknesses will allow the scientific community to pinpoint areas that require optimization.

SELF-HEALING POLYMER SYSTEMS

Over the past few decades, polymeric materials have become ubiquitous across virtually every engineering sector. Nevertheless, continuous exposure to operational stresses—including thermal fluctuations, harsh chemical environments, mechanical fatigue, and UV radiation—inevitably results in material degradation [10]. Such damage typically initiates at a microscopic scale, where micro-cracks develop and propagate over prolonged usage. If left unaddressed, these micro-cracks compromise the structural integrity of the composite, leading to catastrophic macroscopic failure. Consequently, there is an urgent industrial demand for composites that can autonomously repair internal damage to improve their lifespan, reliability, and safety.

Nature knows how to treat its wounds perfectly well; therefore, engineers borrowed this idea from biology when designing self-healing materials. These materials can be classified into non-autonomic and autonomic categories based on their healing stimuli. The classification of autonomic and non-autonomic self-healing systems is shown in Figure 3.

Self-healing Materials: Autonomic (Extrinsic) Systems

Autonomous healing is defined as a spontaneous crack repair that occurs automatically without human intervention. This type of material design was mainly achieved by incorporating the healing agents within the composite itself.

Micro-encapsulation

The concept of embedding small, fragile containers of a liquid healing agent (usually a monomer) within the polymer matrix seems promising. Upon occurrence of a micro-crack, these capsules would break down, releasing the healing agent through capillary forces to flow through the cracks.

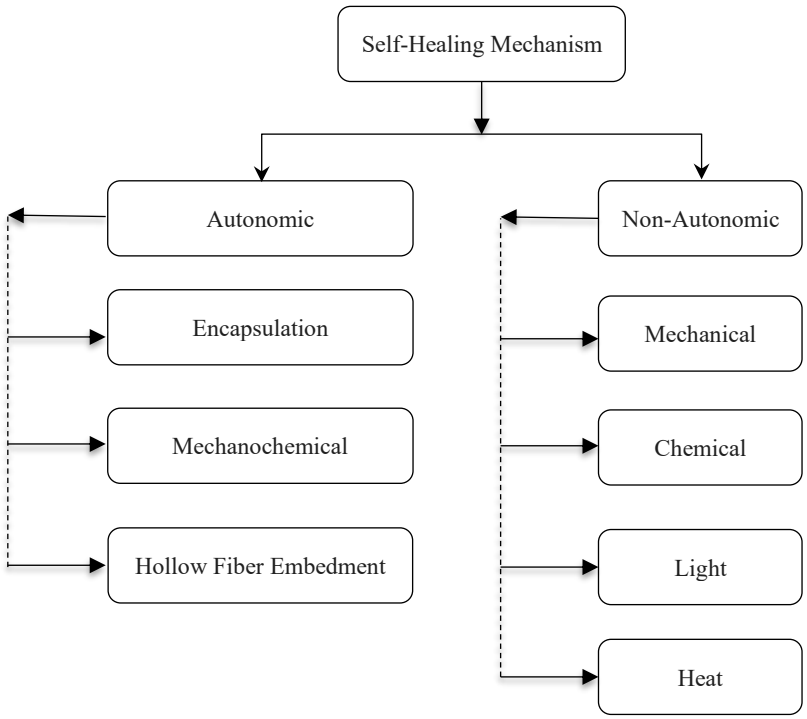


Figure 3. Autonomic and non-autonomic self-healing.

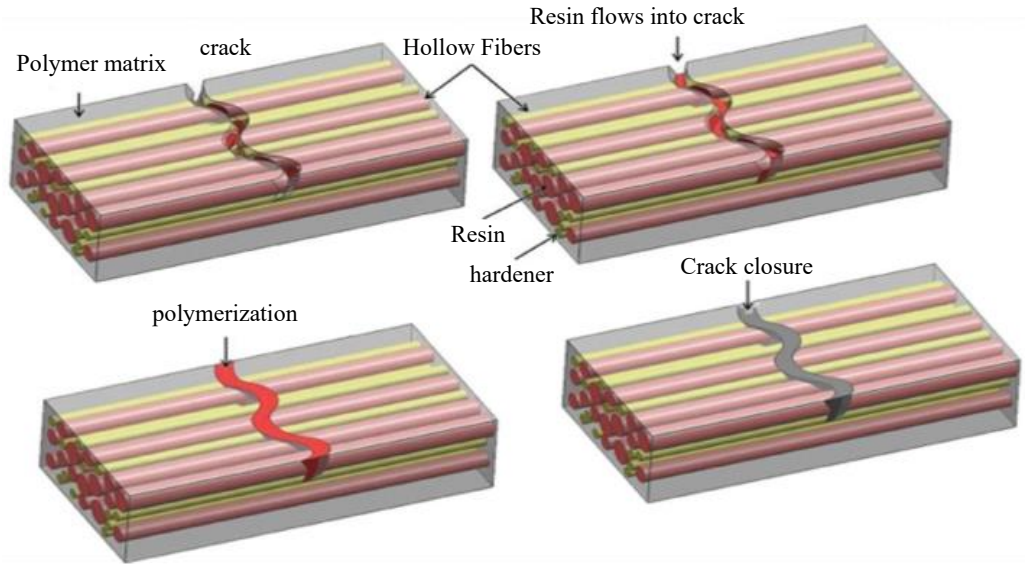


Figure 4. Self-healing approach using hollow fibers (permission from ref. [10].

Once the liquid comes into contact with the catalyst present in the matrix, polymerization begins, leading to crack repair. This healing process has proved effective for one-time use. However, the weaknesses are quite evident: the capsules have a limited lifespan; monomers need to have the desired viscosity and correct rigidity to function effectively, making them brittle and susceptible to rupture upon mechanical shock. Once the capsules break, their content would be completely released, limiting the healing process to one event per location [10].

Hollow Fiber Embedment

Micro-capsules function only one time and can retain only a small amount of liquids, which led scientists to look at something else in people's blood vessels. They constructed tiny tubular systems within the composite itself. This approach provides constant flow of new resin and hardener to the fracture point from these fiber-based channels, so that the composite can repair itself several times in precisely the same place. The hollow fiber-based self-healing mechanism is illustrated in Figure 4.

Non-Autonomic Healing Mechanisms (Intrinsic)

In intrinsic healing, all embedded chemicals have been left behind, and the process relies solely on inherent chemistry of the composite. However, there still should be some kind of stimulation. The operator should trigger the process through manual application of mechanical force, heat, or irradiation. Once this happens, the composite will seal itself through photoreaction, molecular diffusion or creation of dynamic chemical bonds (ionic bonding, Diels-Alder reactions, etc.).

In theory, this type of healing could be performed infinite amount of times in one and the same place. This feature is invaluable. The downside is that application of such stimuli during actual use is not always possible [10].

Critical Assessment and Performance Comparison

The main challenge when trying to transition self-healing polymers from the laboratory to commercialization is achieving a balance between strength and healing capacity. Adding hollow fiber reinforcement or microcapsules to a polymer will decrease its basic strength. The following Table 2 is used for a critical assessment of the performance of various self-healing paradigms. This includes their healing efficiency in practice, repeatable healing ability, and major engineering limitations preventing their use in the wider market.

Table 2. Quantitative and critical comparison of self-healing polymer mechanisms.

Healing mechanism	Category	Typical healing efficiency (%)	Repeatability (at same site)	Primary limitations and research gaps
Microencapsulation	Extrinsic (Autonomic)	70% – 90%	Single-use only	Capsule embedment reduces baseline matrix strength; high risk of premature capsule rupture during manufacturing; limited healing agent volume.
Vascular / Hollow Fibers	Extrinsic (Autonomic)	80% – 100%	Multiple cycles	Highly complex manufacturing process; channels can create significant macroscopic voids leading to localized stress concentrations.
Reversible Dynamic Bonds	Intrinsic (Non-Autonomic)	50% – 85%	Infinite (Theoretically)	Requires external stimuli (e.g., temperatures often >100°C) which may damage surrounding components; slower healing kinetics compared to capsule rupture.
Nanoparticle-Assisted	Intrinsic (Stimuli)	60% – 80%	Multiple cycles	Nanoparticle agglomeration limits uniform healing; requires specific frequencies of light or magnetic fields to trigger.

SUSTAINABLE AND BIO-BASED POLYMER COMPOSITES

Traditional polymer compositions derived from petroleum have been the source of environmental hazards on a gargantuan scale. Not only does their production give rise to greenhouse emissions but also, the long-term accumulation of micro-plastics in the atmosphere is posing severe risks to our environment. Modern materials science needs sustainable solutions to address this problem, and therefore, scientists are increasingly investing their money in developing novel biodegradable bio-polymer composite material directly sourced from renewable materials [1–2].

Major Biopolymers

Currently, some selected few bio-polymers are finding success in entering the industrial market because they possess both sufficient mechanical resistance and biodegradability.

- *Polylactic acid (PLA):* Polylactic acid can be sourced from renewable crops like sugarcane and corn starch, due to its high level of versatility as well as its ability to withstand mechanical forces. Industries make use of it to produce biomedical tissue scaffolds and composite materials due to its very stiff structure [14–15]. Unfortunately, PLA happens to be highly brittle in nature and also lacks sufficient glass transition temperature..
- *Polycaprolactone (PCL):* Unlike PLA, PCL is highly ductile and tough, as well as more durable. The latter means that it will take a considerably longer time before breaking down. While this may be viewed negatively, it is a desirable trait when building structures that need to be maintained for an extended period of time. As such, a common strategy employed by engineers is blending PCL with other polymers, such as PLA, to increase the material's toughness.
- *Polyhydroxyalkanoates (PHA):* Microbes synthesize PHA biopolymers, making them eco-friendly, biocompatible, and degradable in nature. Their major drawback is that they have to undergo complicated extraction procedures. Due to the resulting production cost, PHAs cannot currently be produced on an industrial scale.

Natural Fiber Reinforcements and Bio-Composites

For these composites to become eco-friendlier, scientists have started actively discarding man-made reinforcing materials such as carbon or glass fibers. They are being replaced by much cheaper, easily biodegradable and impressively lightweight natural ones like bamboo, flax, hemp, and jute [11].

However, in terms of engineering, there is one absolutely huge problem. All ordinary polymers have an inherently hydrophobic nature; the natural fibers, conversely, are very hydrophilic. Mixing these two substances leads to poor interface bonding, which results in a drastically lowered composite strength and may even lead to premature material degradation under wet conditions [11]. In order to achieve good bonding between the matrix and reinforcement, special modifications need to be done to the latter, for example, silane coupling or alkalization, before mixing occurs. Of course, adding additional chemicals makes the process more hazardous and, thus, non-green.

Table 3. Comparative analysis of bio-based polymer matrices.

Polymer matrix	Source material	Typical degradation timeframe	Key strengths	Primary engineering limitations
PLA (Polylactic acid)	Renewable (Starch/Sugarcane)	6 months to 2 years (Industrial composting)	High tensile strength; excellent printability (3D printing).	Inherent brittleness; poor thermal stability; requires specific industrial composting conditions to degrade efficiently.
PCL (Polycaprolactone)	Synthetic (Petrochemical) but highly biodegradable	2 to 4 years	High flexibility and toughness; low melting point aids processing.	Low mechanical strength; unsuitable for high-load structural applications.
PHA (Polyhydroxyalkanoates)	Microbial fermentation	Months to 1 year (Marine and soil environments)	Fully biodegradable in natural environments; excellent biocompatibility.	Extremely high production costs; thermal degradation occurs very close to its melting temperature during processing.
Natural fiber composites	Plant-based fibers	Highly variable based on matrix	Lightweight; low carbon footprint; good acoustic insulation.	High moisture absorption; poor interfacial matrix adhesion; variable mechanical properties depending on crop yield.

Critical Analysis of Sustainable Matrices

It is not enough to write about such materials. You must critically evaluate the practical benefits and drawbacks of the sustainable matrices. Table 3 shows a critical comparison of the sustainable matrices discussed in this section. By comparing the specific periods of decomposition to their main structural defects, you can identify their design challenges.

FUNCTIONAL APPLICATIONS

Using advanced polymers and incorporating them in the business arena is aggressively threatening high-performance markets. However, it is essential to remain practical while evaluating these materials. They should be compared to previous benchmarks in terms of performance and examined for the areas in which they may fail under actual conditions of usage.

Biomedical Applications

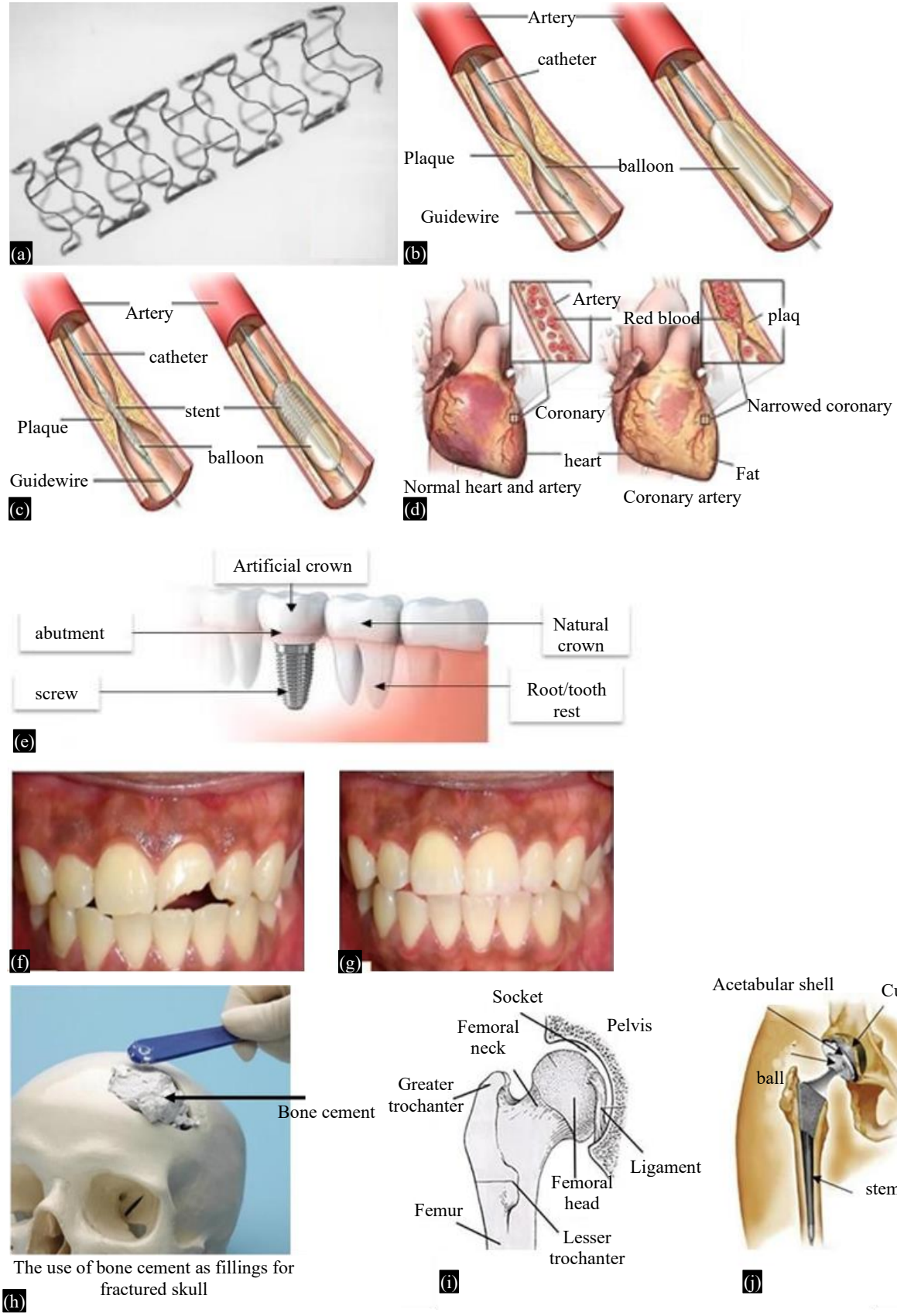
Medical engineering, particularly the design of medical prostheses, has been transformed dramatically due to advanced polymers. Traditionally, surgeons would need to rely on the same metals such as stainless steel or titanium. However, one major issue with this is the extreme difference between the mechanical properties of such materials and those of human tissue. Being so rigid and hard, the metal absorbs virtually all of the loads and causes stress shielding effect to occur. As a result, the natural tissue starts to reabsorb because it is not under any pressure anymore.

There is no such problem with polymer composites at all. Thanks to tuning the composite materials, it is possible to obtain the precise modulus of elasticity of the natural bone. And if you need even more, your body will be able to dispose of the implant as soon as it finishes its mission.

This particular change is happening right now with the development of the BRS stents, which means biodegradable vascular stents based on the PLLA material. Metallic stents allow you to achieve great radial strength immediately, while also causing constant inflammation and making your natural blood vessel unable to move freely. PLLA stents provide you with only temporary support. They keep your vessel open during the crucial period of 6–12 months, and then just dissolves away inside your body.

- *Limitation:* There is, however, one important fact that must not be overlooked. In comparison to the common cobalt-chromium alloys, polymeric stents provide much less radial strength initially. This problem requires increasing the thickness of the struts, which could become very dangerous for optimal blood flow dynamics [14–15].

Different biomedical applications of advanced polymeric materials are presented in Figure 5.



(a) Fully dilated absorbable stent
(b) angioplasty
(c) Stent placement
(e) Natural tooth and dental implant
(f) before tooth filling
(g) after tooth filling heart and the heart with CAD
(h) The use of bone cement as fillings for fractured skull
(i) the schematic diagram of the hip joint
(j) Artificial hip joint showing the stem and cup

Figure 5. Various applications of polymeric advanced materials in biomedical field (permission from ref. [19]).

Aerospace and Automotive Industry Applications

For anyone looking to make significant gains towards enhancing fuel economy or improving the battery performance of EVs, there is no other way to go than making drastic reductions in weight. This is what has been fueling the adoption of advanced composite material across the whole transportation industry. Common metals used in engineering can never match the superiority of FRPs in specific strength. With the introduction of glass and carbon fiber reinforcement within an epoxy matrix, we have seen amazing results.

- *Quantitative benefit:* Take a closer look at the real figures regarding carbon fiber-reinforced polymers (CFRPs). It is possible to preserve the exact structural rigidity and impact resistance properties of a car and reduce the weight of its steel body by up to 50% to 70%. And even relative to the lightweight aluminum alloy, there is an additional weight loss of up to 20% to 30%.
- *Key constraint:* But why are CFRPs not present in all modern consumer cars? First, their production is extremely expensive and slow. Then there is the enormous problem of end-of-life management. Both aerospace and automotive producers have extensive use of thermosets. Since thermoset polymers cannot be remelted, the problem of recycling such materials poses an extraordinary environmental and economic challenge [6].

Electronics and Electrical Applications

As electronics become ever smaller, the associated thermal issues become increasingly severe. New semiconductor-based components produce an enormous amount of localized heat. This heat can seriously reduce the longevity of the product unless managed properly. Here, one should use a special combination of advanced composite materials based on a polymer to provide thermal conductivity while preserving electric insulating properties. Apart from their thermally active properties, such composites are used in other innovative technologies. Advanced polymers are critical for new energy storing devices called supercapacitors. One may see them as something that strikes the perfect balance between high-energy batteries and high-power capacitors.

- *Comparative performance:* Historically, researchers paid much attention to symmetric designs (e.g., RuO_2-RuO_2). However, today, they are working with asymmetric supercapacitors constructed on polymer and graphene matrices. When pairing a RuO2/graphene electrode with a $Ni(OH)_2$/graphene one, a wider stable operating voltage can be achieved. The most important thing is that this increases the energy density of the device without losing its unique property.
- *Critical limitation:* The primary challenge here is scaling the uniform dispersion of graphene within the polymer matrix without particle agglomeration, which currently makes large-scale manufacturing cost-prohibitive [20].

CHALLENGES AND COMMERCIALIZATION BARRIERS

Scalability and Production Expenses

First off, all advanced composites face the same difficulty of expensive large-scale manufacturing process. Consider, for instance, self-healing microcapsules, which work perfectly in the lab. Trying to inject them in viscous industrial resin on a grand scale will inevitably lead to their premature burst and unequal distribution throughout the material. The same holds true with nanocomposites. In order to achieve good quality of graphene or carbon nanotubes, there is no way to avoid a rather expensive chemical vapor deposition process. This makes such materials way too costly to compete with ordinary materials.

Environmental and Emerging Issues of Toxicity

One would think the irony is not lost in the fact that despite designing these materials for saving the planet, some of them create entirely new ecological threats. The inclusion of nanoparticles in polymer matrices is a huge cause for concern when it comes to nanotoxicity. From what one can observe from modern research on graphene family of nanomaterials, the scientists are extremely worried about genotoxicity, both direct and indirect, of such materials [21].

Moving beyond the microscopic realm, there are other disposal issues as well, particularly those concerning end of life disposal of materials. Thermosetting composite materials play an indispensable role in aerospace and automotive industry. Since it is impossible to remelt such thermosets, they are simply disposed in nature. Should we ever hope that the materials can be net positive to the environment, it will become imperative to address the lifecycle of nanomaterials and do away with toxic additives to bio-fibers.

Regulatory and Standardization Challenges

In addition to addressing manufacturing issues and the potential damage to the environment, you will be faced with a total absence of universal standards of testing globally. How can you define the "efficiency of healing" of the self-healing material? As far as today, there is no such universal criterion that would measure the "efficiency of healing." Indeed, the same problem arises in the sphere of medicine, where we lack universal criteria of assessing the speed of decomposition of new bio-implants. Because of the absence of any globally recognized standards, it is practically impossible to receive regulatory clearance from international regulatory bodies like EMA or FDA, due to the fact that the procedure of obtaining it is rather unpredictable, time-consuming, and extremely expensive.

RESEARCH GAPS AND FUTURE DIRECTIONS

To overcome current commercialization barriers and realize the full potential of advanced polymer systems, future multidisciplinary research must address the following highly specific technological gaps:

- *Extreme-environment self-healing:* Current intrinsic self-healing mechanisms primarily function under controlled laboratory conditions or require external heat stimuli. A critical research gap exists in developing autonomic self-healing polymers capable of functioning in extreme, sub-zero temperatures (for aerospace applications) or high-salinity environments (for marine and offshore structures).
- ***Chemical recycling of thermosets:*** While the focus has heavily shifted to biodegradable thermoplastics (like PLA and PHA), the industry desperately needs breakthroughs in dynamic covalent chemistries (such as vitrimers) that allow for the chemical recycling and reshaping of inherently rigid thermoset composites without losing mechanical strength.
- *Mitigation of nanotoxicity:* Future studies must pivot from merely proving the functional efficacy of nanocomposites to conducting long-term, longitudinal *in-vivo* studies on the biological accumulation and degradation byproducts of nanomaterials to fully address genotoxicity concerns [21].
- *Roll-to-roll manufacturing for smart electronics:* For flexible electronics and hybrid polymer supercapacitors to become commercially viable, future engineering efforts must focus on translating batch-synthesis methods into continuous roll-to-roll manufacturing processes, ensuring uniform nanoparticle dispersion at high speeds.

CONCLUSIONS

This state-of-the-art review critically evaluated the paradigm shift from static, conventional materials to highly engineered, dynamic advanced polymer systems. Rather than merely offering incremental improvements, targeted material classifications—such as bio-inspired architectures, nanocomposites, and intrinsically conducting polymers—fundamentally redefine the operational limits of structural and functional engineering.

The critical analysis of self-healing systems revealed that while autonomic microencapsulation provides robust initial repair, the field must overcome localized volume limitations and reduced baseline matrix strength to achieve multi-cycle reliability. Simultaneously, the evaluation of sustainable bio-composites demonstrated that the transition to renewable matrices (such as PLA, PCL, and PHA) and natural fiber reinforcements is a mandatory ecological step, yet it introduces significant engineering trade-offs regarding interfacial adhesion, thermal stability, and moisture absorption.

Ultimately, the successful deployment of these materials across biomedical, aerospace, and electronic applications is not limited by theoretical potential, but by practical commercialization barriers. By addressing the identified research gaps—specifically concerning scalable manufacturing, nanotoxicity, and standardized testing protocols—future multidisciplinary innovations will fully unlock the transformative capabilities of advanced polymer materials across global industries.

Declaration of interest

Authors should reveal any possible conflict of interest in their submitted manuscripts. A competing interest exists when professional judgment concerning the validity of work is influenced by a secondary interest, such as financial gain. The author(s) declare(s) that there is no conflict of interest regarding the publication of this manuscript.

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The acknowledgements come at the end of an article after the conclusions and before the notes and references.

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