Sustainable Smart Polymer Composite Materials: A Comprehensive Review

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Abstract. This review provides a thorough analysis of the progress made in smart polymer composite materials, which have recently been seen as potential game-changers in areas such as construction, aerospace, biomedical engineering, and energy. This article emphasizes the distinctive characteristics of these materials, including their responsiveness to stimuli like temperature, light, and pressure, and their potential uses in different industries. This paper also examines the difficulties and restrictions associated with the creation and utilization of smart polymer composite materials. This review seeks to provide a thorough understanding of smart polymer composite materials and their potential to offer innovative solutions for a variety of applications.

Keyword. Advanced engineering, Composite technology, Cutting-edge, Futuristic materials, Polymer composites, Smart materials

1 Introduction

The global polymer composite market is anticipated to expand rapidly in the near future, propelled by various factors, including the rising demand from the transportation and aerospace industries [1]. In 2020, the market size was estimated to be USD 73.56 billion and is projected to reach USD 102.79 billion by 2028, increasing at a CAGR of 4.5% [2]. The use of polymer composites in the transportation sector is anticipated to expand at a CAGR of 7.2% from 2020 to 2027, while the aerospace industry is projected to be the main driver of the polymer composite market with an estimated CAGR of 5.9% from 2020 to 2027 [3]. The construction sector is also anticipated to make a substantial contribution, with an estimated compound annual growth rate of 6.7% from 2020 to 2027. The Asia-Pacific region is projected to account for 42.3% of the polymer composite market in 2020. These figures demonstrate the increasing potential of polymer composites, including smart polymer composites, to revolutionize multiple industries around the world [4].

Polymer composites, including smart polymer composites, are essential in many industries due to their durability, lightweight, cost-efficiency, versatility, and eco-friendly characteristics [5]. Polymer composites are renowned for their strength and durability, making them suitable for use in demanding applications, such as aerospace and transportation. Additionally, they are lighter than traditional materials, a key factor for lightweight structures and vehicles. Furthermore, polymer composites can be produced more quickly and in larger amounts, making them more economical than traditional materials. Their versatility makes them suitable for a variety of uses, and many are made from renewable resources and are recyclable, making them eco-friendly. Smart polymer composites go a step further by reacting to environmental stimuli such as temperature, humidity, or pressure fluctuations, leading to improved performance and greater efficiency [6]. In general, the utilization of polymer composites, including smart polymer composites, has the potential to revolutionize a variety of industries and provide lighter, stronger, and more economical materials.

Although there is increasing interest in polymer composites, there is a dearth of thorough research on the capacity of smart polymer composites to revolutionize various industries. This research seeks to bridge this gap by offering a thorough overview of the current status of smart polymer composite materials and their potential to revolutionize the world. The field of smart polymer composite materials is constantly changing, and it is essential to assess the current state of the art to gain a comprehensive understanding of its potential and restrictions. In the last few years, the capacity of these materials to revolutionize industries like transportation, aerospace, and construction has become more and more evident. Despite this, the widespread use of smart polymer composites is impeded by a number of challenges and restrictions. To progress further in this field, it is essential

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to recognize these challenges and offer suggestions for future research and development. By conducting a thorough review and assessment of the current state-of-the-art, it is possible to create a platform for the ongoing development and progress of smart polymer composite materials.

2 Current State of the Art

In recent years, the current state-of-the-art smart polymer composite materials have been widely recognized for their various exceptional properties. Smart polymer composites are materials that can react to environmental stimuli like temperature, humidity, or pressure fluctuations and display changes in their mechanical, electrical, or optical properties [7]. The capacity to react to environmental stimuli offers numerous potential advantages, including enhanced performance, enhanced efficiency, and self-healing capabilities. Examples of the most renowned smart polymer composites include shape-memory, conductive, and self-healing polymers. Shape memory polymers can revert to their original form after being deformed, while conductive polymers can conduct electricity, making them useful for applications like sensors and actuators. Self-healing polymers are able to fix damage caused by external factors such as cracks or fractures, thus increasing the material's lifespan [8].

Smart polymer composites have already been employed in a variety of industries, including aerospace, transportation, and construction [9]. In the aerospace industry, they have been utilized to make lightweight and resilient structural components, while in the transportation industry, they have been employed to manufacture fuel-efficient and lightweight vehicles. In the construction sector, they have been employed to create self-healing concrete and structural materials with enhanced durability. In general, the current state-of-the-art smart polymer composite materials are a rapidly expanding field with great potential for use in a variety of industries. Despite this potential, many obstacles still need to be addressed, including the need for further research and development, enhanced processing techniques, and a better comprehension of their characteristics and behavior.

3 Types of Smart Polymer Composites

3.1 Shape Memory Polymers

Shape memory polymers (SMPs) are intelligent polymer composites that can revert to their original form after being subjected to distortion. These materials are activated by fluctuations in temperature, humidity, or pressure, and their capacity to return to their original form is due to a transition temperature or pressure, which determines the temperature or pressure at which the material shifts from a pliable, malleable state to a rigid, shape-maintaining state. SMPs are usually created by combining a polymer with a shape-memory material, such as a shape-memory polymer or shape-memory alloy [10]. The shape memory agent is responsible for enabling the material to revert back to its original shape, while the polymer provides the necessary mechanical strength. The outcome has distinctive characteristics, such as the capacity to be formed into a desired shape, maintain this shape at high temperatures or pressures, and revert to the original shape when the temperature or pressure decreases. Table 1 outlines the characteristics of shape memory polymers.

The potential uses of SMPs are varied, including medical instruments like stents and catheters, which can be inserted into the body in a flexible state and then revert to their original shape to fulfill their purpose [11]. SMPs have been employed in the aerospace sector to manufacture lightweight and resilient structural components, and in the transportation sector to make fuel-efficient and lightweight vehicles. There are a variety of ways to regulate the transition temperature or pressure of SMPs, such as employing different polymers or shape memory agents, adding plasticizers, and utilizing cross-linking agents. Despite this progress, there are still numerous obstacles to be addressed in the development of SMPs, including the need for additional research and development, enhanced processing techniques, and a better comprehension of their characteristics and behavior. In conclusion, shape-memory polymers are a promising type of material with distinctive characteristics and potential applications in a variety of industries. The capacity to return to its original form after being subjected to distortion offers numerous advantages, and the possibility for further growth and enhancement makes SMPs a field with immense potential for future exploration and invention [12]. Figure 1 illustrates the different kinds of smart polymers (SMPs).

Table 1. Shape memory polymer properties.

Shape memory polymers	Properties
Polyurethane	High thermal stability, good recovery force and deformation, good thermal and mechanical stability
Polycaprolactone	Good shape memory properties, biodegradable and biocompatible, good mechanical properties
Polyvinyl alcohol	Good shape memory properties, hydrophilic and biocompatible, low melting temperature
Polyethylene	High shape recovery rate, good dimensional stability, high resistance to oxidation and UV

Table 2. Conductive polymer properties.

Conductive polymers	Electrical Conductivity (S/cm)	Other Properties
Polyaniline	10^{-3} to 10^{-1}	High mechanical strength, good stability and processability, good transparency in the doped form
Polypyrrole	10^{-2} to 10^{1}	Good stability and processability, good thermal stability, good transparency in the doped form
Polythiophene	10^{-3} to 10^{-1}	Good thermal stability, good stability and processability, good transparency in the doped form
Polyacetylene	10^{3} to 10^{5}	High electrical conductivity, good processability, good stability

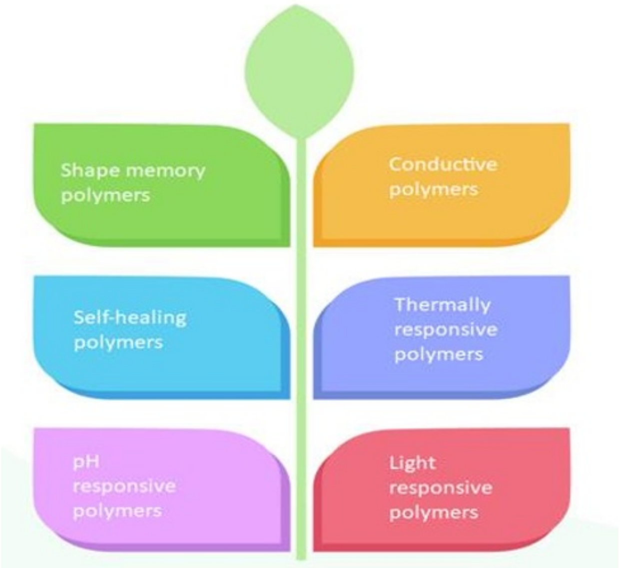

Fig. 1. Types of smart polymers.

3.2 Conductive Polymers

Conductive polymers are a type of polymer that can be used to produce electricity. They are produced by incorporating conductive fillers, such as metals or carbon-based materials, into a polymer matrix, thereby increasing the electrical conductivity of the material [13]. The electrical conductivity of conductive polymers can vary from 10-3 to 103 S/cm, depending on the particular material and how it is prepared [14]. For instance, polyaniline, one of the most renowned conductive polymers, has a conductivity range of 10-3 to 10-1 S/cm [15]. The electrical conductivity of these materials is much lower than that of conventional conductors like copper or silver, yet is adequate for many uses, including electronics and energy storage. Table 2 outlines the characteristics of conductive polymers.

Conductive polymers are extremely versatile and have a multitude of uses, including in electronic devices such as displays, batteries, and sensors [16]. These materials can be processed into various forms, such as films, fibers, and composites, and can be tailored to suit the particular needs of a given application. In terms of durability, conductive polymers are relatively stable, yet they can be impacted by environmental elements such as temperature, humidity, and light exposure. Nevertheless, this can be addressed by utilizing suitable encapsulation techniques or by adding protective layers to the material. Conductive polymers are a promising group of materials that possess exceptional electrical conductivity and versatility. The capacity to incorporate conductive fillers into a polymer matrix offers a variety of possible applications, and the potential for further advancement and enhancement makes conductive polymers an area with immense potential for future exploration and invention.

3.3 Self-Healing Polymers

Self-healing polymers are materials that are able to mend themselves after being damaged. This characteristic is accomplished through the inclusion of a self-healing mechanism, like the presence of microencapsulated healing agents or the formation of covalent bonds between polymer chains [17]. Figure 2 illustrates the features of self-healing polymers.

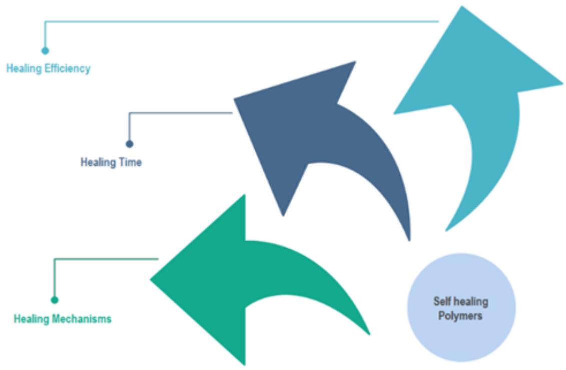

Fig. 2. Characteristics of self-healing polymers.

Depending on the material and the method of preparation, self-healing polymers can reach healing efficiencies of up to 95% [18]. The healing efficiency is defined as the ratio of the mechanical strength regained after the healing process to the original strength. The curing time of self-healing polymers can differ greatly depending on the particular material and method of manufacture. For instance, some self-healing polymers can be fully restored in a matter of minutes, while others may take several hours or even days to complete the healing process. Self-healing in polymers can be accomplished through various methods, such as microencapsulation, covalent bond formation, and supramolecular interactions. The particular mechanism employed depends on the desired characteristics and the particular use of the self-healing polymer. Figure 3 illustrates the categorization of different self-healing polymers. SMP is a field with immense potential for future exploration and invention [12]. Figure 1 illustrates the different kinds of smart polymers.

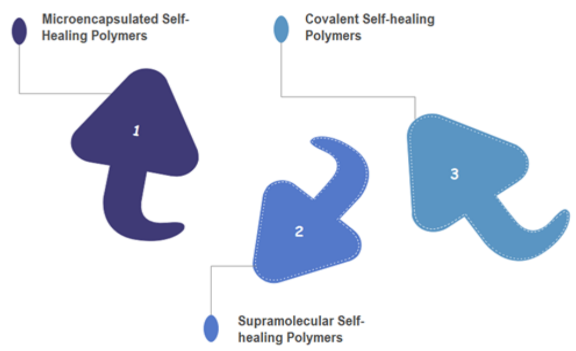

Fig. 3. Classifications of self-healing polymers.

One of the most extensively researched self-healing polymers is the microencapsulated self-healing polymer, which uses microencapsulated healing agents dispersed throughout a polymer matrix [19]. When damage occurs, the capsules break open and release agents that promote healing, which then diffuse and act to fix the damage. Supramolecular Self-healing Polymers are another kind of self-healing polymer that utilizes supramolecular interactions to accomplish self-healing. In these materials, the polymer chains are designed to self-organize into specific configurations that enable them to reconnect when damage occurs. Covalent self-healing polymers gain their self-healing properties through chemical reactions. In these materials, when damage occurs ,the polymer chains interact with each other, forming covalent bonds that mend the damage [20].

3.4 Thermally Responsive Polymers

Thermally responsive polymers are a type of intelligent materials that alter their physical characteristics in response to temperature fluctuations [21]. Examples of thermally responsive polymers include poly(N-isopropylacrylamide) (PNIPAM), poly (ethylene oxide) (PEO), and poly (propylene oxide) (PPO) [22]. PNIPAM is a temperature-sensitive polymer that experiences a volume phase transition at a lower critical solution temperature (LCST) of around 32-34°C [23]. This transformation results in considerable alterations in the hydrophobicity and mechanical characteristics of the polymer. For instance, when temperatures are below the LCST, PNIPAM is hydrophobic and has a low modulus, while when temperatures are above the LCST, it is hydrophilic and has a high modulus. PEO is a temperature-sensitive polymer with a glass transition temperature (Tg) of roughly -120°C [24]. This transformation results in considerable alterations in the mechanical characteristics of the polymer, including its glass transition temperature and mechanical strength. PPO is a temperature-sensitive polymer that has a glass transition temperature (Tg) of roughly -70°C. This transformation results in considerable alterations in the mechanical characteristics of the polymer, including its glass transition temperature and mechanical strength. Generally, thermally responsive polymers are very beneficial in a variety of applications, including drug delivery, cell culture, and tissue engineering. By incorporating these polymers into different materials, scientists and engineers can create materials that can alter their properties in response to temperature fluctuations. Table 3 outlines the characteristics of thermally responsive polymers.

3.5 pH Responsive Polymers

pH-responsive polymers are materials that alter their characteristics in reaction to fluctuations in the pH of the surrounding environment. These polymers have gained significant interest in recent times due to their potential uses in various areas such as drug delivery, bio-separation, and tissue engineering [25]. pH-responsive polymers can alter their characteristics in response to pH fluctuations through a variety of mechanisms, including ionization of acidic or basic groups, protonation/deprotonation of amine or carboxylic groups, or modifications in the charge density of the polymer backbone. Several pH-responsive polymers have been developed, such as poly (acrylic acid) (PAA), poly(2-vinylpyridine) (PVP), poly(ethyleneimine) (PEI), and poly(amidoamine) (PAMAM) dendrimers [26]. The lower critical solution temperature (LCST) or pKa value of a pH-responsive polymer is a critical factor that hydrophobic state when the pH falls below 4.7. PVP has a pKa of 5.5 and changes from a hydrophilic to a hydrophobic state when the pH falls below 5.5. [27]. The pH sensitivity of a polymer can be affected by its molecular weight, concentration, and the presence of other chemical groups. pH-sensitive polymers have numerous uses, including drug delivery, bio-separation, and tissue engineering. As an example, pH-responsive

Table 3. Properties of thermally responsive polymers.

Polymer	LCST/Tg (°C)	Transition	Properties Change
PNIPAM	32-34	Volume	Hydrophobicity, Modulus
PEO	-120	Glass	Glass Transition Temperature, Mechanical Strength
PPO	-70	Glass	Glass Transition Temperature, Mechanical Strength

Table 4. Mechanisms of pH responsive polymers.

Polymer	Mechanism	pKa/LCST	Responsiveness	Applications
Poly(acrylic acid) (PAA)	Ionization	4.7	Hydrophilic to hydrophobic transition below pH 4.7	Drug delivery, bio-separation
Poly(2-vinylpyridine) (PVP)	Protonation	5.5	Hydrophilic to hydrophobic transition below pH 5.5	Drug delivery, bio-separation
Poly(ethyleneimine) (PEI)	Protonation	10.0	Hydrophilic to hydrophobic transition below pH 10.0	Drug delivery, bio-separation
Poly(amidoamine) (PAMAM) dendrimers	Protonation	7.0-8.0	Hydrophilic to hydrophobic transition below pH 7.0-8.0	Drug delivery, bio-separation

polymers can be employed as carriers for drugs that must be released in response to alterations in the body's pH. They can also be employed in separation processes to eliminate impurities based on the pH-induced changes in solubility. The characteristics of the pH-responsive polymer are outlined in Table 4.

3.6 Light Responsive Polymers

Light-responsive polymers, also referred to as photoresponsive polymers, are a type of material that alters its characteristics when exposed to light [28]. These materials have numerous uses in the realms of optics, electronics, and biomedicine. The refractive index of a light-responsive polymer can be modified by exposure to light, leading to alterations in the transmission and reflection of the light. Generally, the alteration in the refractive index is between 0.01 and 0.1. Light-responsive polymers can undergo various shape transformations when exposed to light, such as shrinking, swelling, or bending [29]. Light exposure can alter the conductivity of light-responsive polymers, making them useful for electronics and optoelectronics applications. Depending on the material and intensity of the light, the change in conductivity can vary from several orders of magnitude to several hundred percent. Light-sensitive polymers can display alterations in their optical characteristics, including absorption, fluorescence, and birefringence, when exposed to light. These modifications can be employed in applications such as optical data storage, optical switching, and optical sensing [30]. The temperature and viscosity of light-responsive polymers can be altered by exposure to light, altering their thermal properties. These modifications can be beneficial for applications like energy conversion, thermal management, and biomedical engineering [31]. Table 5 outlines the characteristics of light responsive polymers.

4 Potential of Smart Polymer Composite Materials in Various Industries

4.1 Transportation applications

Smart polymer composites are a type of material made up of a polymer matrix and smart fillers or particles that can react to external stimuli like temperature, light, or pH [32]. By combining a flexible polymer matrix with responsive fillers or particles, materials with adjustable and distinctive characteristics can be produced. Smart polymer composites have the potential to revolutionize the transportation industry due to their capacity to offer enhanced performance characteristics [33]. Smart polymer composites, with their lightweight structure and high strength and stiffness, are perfect for use in lightweight vehicles, aircraft, and marine vessels. Smart polymer composites can be developed to adjust to fluctuating loads and conditions, thereby delivering improved performance in both dynamic and extreme situations [34].

Smart polymer composites can be engineered to possess shape-memory properties, enabling them to revert back to their original form after being exposed to external loads or distortions. Smart polymer composites can be engineered to transform ambient energy from sources like light, heat, or vibration into electrical energy, offering a renewable and self-powered alternative to conventional energy sources [35]. Smart polymer composites can be engineered to incorporate multiple functionalities, such as self-healing, self-lubrication, and self-sensing, into a single material. These special characteristics make smart polymer composites desirable for a variety of transportation uses, including lightweight and energy-efficient vehicle structures, self-healing and self-sensing

Table 5. Properties of light responsive polymers.

Polymer	Property altered by light exposure
Spiropyrans	Refractive index, optical absorption
Azobenzene polymers	Refractive index, optical absorption, shape
Polymer dispersed liquid crystals (PDLCs)	Optical transmittance, refractive index
Hydrogels	Shape, swelling, mechanical properties
Liquid crystal polymers (LCPs)	Optical birefringence, mechanical properties

composites for aerospace and marine vessels, and multifunctional materials for advanced transportation systems.

4.2 Aerospace Applications

Smart polymer composites are a type of material made up of a polymer matrix and smart fillers or particles that can react to external stimuli like temperature, light, or pH [36]. These materials could revolutionize the aerospace industry by offering enhanced performance characteristics, such as smart polymer composites for aerospace applications, lightweight and fuel-efficient aircraft structures, repair of minor cracks and damage in aircraft structures, deployment of wing flaps and other aerodynamic devices, and advanced aerospace systems such as self-sensing systems for structural health monitoring [37].

4.3 Construction Applications

Smart polymer composites are a type of material made up of a polymer matrix and smart fillers or particles that can react to external stimuli, such as temperature, light, or pH [38]. These materials could revolutionize the construction industry by offering enhanced performance characteristics. Smart polymer composites can be engineered to adjust to fluctuating loads and conditions, offering improved performance in dynamic and extreme circumstances, making them suitable for use in high-performance and disaster-resistant structures [39]. Smart polymer composites can be engineered to possess shape-memory properties, enabling them to revert back to their original form after being exposed to external loads or distortions. Smart polymer composites can be engineered to self-repair in the event of damage, thereby reducing maintenance and repair costs and extending the life of the structure. Smart polymer composites can be engineered to regulate temperature and thermal insulation, thereby reducing energy costs and creating a comfortable living environment. It can be engineered to incorporate multiple functionalities like self-healing, self-lubrication, and self-sensing into a single material [40]. Smart polymer composites have a variety of applications in the construction industry, such as the following. (i) Structures with high performance and that are resistant to disasters; (ii) composites with self-healing and shape-memory capabilities for the repair and upkeep of building structures; (iii) insulation materials that are smart for energy-efficient buildings; and (iv) multifunctional composites for advanced building systems, such as self-sensing systems for structural health monitoring.

5 Challenges and Opportunities

Smart polymer composites face the challenge of being compatible with the polymer matrices. Incongruous fillers can lead to phase separation and deterioration of composite materials, thus diminishing their overall performance [41]. Despite advances in the laboratory, scaling up and commercializing smart polymer composites is still a challenge. This is due to the expensive cost of production and the limited availability of smart fillers, as well as the requirement for dependable and efficient production processes. Smart polymer composites can experience a decline in performance over time, which can be caused by environmental elements like UV light and humidity, as well as the natural aging of the material [42]. Figure 4 illustrates the difficulties associated with smart polymer composites.

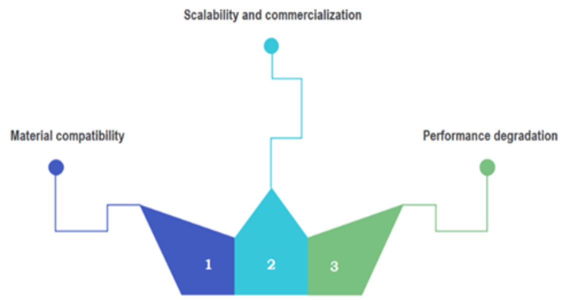

Fig. 4. Challenges for smart polymer composites.

Despite the difficulties, there are a number of opportunities and potential future developments in the area of smart polymer composite materials. The creation of new smart fillers with enhanced performance, stability, and scalability is essential for the progress of this field [43]. Enhancing processing techniques for the manufacture of smart polymer composites, such as 3D printing, is essential for their commercialization and scalability. It will be essential for the advancement of this field to create new applications for smart polymer composites, such as in energy storage, biomedicine, and wearable technologies. Ongoing progress and enhancement of smart polymer composites necessitates collaborative interdisciplinary research that involves materials science, engineering, physics, chemistry, and biology [44]. Figure 5 illustrates the potential of smart polymer composites for future growth.

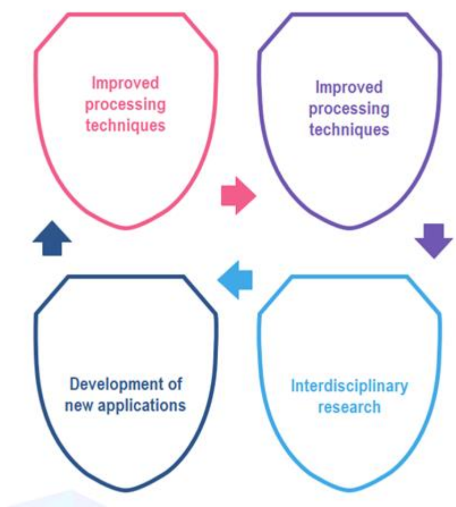

Fig. 5. Opportunities for smart polymer composites.

6 Conclusion

Smart polymer composites are a rapidly expanding area of research, with numerous potential applications that are exciting to explore. Smart polymer composites, made up of a polymer matrix and responsive fillers or particles that can react to environmental factors like temperature, light, and pH, have the potential to revolutionize industries like construction, aerospace, and transportation due to their ability to provide adjustable properties that can satisfy the rigorous demands of these fields. Despite this, there are still many challenges in this field, including material compatibility, scalability, and performance deterioration. Despite the difficulties, there are numerous possibilities and future directions in the field, including the creation of new intelligent fillers, enhanced processing methods, and novel applications. Interdisciplinary research is essential for the ongoing expansion and advancement of this area. In conclusion, the field of smart polymer composites has the potential to revolutionize the world, but further research and development is needed to unlock its full potential.

Availability of data and materials
All the data were included within the article.

Competing interest
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References

1. J. Zhang, G. Lin, U.Vaidya, H.Wang, Past present and future prospective of global carbon fibre composite developments and applications, Composites Part B: Engineering, (2022): 110463
2. M.E. Hoque, A.M. Rayhan, S.I. Shaily, Natural fiber-based green composites: processing properties and biomedical applications, Applied Science and Engineering Progress, **14**, 4 (2021): 689-718
3. V. Chauhan, T. Kärki, J. Varis, Review of natural fiber-reinforced engineering plastic composites their applications in the transportation sector and processing techniques, Journal of Thermoplastic Composite Materials, **35**, 8 (2022): 1169-1209
4. C.I. Idumah, Recent advancements in self-healing polymers polymer blends and nanocomposites, Polymers and Polymer Composites, **29**, 4 (2021): 246-258
5. P. Jagadeesh, M. Puttegowda, S.M. Rangappa, S. Siengchin, Role of polymer composites in railway sector: an overview, Applied Science And Engineering Progress, **15**, 2 (2022): 5745-5745
6. R.C. Verpaalen, T. Engels, A.P. Schenning, M.G. Debije, Stimuli-responsive shape changing commodity polymer composites and bilayers, ACS Applied Materials and Interfaces, **12**, 35 (2020): 38829-38844
7. X. Bi, R. Huang, 3d printing of natural fiber and composites: a state-of-the-art review, Materials and Design, (2020): 111065
8. G. Ehrmann, A. Ehrmann, 3d printing of shape memory polymers, Journal of Applied Polymer Science, **138**, 34 (2021): 50847
9. I.O. Oladele, T.F. Omotosho, A.A. Adediran, Polymer - based composites: an indispensable material for present and future applications, International Journal of Polymer Science, (2020): 1-12
10. M.C. De Souza, I. Moroz, I. Cesarino, A.L. Leão, M. Jawaid, O.A.T. Dias, A review of natural fibers reinforced composites for railroad applications, Applied Science and Engineering Progress, **15**, 2 (2022): 5800-5800
11. Z. Wang, H. Jiang, G. Wu, Y. Li, T. Zhang, Y. Zhang, X. Wang, Shape-programmable three-dimensional microfluidic structures, ACS Applied Materials and Interfaces, **14**, 13 (2022): 15599-15607
12. N. Zheng, Y. Xu, Q. Zhao, T. Xie, Dynamic covalent polymer networks: a molecular platform for designing functions beyond chemical recycling and self-healing, Chemical Reviews, **121**, 3 (2021): 1716-1745
13. N. Maity, A. Dawn, Conducting polymer grafting: recent and key developments, Polymers, **12**, 3 (2020): 709
14. V. Dogra, C. Kishore, A. Verma, A.K. Rana, A. Gaur, Fabrication and experimental testing of hybrid composite material having biodegradable bagasse fiber in a modified epoxy resin: evaluation of mechanical and morphological behavior, Applied Science and Engineering Progress, **14**, 4 (2021): 661-667
15. A.M. Youssef, M.S. Hasanin, M.E. Abd El-Aziz, G.M. Turky, Conducting chitosan / hydroxylethyl cellulose polyaniline bionanocomposites hydrogel based on graphene oxide doped with Ag-Nps, International Journal of Biological Macromolecules, **167** (2021): 1435-1444
16. X.X. Wang, G.F. Yu, J. Zhang, M. Yu, S. Ramakrishna, Y.Z. Long, Conductive polymer ultrafine fibers via electrospinning: preparation, Physical Properties and Applications, Progress In Materials Science, **115** (2021): 100704

17. P.S. Tan, A.A. Somashekar, P. Casari, D. Bhattacharyya, Healing efficiency characterization of self-repairing polymer composites based on damage continuum mechanics, Composite Structures, **208** (2019): 367-376
18. J. Xu, X. Wang, X. Zhang, Y. Zhang, Z. Yang, S. Li, T. Wang, Room-temperature self-healing supramolecular polyurethanes based on the synergistic strengthening of biomimetic hierarchical hydrogen-bonding interactions and coordination bonds, Chemical Engineering Journal, **451** (2023):138673
19. A.N. Santos, D.J.D. Santos, D.J. Carastan, Microencapsulation of reactive isocyanates for application in self-healing materials: a review, Journal of Microencapsulation, **38**, 5 (2021): 338-356
20. Z. Li, R. Yu, B. Guo, Shape-memory and self-healing polymers based on dynamic covalent bonds and dynamic noncovalent interactions: synthesis mechanism and application, ACS Applied Bio Materials, **4**, 8 (2021): 5926-5943
21. S.M. Rangappa, S. Siengchin, Natural fibers as perspective materials, Applied Science and Engineering Progress, **11**, 4 (2018)
22. J. He, D. Lin, Y. Chen, L. Zhang, J. Tan, One - step preparation of thermos - responsive poly (N - Isopropylacrylamide) - based block copolymer nanoparticles by aqueous photoinitiated polymerization - induced self - assembly, Macromolecular Rapid Communications, **42**, 18 (2021): 2100201
23. A. Okudan, A. Altay, Investigation of the effects of different hydrophilic and hydrophobic comonomers on the volume phase transition temperatures and thermal properties of N-Isopropylacrylamide-based hydrogels, International Journal of Polymer Science, (2019): 1-12
24. I. Łukaszewska, A. Bukowczan, E. Hebda, K.N. Raftopoulos, K. Pielichowski, Calorimetric study of hydrated poloxamer - based polyurethanes - thermoresponsive transition and peculiar antiplasticization.
25. H. Chi, Z. Xu, T. Zhang, X. Li, Z. Wu, Y. Zhao, Randomly heterogeneous oleophobic/ph-responsive polymer coatings with reversible wettability transition for multifunctional fabrics and controllable oil – water separation, Journal of Colloid and Interface Science, **594** (2021): 122-130
26. N. Deirram, C. Zhang, S.S. Kermaniyan, A.P. Johnston, G.K. Such, pH - responsive polymer nanoparticles for drug delivery, Macromolecular Rapid Communications, **40**, 10 (2019): 1800917
27. S.C. Ko, S.H. Lee, Protocatechuic aldehyde inhibits α – msh - induced melanogenesis in b16f10 melanoma cells via pka / creb-associated mitf downregulation, International Journal of Molecular Sciences, **22**, 8 (2021): 3861.
28. A. Romano, I. Roppolo, E. Rossegger, S. Schlögl, M. Sangermano, Recent trends in applying ortho - nitrobenzyl esters for the design of photo - responsive polymer networks, Materials, **13**, 12 (2020): 2777
29. E. Pantuso, G. De Filpo, F.P. Nicoletta, Light-Responsive Polymer Membranes, Advanced Optical Materials, **7**, 16 (2019): 1900252
30. P. Talianov, L.I. Fatkhutdinova, A.S. Timin, V.A. Milichko, M.V. Zyuzin, Adaptive nanoparticle-polymer complexes as optical elements: design and application in nanophotonics and nanomedicine, Laser and Photonics Reviews, **15**, 9 (2021): 2000421
31. B. Sana, A. Finne – Wistrand, D. Pappalardo, Recent development in near infrared light - responsive polymeric materials for smart drug - delivery systems, Materials Today Chemistry, **25** (2022): 100963
32. K. Umar, A.A. Yaqoob, M.N.M. Ibrahim, T. Parveen, M.T.U. Safian, Environmental applications of smart polymer composites in smart polymer nanocomposites, Woodhead Publishing, (20221): 295 - 312
33. D.M. Correia, L.C. Fernandes, P.M. Martins, C. García - Astrain, C.M. Costa, J. Reguera, S. Lanceros - Méndez, Ionic liquid – polymer composites: a new platform for multifunctional applications, Advanced Functional Materials, **30**, 24 (2020): 1909736.
34. C. Zhao, X. Jia, K. Shu, C. Yu, G.G. Wallace, C. Wang, Conducting polymer composites for unconventional solid - state supercapacitors, Journal of Materials Chemistry A, **8**, 9 (2020): 4677-4699
35. H. Moustafa, A.M. Youssef, N.A. Darwish, A.I. Abou - Kandil, Eco - friendly polymer composites for green packaging: future vision and challenges, Composites Part B: Engineering, **172** (2019): 16-25
36. F. Li, Y. Liu and J. Leng, Progress of shape memory polymers and their composites in aerospace applications, Smart Materials and Structures, **28**, 10 (2019): 103003
37. W.S. Chow, Z.A. Mohd Ishak, Smart polymer nanocomposites: a review, Express Polymer Letters, **14**, 5 (2020)
38. M.Y. Khalid, Z.U. Arif, R. Noroozi, A. Zolfagharian, M. Bodaghi, 4d printing of shape memory polymer composites: a review on fabrication techniques, applications and future perspectives, Journal of Manufacturing Processes, **81** (2022): 759-797
39. A. Mirabedini, A. Ang, M. Nikzad, B. Fox, K.T. Lau, N. Hameed, Evolving strategies for producing multiscale graphene - enhanced fiber - reinforced polymer composites for smart structural applications, Advanced Science, **7**, 11 (2020): 1903501
40. H.N. Kim, S. Yang, Responsive smart windows from nanoparticle – polymer composites, Advanced Functional Materials, **30**, 2 (2020): 1902597

41. S.M. Rangappa, S. Siengchin, S. Fischer, Sustainable natural fibers for environmental - friendly materials, Applied Science and Engineering Progress, **15**, 4 (2022): 5802-5802
42. H. Moustafa, A.M. Youssef, N.A. Darwish, A.I. Abou - Kandil, Eco - friendly polymer composites for green packaging: future vision and challenges, Composites Part B: Engineering, **172** (2019): 16-25
43. S. Malekmohammadi, N. Sedghi Aminabad, A. Sabzi, A. Zarebkohan, M. Razavi, M. Vosough, H. Maleki, smart and biomimetic 3d and 4d printed composite hydrogels: opportunities for different biomedical applications, Biomedicines, **9**, 11 (2011): 1537
44. M.Y. Khalid, Z.U. Arif, R. Noroozi, A. Zolfagharian, M. Bodaghi, 4d printing of shape memory polymer composites: a review on fabrication techniques applications and future perspectives, Journal of Manufacturing Processes, **81** (2022): 759-797