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REVIEW ARTICLE

Recent Advancements in Biomaterial Applications: A Review

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Abstract

Biomaterials have been developed as a transformative tool in various applications of the modern world. Biomaterials have advanced with time and applications, from structural implants to replacing biological functions in the human body, and so on. This review article provides a detailed examination of the diverse categories of biomaterials, including natural, synthetic, and composite materials. Recent unique properties, advantages, and challenges have been described in the article. Natural biomaterials are known for their excellent biocompatibility, biodegradability, and versatility in healthcare applications. Those are used in different applications such as wound healing, drug delivery, and tissue scaffolding. Synthetic biomaterials are critical for load-bearing applications. Composite biomaterials combine the strengths of individual materials to offer superior mechanical performance and biological functionality. The field of biomaterials is fast-growing sector to meet the demand for personalized medical treatment. Future research will focus on the development of multifunctional biomaterials that integrate healthcare solutions and daily life needs. This review highlights recent advancements, emerging trends, and future directions in biomaterial research that will help in shaping the next generation of biomedical innovations.

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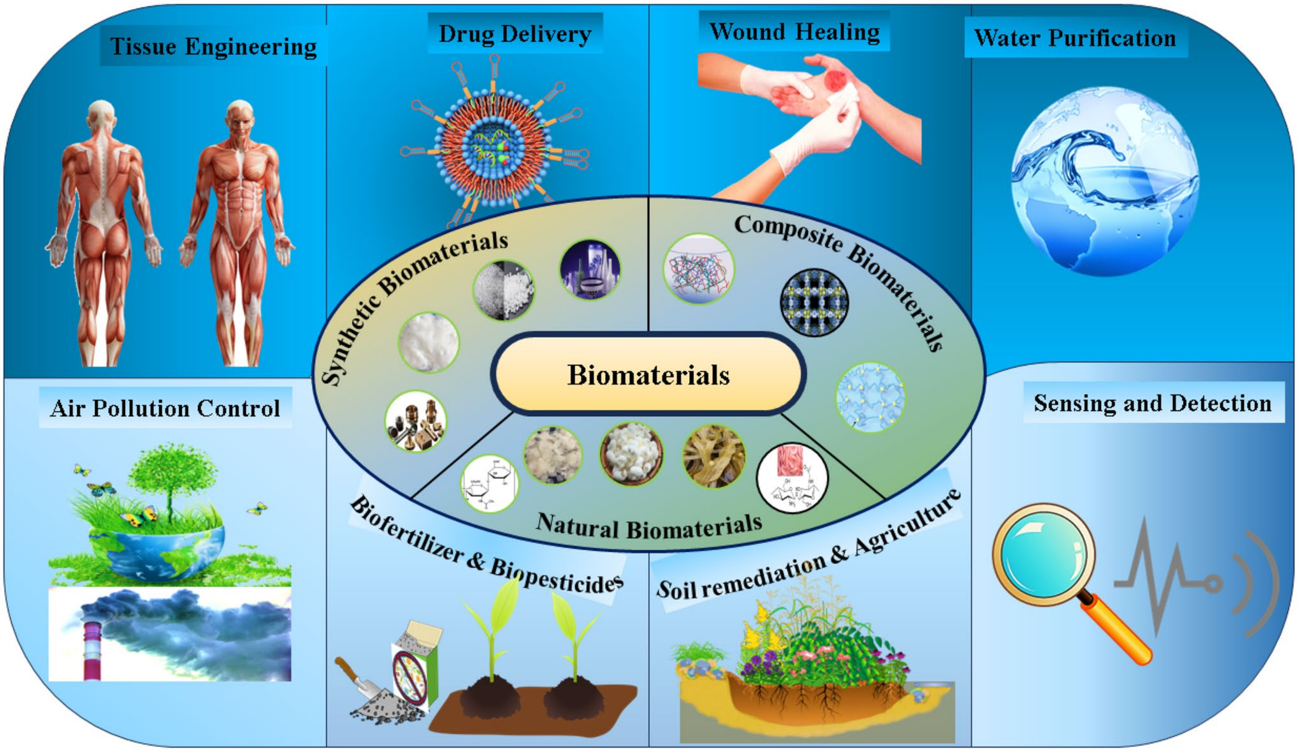
Graphical Abstract



Highlights

- *Comprehensive overview of biomaterials:* This review discusses natural, synthetic, and composite biomaterials, detailing their structures, properties, and biomedical applications.
- *Emphasis on biocompatibility and biodegradability:* Highlights the critical importance of these properties in the successful integration and functionality of biomaterials within biological systems.
- *Recent advancements in fabrication and surface modification:* Explores how techniques such as additive manufacturing and nanoscale surface modifications enhance the performance of biomaterials.
- *Applications across diverse sectors:* Describes how biomaterials are used in wound healing, drug delivery, implants, tissue engineering, packaging, pollution control, and more.
- *Challenges in mechanical strength and scalability:* Addresses limitations including low mechanical properties, high production costs, and short biological half-life, with proposed solutions.
- *Emergence of smart and multifunctional biomaterials:* Discusses the future direction toward bioinspired materials for real-time health monitoring and regenerative medicine.
- *Focus on sustainable and eco-friendly alternatives:* Considers the potential of biomaterials to replace synthetic plastics and reduce environmental impact.

Keywords Sustainable · Biomedical · Tissue engineering · Biocompatibility · Pollution control

Introduction

The term "biomaterial" has been defined in various ways over time, depending on the clinical context (Rahmati et al. 2020). It generally refers to any non-pharmaceutical material designed to support, enhance, restore, or replace the biological function of damaged tissues, organs, or other biological structures in the human body. Biomaterials are in continuous contact with the human body, including tissues, blood, and biological fluids, making biocompatibility a critical characteristic (Chelu and Musuc 2023a). More recent definitions emphasize the need for "adequate functionality" as a criterion for a material to be classified as a biomaterial (Arjunan et al. 2022). Biomaterials can be derived from natural sources (e.g., collagen, silk), synthetic sources (e.g., metals, ceramics, polymers), or composites (e.g., chitosan-gelatin composites) and are widely utilized in medical applications to repair, enhance, or replace damaged tissues or biological functions. The multidisciplinary field of biomaterials originated from physicians' efforts to address life-threatening medical challenges. This effort was later joined by researchers and engineers from fields such as medicine, tissue engineering, material science, clinical science, biology, and chemistry, who explored the concept of biocompatibility. Over time, the evolution of biomaterials has shifted from enhancing the structural properties of implants to innovations in bioactivity, soft tissue replacement, and, more recently, the regeneration of functional tissues (Zadpoor 2017). Current advancements focus on the functionality, resorption, and degradation of biomaterials. Assessing biomaterials based on their functionalities is crucial, particularly in light of recent advancements in fabrication techniques, such as additive manufacturing, material characterization, and tissue engineering (Arjunan et al. 2022). The functionality of a biomaterial is determined by its ability to perform a specific task and its intended application. In this evolving context, biomaterials are increasingly expected to serve as substrates or facilitate host tissue integration, rather than functioning as standalone devices (Soro et al. 2019). Biomaterials with immobilized bioactive ligands have been extensively developed and employed in tissue engineering and regenerative medicine to enhance functionality. Additionally, various physical and chemical methods have been applied to improve biomaterial performance, particularly at the material interface (Drobota et al. 2022).

The demand for biocompatible, biodegradable, and bioresorbable materials has surged significantly over the past decade. An ideal biomaterial is characterized as nonimmunogenic, biocompatible, and biodegradable, with the capability to be functionalized with bioactive proteins and chemicals. Among these, biodegradability stands out as one of the most critical properties. It is a common practice to modify biomaterial surfaces on a micro or nanoscale without altering the substrate's intrinsic properties. (Xiang et al. 2022; Abesekara and Chau 2022). Such surface modifications can alter the physical, chemical, and biological properties of the material, enhancing its functionality. These modifications also help improve cytocompatibility, antibacterial, antifouling, and surface hydrophobic properties, making biomaterials better suited for integration within the human body (Murphy et al. 2014). Due to their exceptional mechanical properties, including high strength, toughness, and fatigue resistance, as well as favorable chemical properties, metal-based biomaterials have been widely adopted as artificial implants in biomedical engineering (Hu et al. 2023). Some important properties of biomaterials are shown in Fig. 1.

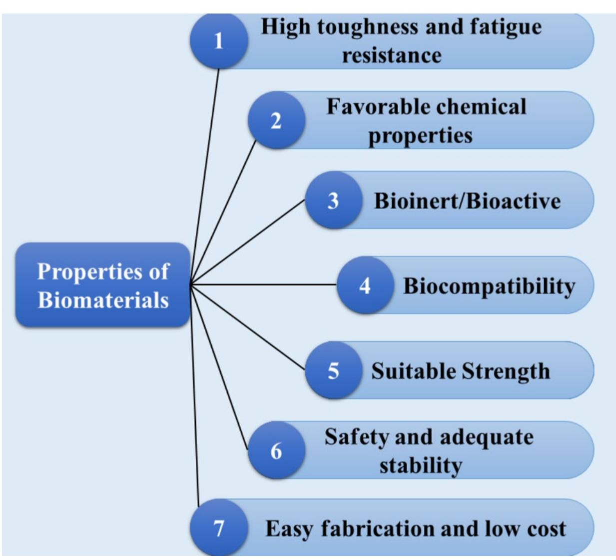


Fig. 1 Key properties of biomaterials

The study and advanced development of biomaterials have recently gained significant momentum, driven by their potential applications in the medical and healthcare fields. This interest stems from their role in drug delivery, tissue engineering, the medical device industry, and both permanent and temporary implants (Chelu and Musuc 2023a). Current research focuses on creating innovative and efficient bioactive materials to meet the demand for advanced applications, including regenerative medicine and theragnostic biomaterials with combined diagnostic, monitoring, and therapeutic capabilities. These developments aim to support the growing need for precise and personalized treatments (Sam et al. 2023).

Biomaterials, available in natural, synthetic, and composite forms, are widely utilized in medical applications due to their biocompatibility (Mateu-Sanz et al. 2024). Natural biomaterials, in particular, have shown great promise in healthcare applications and are expected to experience significant advancements in both research and commercialization within the biomedical sector. These materials have been extensively tested for applications such as drug delivery systems (e.g., oral drug delivery, mucoadhesive films, hydrogels, matrix tablets, aerogel microparticles), tissue engineering (e.g., skin scaffolds, dental tissue regeneration, bone grafts, hydrogel-based cartilage), wound healing (e.g., bandages, biosheets, sol-gel films, sponges, fish-skin grafts), and mechanical materials (Zimba et al. 2024; Sun et al. 2024). These advancements are expected to bring both scientific innovation and substantial commercial benefits to the biomedical industry.

Among synthetic biomaterials, metallic materials are predominantly used for load-bearing applications, including hard-tissue internal fixation devices such as orthopedic wires, screws, plates, scaffolds, and total joint replacements like knees and hips (Choi et al. 2023). Titanium (Ti), cobalt-chromium (Co–Cr), and stainless steel are the most commonly used metals in these applications due to their mechanical strength and durability (Bandyopadhyay et al. 2023). Polymers represent the most extensively utilized category of synthetic biomaterials due to their excellent compatibility. Advances in polymer chemistry have enabled the development of functional films for the dental industry, as well as custom dental sealants, drug carriers, and biodegradable scaffolds (Beilharz et al. 2024). Key properties of biomaterials are shown in Fig. 1. Ceramics are valued as reinforcing components in composite biomaterials due to their unique mechanical properties. Unlike metals and polymers, the strong bonds in ceramics make them resistant to plastic deformation (Arjunan et al. 2022). Composite biomaterials, combining ceramics with other materials, often take the form of particles or fibers embedded in a matrix material (Ikumapayi et al. 2023). Composite biomaterials are highly biocompatible and versatile for various biomedical applications. Their mechanical performance, particularly in replicating the properties of hard tissues like bone, often surpasses that of monolithic biomaterials. For instance, composites like hydroxyapatite-collagen exhibit superior biomechanical and tissue attachment properties compared to their components (Yu and Zhu 2024). This makes them ideal for applications requiring both structural integrity and biological functionality.

Though numerous studies have documented the different application fields of biomaterials, most of them have focused on a specific application area, such as drug delivery or wound healing, or water purification, etc. There is a negligible number of studies that have discussed diversified application fields of different biomaterials available in the current world. Despite the presence of several reviews on biomaterial applications, there is a gap that remains in comprehensively connecting the available types of biomaterials and their different fields of application. Hence, this review widens its focus, targeting different biomaterials (natural, synthetic, and composite) and advancements in their possible application fields. This review can be a useful supplement for future research focusing on biomaterial applications, as it is comprised of the information obtained from the current literature by comparing and evaluating the latest findings.

The literature for this study was gathered by doing a thorough search of scholarly databases (including Web of Science, Scopus, and PubMed) using keywords such as "biomaterials", "drug delivery", "tissue engineering", "air pollution", and "soil remediation", among others. Publications from 2015 to 2025 were emphasized to capture recent advances, though some older studies were included for contextual purposes. Furthermore, information from relevant patents was gathered to better comprehend technical advancements in biological applications. Sources that were in English were considered only. The gathered articles were screened for relevance to biomaterial types, application fields, and technological advancements. Data from research works and review articles were synthesized to provide detailed comparisons and to ensure adherence to the topics discussed in the discussion (Basak and Das 2025a).

This review paper complements previous studies related to biomaterials and provides a comprehensive overview of their application in fields like biomedical, agricultural, and environmental remediation. In this review, the application of biomaterials ranging from natural to synthetic and hybrid materials was thoroughly reviewed, and their suitability for different applications was also discussed. The challenges encountered by several biomaterials during manufacturing, application, and afterwards, up to their degradation, have also been discussed in detail. New ideas and future directions to expand their application areas are also discussed.

Future research will emphasize the development of next-generation bioinspired “smart” multifunctional biomaterials designed for health monitoring and the prevention of biological crises. A key aspect of biomaterial design and synthesis will involve using biopolymers and natural organisms as models or templates for creating multifunctional and active devices. Additionally, efforts to reduce production costs through the exploration of diverse biomaterial sources will help mitigate the economic and social impact of these innovations. This review aims to inspire fresh perspectives on the latest technologies associated with advanced biomedical applications of multifunctional biomaterials, including their classification based on their sources. The primary goal of this work is to highlight the innovative design and functional capabilities of this new generation of biomaterials.

Diversity of Biomaterials

A Schematic illustration of natural, synthetic, and composite biomaterials is shown in Fig. 2.

Natural Biomaterials

Naturally derived biomaterials have gained significant attention from scientists worldwide due to their diverse applications. These materials, which are sourced from the growth cycles of living organisms, offer a wide range of uses. Ideal natural biomaterials are nonimmunogenic, biocompatible, biodegradable, easy to produce, readily available, cost-effective, sterilizable, and renewable. Through evolution, nature has created materials with sophisticated properties, demonstrating excellent biocompatibility, biodegradability, mechanical, physical, and chemical properties, biological

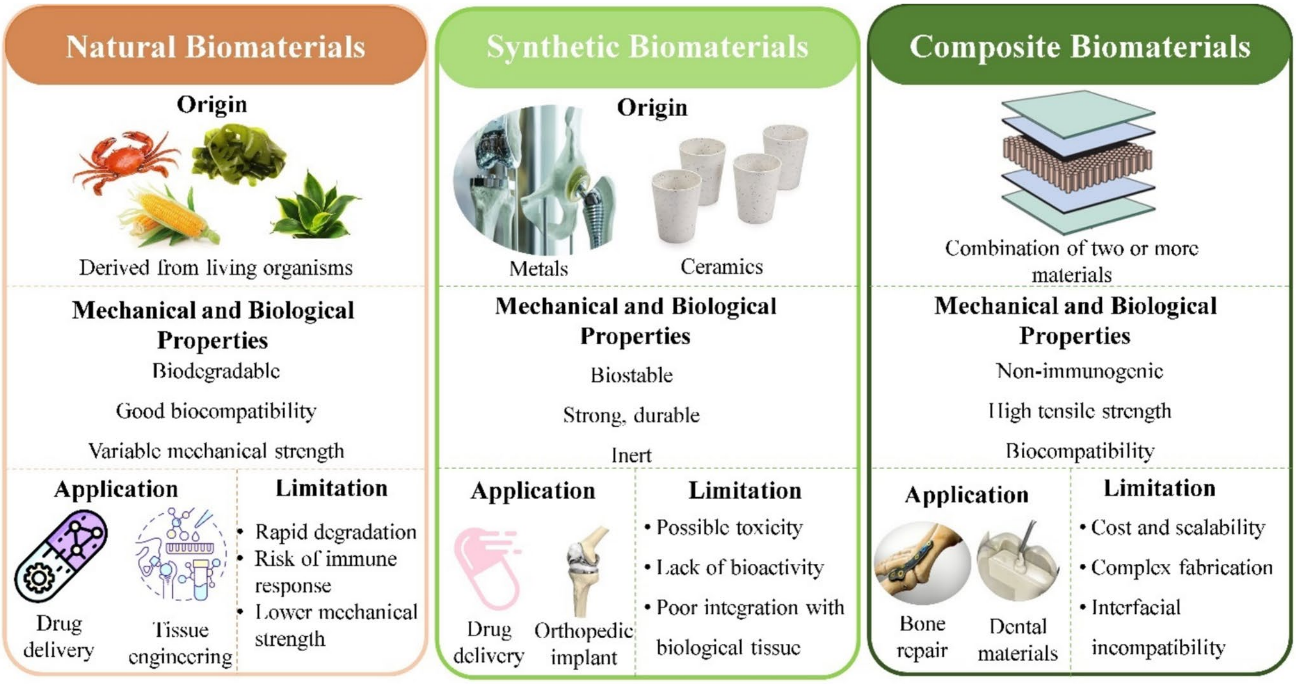


Fig. 2 Schematic illustration of natural, synthetic, and composite biomaterials

activities, and exceptional biomimicry. The potential of using animals, plants, and microorganisms as sources of biomaterials is substantial, but such exploitation must be carefully regulated and conserved (Liu et al. 2023). In contrast, natural biomaterials from marine, terrestrial, and aerial organisms possess properties shaped by evolution.

These naturally derived biomaterials can be categorized into several groups (Table 1), including protein-based biomaterials (such as collagen, gelatin, and silk), lipid-based biopolymers (like phospholipids and triglycerides), polymer-based biomaterials (such as cellulose, dextran, and chitin/chitosan), and ceramic-based biomaterials (including aragonite and hydroxyapatite) (Insuasti-Cruz et al. 2021). Insects are the most diverse and numerous animal species, followed by arachnids and mollusks. Among plants, flowering plants are the most abundant. This vast diversity provides a wealth of opportunities for biomaterials, from fundamental research to applied science and products, due to their unique structural features and physico-chemical properties. However, our understanding of natural biomaterials remains limited, and the discovery of new biomaterials with unexpected properties from marine and terrestrial species continues (Khrunyk et al. 2020). Despite this potential, the commercialization of natural biomaterials faces challenges such as scaling, achieving purity, and ensuring reproducibility. This review examines the current advancements in biomaterials derived from marine and terrestrial organisms and explores how biodiversity contributes to their properties.

Synthetic Biomaterials

Recently, synthetic polymers have emerged as effective biomaterials that interact with biological systems (Yang and Du 2019). These polymers offer distinct advantages, including chemical diversity, ease of functionalization, customizable structures and properties, biocompatibility, biodegradability, and responsiveness to stimuli (Deng et al. 2021). As a result, synthetic polymers have been widely utilized in biomedical and pharmacological fields, including surgical devices, diagnostics, tissue engineering, regenerative medicine, and drug delivery systems (Satchanska et al. 2024). Biomaterials derived from synthetic sources can be classified into metals, ceramics, and both biodegradable and non-biodegradable polymers (Table 2).

Metals

Metallic biomaterials are primarily used to replace damaged hard tissues. High-strength alloys containing non-toxic elements are commonly employed in various biomedical applications. Metals such as Fe, Cr, Co, Ni, Ti, Nb, Mo, and W are used to create alloys for implants, but these elements can only be tolerated by the body in trace amounts. While some of these metals, in their natural forms, are essential for functions like red blood cell formation (Fe) or the synthesis of vitamin B-12 (Co), they cannot be present in large quantities in the body. Nitinol (NiTi) alloys, for example, are used to create self-expanding stents for cardiovascular

Table 1 Natural biomaterials from different sources

	Biomaterials types	Biomaterials	Source	References
Biomaterials from animals .	Bioceramics	Hydroxyapatite	Poultry and food industry wastes (eggshells and bones)	Mohd Pu'ad et al. (2019)
		Calcium carbonate	Chicken, duck, and ostrich egg shells *Madreporaria* sp.; *Millepora spp.*	Boissin et al. (2020)
		Aragonite	Corals, mollusks, and crustaceans	Toffolo (2021)
		β-tricalcium phosphate	Terrestrial and marine sources	Insuasti-Cruz et al. (2021)
		Natural coral	Nacre, aragonite, calcium carbonate, and calcium sulfate *Porosites* sp.; *Acropora* sp.; *Acropora nobilis; Acropora hyacinthus; Acropora abrotanoides; Acropora samoensis; Goniopora* sp.; *Madreporaria* sp.	Moynihan et al. (2021)
	Biopolymers	Chitin and chitosan	*Litopenaeus vannamei* (White leg shrimp) *Penaeus monodon* (Black tiger shrimp) *Callinectes sapidus* (Blue crab)	Mohan et al. (2023)
		Tunicates	Marine environments	Insuasti-Cruz et al. (2021)
		Chondroitin sulfate	Cartilage of animals, such as pigs, birds, cattle, sharks, squid, skate, sturgeon, and other bony fish	
		Sulfated glycosaminoglycans	Fish	
		Hyaluronic acid	Animal bones: bovine, ovine, and avian; Poultry egg shells; Marine shells; Fishbone scales, Birds	Graciela et al. (2023)
	Proteins	Collagen	Bovine, porcine, human collagen, marine organisms (scale fish and fish skin), chicken, kangaroo tail, rat tail tendons, duck feet, equine tendon, alligators' bone/skin, bird's feet, sheepskin, and frog skin	Rezvani Ghomi et al. (2021)
		Silk	*Bombyx mori*	Müller et al. (2024)
		Gelatin	Skins, hides, and bones of cattle; pork skin; skin, bone, and swim bladder of fish.	Nurilmala et al. (2022)
		Keratin/wool keratin	Hair, feathers, wool, hooves, horns, claws, beaks, pig bristles, fish scales, and wool fibers (Sheep)	Sharma (2020), Banasaz and (Ferraro 2024)
		Glycoprotein (Ovomucoid, Ovomucin, Conalbumin, Ovalbumin)	Total egg white proteins	Jalili-Firoozinezhad et al. (2020)
		Fibrous extracellular matrix (ECM) (Elastin)	Blood vessels, elastic ligaments, lungs, skin, and other connective tissues	Krymchenko et al. (2024)
		Casein	Milk protein	Khatun et al. (2022)
		Thrombin	Human plasma	Zhang et al. (2023a)
		Fibrin	Human plasma-derived	Sanz-Horta et al. (2022)
		Lactoferrin	Milk, tears, saliva, and other tissues	Wang et al. (2023)
	Lipids	Waxes	Beeswax	Tijani et al. (2024)
		Omega-3 fatty acids (EPA and DHA)	Fish skin grafts	Kotronoulas et al. (2021)
		Triglycerides (oleic, palmitic, and linoleic acids)	Egg yolk; Northern shrimp *(Pandalus borealis)*; Japanese tiger prawn (*Penaeus japonicus*); Norway lobster *(Nephrops norvegicus)*; Giant squid (*Dosidicus gigas*)	Phadtare et al. (2021), Monteiro et al. (2024)
		Phospholipids	Egg yolk; Brown shrimp *(Penaeus californiensis)*; *Northern shrimp (Pandalus borealis)*; White shrimp *(P. vannamei)*; Tiger prawn *(P. monodon)*; Whiteleg shrimp *(P. vannamei)*; *Striped prawn (P. kerathurus)*; Norway lobster *(Nephrops norvegicus)*; Giant squid (*Dosidicus gigas*)	
		Carotenoids (lutein and zeaxanthin)	Egg yolk Crustaceans (e.g., lobsters, shrimp, crabs, and krill)	
		Sterols	Brown shrimp *(Penaeus californiensis)* Northern shrimp *(Pandalus borealis)* Norway lobster *(Nephrops norvegicus)* Giant squid (*Dosidicus gigas*)	

Table 1 (continued)

	Biomaterials types	Biomaterials	Source	References
Biomaterials from plants	Bioceramics	Hydroxyapatite	Peel (potato and orange), leaves (papaya), flower (calendula), and plants (basil, green tea, trifolium, mint, and *Catha edulis*)	Kumar and Mohanty (2022)
		β-tricalcium phosphate	Prickly pear peel (*Opuntia ficus indica*) Bitter orange peel (*Citrus aurantium*)	Alorku et al. (2020)
		Calcium oxide/carbonate	Finger citron (*Citrus medica var. sarcodactylis*)	Yadav et al. (2021)
		Aragonite	Plant seeds	Toffolo (2021)
	Biopolymers	Cellulose	Cotton (*Gossypium* spp.); *Eucalyptus* species; Hemp *(Cannabis sativa);* Bamboo fibers; Sugarcane (*Saccharum officinarum*); Rice Straw (*Oryza sativa*); Wheat Straw	Ren et al. (2022), Bangar et al. (2023), Sharma et al. (2023), Mubarak et al. (2024)
		Lignin	*Eucalyptus* spp. Bamboo (subfamily: *Bambusoideae*)	Verma et al. (2021, Tavares et al. (2022)
		Hyaluronic acid	*Nicotiana tabacum*	Nazeri et al. (2023)
		Starch	Zea mays (Corn or Maize); Cassava (*Manihot esculenta*) Potato (*Solanum tuberosum*); Wheat and Rice	Khatefov et al. (2023), Farid et al. (2024)
		Pectin	Most plants' primary cell wall, Orange Peel (*Citrus* Sp.)	Insuasti-Cruz et al. (2021)
		Polyols	Eugenol, Cardanol, Terpenes, Terpenoids, and Rosins	Malani et al. (2022)
	Proteins	Soy protein	Soybean	Kalouta et al. (2024)
		Zein	Corn	Jaski et al. (2022)
		Wheat protein or Gluten	Wheat grain	Shewry (2022)
		Pea protein	Yellow pea (*Pisum sativum L.*)	Asen et al. (2023), Kalouta et al. (2024)
		Sunflower protein	Sunflower seeds	Evon et al. 2021)
		Lupin protein	*Lupinus albus* L. (white lupin); *L. luteus* L. (yellow lupin); *L. angustifolius* L. (blue lupin), and *L. mutabilis* (Andean lupin)	Shrestha et al. (2021), Buonvino et al. (2023)
	Lipids	Triglycerides	Vegetable oils (olive, soybean, peanut, sunflower, flax, corn, and canola)	Nurchi et al. (2023)
		Phospholipids	*Arabidopsis* leaf	Noack and Jaillais (2020)
		Waxes	Plant leaf (*Plerocarpus indicus*, *Sansevieria trifasciata, Dracaena sanderiana, Homalomena rubescens, Ficus religiosa, Dieffenbachia picta, Musa paradisiaca, Alstonia scholaris, Mangifera indica, Cananga odorata, Polyalthia longifolia, Acrostichum aureum,* and *Lagerstroemia inermis*)	Boraphech and Thiravetyan (2015)
		Fatty acid (ricinoleic, palmitic, stearic, oleic, and linoleic acid)	Castor oil, vegetable oil	Bhukya and Kaki (2024)
		Lignin, suberin, and/or cutin	Extracellular matrix of plants	Xin and Herburger (2021)

Table 1 (continued)

	Biomaterials types	Biomaterials	Source	References
Biomaterials from bacteria	Bioceramics	Biogenic hydroxyapatite	*Pseudomonas fluorescens*	Turner et al. (2017)
	Biopolymers	Polyhydroxybutyrate (PHB)	*Bacillus megaterium; Azotobacter* and *Alcaligenes* sp.	Rysbek et al. (2022)
		Xanthan	*Xanthomonas campestris*	de Souza et al. (2022)
		Hyaluronic acid	*Streptococcus* genus *(uberis, equisimilis, zooepidermicus, pyogenes, equi Pasteurella multocida Corynebacterium glutamicum*	Snetkov et al. (2020)
		Dextran	*Leuconostoc mesenteroides*	Yáñez-Fernández et al. (2021)
		Bacterial cellulose	*Komagataeibacter maltaceti* (isolated from grape and apple vinegars) and *Komagataeibacter nataicola* (isolated from thorn apple vinegar)	Greser and Avcioglu (2022)
		Bacterial alginate	*Azotobacter vinelandii, Pseudomonas aeruginosa*	Valentine et al. (2019), Núñez et al. (2022)
		Polyglutamic acid	Gram (+) bacteria, especially *Bacillus subtilis and B. licheniformis*	Insuasti-Cruz et al. (2021)
		ε-poly-lysine	Cationic homopolyamine synthesized by *Streptomycetaceae* and some *Bacillaceae*	
		Polyhydroxy alkanoates	*Cupriavidus necator; Bacillus* sp.; *Pseudomonas* sp.; *Methylobacterium* sp.; *Azospirillum*	(Patil et al. (2022), Tyagi et al. (2022), Nawaz et al. (2023), Morlino et al. (2023)
	Proteins	Silk-elastin-like proteins	*E. coli*	Feng et al. (2024)
		Collagen-like proteins	*Streptococcus pyogenes, Bacillus anthracis, Clostridium difficile, Clostridium perfringens, Legionella pneumophila, and Burkholderia*	Picker et al. (2022)
		Recombinant Proteins	*E. coli*	Chiang et al. (2020)
	Lipids	Polyunsaturated fatty acids (EPA and DHA)	*Colwellia* spp; *Moritella* spp.; *Shewanella* spp.; *Photobacterium* spp.; *Psychromonas* spp.; *Vibrio* spp.	Moi et al. (2018)
		Phospholipid	*Bacillus subtilis*	Machinandiarena et al. (2020)
		Glycolipids (trehalose lipids)	*Rhodococcus sp.*	Pirog et al. (2020)
		Glycerolipids (diacylglycerols)	*Rhodococcus, Metschnikowia, Dietzia, Nocardia, Streptomyces, Marinobacter, and Pseudomonas*	Gupta et al. (2021)

Table 1 (continued)

	Biomaterials types	Biomaterials	Source	References
Biomaterials from algae	Bioceramics	Hydroxyapatite	Red algae (*C. Officinalis*) Micro algae (*Scenedesmus* sp.)	Kumar and Mohanty (2022)
	Biopolymers	Alginate	Brown seaweed (*Phaeophyceae*)	Ye et al. (2023)
		Chitin and chitosan	Green algae	Terkula Iber et al. (2022)
		Cellulose	*Chlorella* vulgaris; *Chlorella pyrenoidosa*; *Nannochloropsis gaditana*; *Staurastrum* sp. (Microalgae); *Cladophora* glomerata; *Cladophora rupestris*; *Chaetomorpha melagonium*; *Enteromorpha* sp.; *Ptilota plumosa*; *Ulva Lactuca*; *Ulva prolifera*; *Ulva pertusa*; *Ulva* sp.; *Cystosphaera jacquinottii*; *Gelidium elegans*; (Macroalgae)	Li et al. (2016), Chen et al. (2016), Jmel et al. (2019), Paniz et al. (2019)
		Ulvan	Green seaweed (*Chlorophyceae*)	
		Carrageenan	Red seaweed (*Rhodophyceae*)	
		Laminarin and fucoidan	Brown seaweed (*Phaeophyceae*)	Sanniyasi et al. (2023)
		Hydroxyapatite	Marine algae	Galindo-Moreno et al. (2020)
	Proteins	Phycocyanin	Spirulina (*Arthrospira platensis*)	Sánchez-Laso et al. (2023)
		Algal lectins	Red algae	Hung and Trinh (2021)
		Arabinogalactan-like glycoproteins	*Ulva lactuca*	Přerovská et al. (2021)
		Phycoerythrin	Rhodophytes (*Pyropia yezoensis*), cryptophytes, and blue-green algae	Ulagesan et al. (2021), Tan et al. (2022)
	Lipids	Omega-3 and glycolipids	*Nannochloropsis gaditana* *Nannochloropsis oceanica*	Castejón and Señoráns (2019), Costa et al. (2020)
		Neutral lipids, glycolipids, and phospholipids	*Chlorella vulgaris* and *Nannochloropsis oculate*	Obeid et al. (2018)
		Eicosapentaenoic acid (EPA)	*Chlorella minutissima* (Microalgae)	Orejuela-Escobar et al. (2021)
		Decahexaenoic acids (DHA)	*Dunaliella salina*	
Biomaterials from fungi	Bioceramics	Hydroxyapatite	*Aspergillus niger*	Kalaiselvi et al. (2018)
	Biopolymers	Melanin	*Cryptococcus neoformans, Aspergillus niger*	AL-Zubaidy and Shabaa (2023)
		Pullulan	*Aureobasidium pullulans*	Hernandez-Tenorio and Giraldo-Estrada (2022)
		Chitin and chitosan	*Agaricus bisporus, Cunninghamella echinulate, Ganoderma lucidum, Hericium erinaceus*	Azeez et al. (2022)
		β-D-glucans (beta-glucan)	*Saccharomyces cerevisiae, Schizophyllum commune*	Pham et al. 2020; Gou et al. (2023)
	Proteins	Fungal proteins	Mushrooms (*Basidiomycetes*) *Fusarium venenatum*, *Ascomycetes,* and *Zygomycetes* (*Aspergillus*, *Rhyzopus*, and *Neurospora*)	Li et al. (2023)
	Lipids	Polyunsaturated fatty acids (PUFAs)	*Mucor circinelloides, Mucor ctenidius (Thamnidium ctenidium, Mortierella* sp.	Mhlongo et al. (2021)
		Glycolipids (Sophorolipids)	*Candida bombicola*	Daverey et al. (2021)
		Phospholipids	*Fusarium oxysporum*	Sepúlveda-Rivera (2018)
		Phosphatidylserine	*Pichia pastoris*	Liu et al. (2019)

Table 2 Biomaterials from synthetic materials

Category	Biomaterials	References
Metals	Titanium alloys	Liu et al. (2020a)
	Mg alloys	Jamel et al. (2022)
	Conventional stainless steel	West et al. (2021)
	Platinum	Antonarelli et al. (2022)
	CoCr alloys	Padrós et al. (2020)
	Nitinol	Bernini et al. (2022)
	Nickel	Khodair et al. (2022)
Ceramics and glasses	Amorphous alumina	Nakonieczny et al. (2022)
	Zirconia	
	Silicate glass ceramics	da Silva et al. (2023)
	Bioglass	Okereke et al. (2024)
	Porcelain	Inchingolo (2024)
Non-biodegradable	Polyethylene (PE)	Chelu and Musuc (2023a)
	Polyamides	Winnacker (2023)
	Polypropylene (PP)	Zielińska et al. (2023)
	Polytetrafluoroethylene (PTFE)	Zhou et al. (2024)
	Polymethyl methacrylate (PMMA)	Charasseangpaisarn et al. (2023)
	Polyurethanes	Chelu and Musuc (2023a)
	Poly(dimethylsiloxane)	Kadziński and Banecki (2024)
	Polyethylene terephthalate (PET)	Zhang et al. (2024)
	Poly(sulfone)	Zaman and Mehdi (2024)
	Poly (ethylene oxide)	Edmans et al. (2024)
	Polysiloxanes	Chen et al. (2023a)
	Acrylics	Hashimoto et al. (2024)
	Poly(N-isopropyl acrylamide)	Shaibie et al. (2023)
	Poly (N, N-diethyl acrylamide)	Bayliss et al. (2023)
Biodegradable polymers	Saturated aliphatic polyesters	Shan et al. (2023)
	Polyanhydrides	Eriksson et al. (2023)
	Saturated aliphatic polyurethanes	Chelu and Musuc (2023a)
	PGA	Sueyoshi et al. (2022)
	PLA	Yang et al. (2024)
	PLGA	Mittapelly et al. (2024)
	poly (ε-caprolactone (PCL)	Bhattacharjee et al. (2023)
	Poly (ethylene succinate)	Kumagai et al. (2024)
	Synthetic collagen	Rezvani Ghomi et al. (2021)
	PHB	Rana and la Hoz Siegler (2024), Acharjee et al. (2024), Tejada-Tovar et al. (2025)
	Poly (glycerol sebacate)	Godinho et al. (2022)

surgery and orthodontic wires for dental procedures (Ijaz et al. 2020). Patient-specific implants, including bone plates, screws, and cranial or dental devices, are designed to meet specific requirements for biocompatibility, bioactivity, surface integrity, and wear resistance (Davis et al. 2022).

Ceramics and Glasses

The biocompatible properties of ceramics, such as being non-toxic, non-carcinogenic, non-allergenic, and non-inflammatory, make them ideal for use in implants, tissue regeneration, and engineering applications. Ceramics used in implant fabrication can be categorized into non-absorbable (relatively inert), bioactive or surface-reactive (semi-inert) (Atheena et al. 2024), and biodegradable or resorbable (non-inert) (Suamte et al. 2023). Inert bioceramics include alumina, zirconia, silicon nitrides, and carbons, while semi-inert (bio-reactive) materials include certain glass ceramics and dense hydroxyapatites. Resorbable ceramics consist of calcium phosphates and calcium aluminates. Biofunctional materials, such as silicate glass ceramics, are being researched and utilized for bone tissue regeneration and healing, cancer treatment through hyperthermia, as implants, or for total replacement in articulating surfaces to promote osseointegration (Shanmugam 2024).

Nonbiodegradable Polymers

Nondegradable polymers are strong and have excellent mechanical properties (Liu et al. 2018a). In medicine, these polymers are used to make tissue engineering scaffolds, orthopedic implants, heart valves, bone and cartilage replacements, vascular grafts, artificial hips, eye lenses, dental fillings, and bone cement. Many nondegradable polymers, like PE, PP, PTFE, and PMMA, are processed under brand names by various companies for use in medical devices and treatments. The key factors for long-term implants made from nondegradable materials are their biocompatibility, stability, and resistance to wear (Khodaei et al. 2023)

Biodegradable Polymers

Some of the most commonly used biodegradable synthetic polymers in biomedical applications include saturated aliphatic polyesters, polyanhydrides, and polyurethanes. Poly(glycolic acid) (PGA), polylactic acid (PLA), and the copolymer poly(lactic-co-glycolic acid) (PLGA) are saturated aliphatic polyesters that are frequently used to create 3D scaffolds for tissue engineering due to their biocompatibility and biodegradability (Song et al. 2018a). Biodegradable synthetic biomaterials offer two main advantages: first, they do not cause chronic foreign-body reactions, as they are gradually absorbed by the body and leave no permanent residue at the implant sites. Second, some of these materials have been shown to support tissue regeneration or tissue engineering through the interaction of their biodegradation with immune cells like macrophages (Zhang and King 2020).

PLA is used in cardiac, dental, orthopedic, and implantable devices because it is both biocompatible and biodegradable. PGA is applied in drug delivery, biological adhesives, oral surgeries, and injectable microspheres (Brugnera et al. 2022). Polyurethanes are biocompatible, biodegradable polymers known for their flexibility, durability, and resistance. Due to their biostability, they are preferred as inert materials in the development of medical devices (Cui et al. 2023), as well as for vascular grafts, heart valves, and prostheses (Nakamori et al. 2023), catheters, drug delivery systems, and porous scaffolds for tissue regeneration (Sanati et al. 2022).

Hybrid/Composite Biomaterials

Composites are materials made from two or more different substances to enhance their individual properties, such as surface characteristics, mechanical strength, and biocompatibility, making them easier to manufacture. Examples of composite materials include reinforced plastics like fiberglass and natural materials like bone. Natural composites encompass bone, wood, dentin, cartilage, and skin, often exhibiting hierarchical structures with particulate, porous, and fibrous features at various micro-scales (Nasir et al. 2023). Polymer-based composites have gained significant interest in biomedical applications, including drug release, tissue engineering, regenerative medicine, wound dressings, surgical procedures, medical imaging for cancer detection, and dental resin composites (Chelu and Musuc 2023b). The recently developed biomaterials for biomedical applications are shown in Table 3.

Results and Discussion

Application of Biomaterials

Applications of Biomaterials in Tissue Engineering

Tissue engineering is a diverse field that incorporates different principles of chemistry, biology, and engineering to create functional substitutes for damaged tissues. Tissue engineering integrates biological cues with bio-scaffold techniques to repair, preserve, or improve the structure and function of damaged tissues or organs. (Aslam Khan et al. 2024). Biomaterials are highly suitable materials for tissue engineering applications because they can form structural scaffolds and facilitate cellular interaction, growth, and differentiation. In tissue engineering, biomaterials are used to mimic the in vivo extracellular matrix (ECM), providing a favorable environment for cellular attachment, tissue regeneration, and proliferation (Liu et al. 2023).

The application of biomaterials in tissue engineering is shown in Table 4. Depending on the applications, biomaterials can be classified into 3 categories. These are natural, synthetic, and hybrid biomaterials. Natural biomaterials, such as collagen, chitosan, fibrin, alginate, hydrogels, and gelatin, possess several properties like microstructure interconnectivity, biocompatibility, mechanical adaptability, well-defined molecular structures, and bioactivity, which facilitate cellular function. However, natural biomaterials have some drawbacks, including batch variability, rapid degradation, weak mechanical properties, and limited processability, which hinder their medical applications (Farris et al. 2016). Polyglycolic acid, PLA, PLGA, Co-poly (LL-GA), and polyurethane are some examples of synthetic biomaterials that possess controllable properties such as mechanical strength, degradation rates, and ease of fabrication. Synthetic biomaterials are advantageous for engineering complex tissues. The potential of biomaterials in tissue engineering has been increased by recent advancements in

Table 3 Hybrid/composite biomaterials

Material	References
Polydopamine (PDA)-coated hydroxyapatite (HA)-reinforced polyvinyl alcohol (PVA) films	Erdem et al. (2022)
Electrospun graphene oxide/calcium hydroxyapatite/polycaprolactone composites	Daulbayev et al. (2022)
Ternary nanocomposites, including graphene oxide (GO), hydroxyapatite (HAP), and cadmium selenite (CdSe), were encapsulated into nanofibrous scaffolds of PLA.	Saha et al. (2025)
Dual mineral-substituted hydroxyapatite (DM-HAP) combined with biodegradable polymer alginate–chitosan (ALG-CS) and graphene oxide	Liu et al. (2021)
Shrimp chitosan-MXene composite	Munshi et al. (2025)
$NiFe_2O4$/NG/cellulose composites	Anbu (2021)
Biocomposite based on alginate/gelatine crosslinked with genipin	Hackenhaar et al. (2022)
Chitosan/ PVA/graphene oxide nanocomposites	Ruiz et al. (2019)
Chitosan-gelatin composite	Herliana et al. (2023)
CNF-NCGreinforced drug-loaded PVA/MC/PEG glutaraldehyde cross-linked novel electrospun nanofibrous bio-nanocomposites	Samanta et al. (2022)
Biowaste-derived nanophase yttrium-substituted hydroxyapatite/citrate cellulose/opuntia mucilage (Y-nHAP/CC/OM) biocomposites	Irwansyah et al. (2022)
Hydroxyapatite (HA)/nanostructured monticellite ceramic composites	Kalantari et al. (2019)
Polypropylene oxide/polyethylene oxide-cellulose hybrid nanocomposite hydrogels	Prusty and Swain (2020)
Chitosan/polypropylene glycol hydrogel composite	Ulu et al. (2020)
Collagen/apatite	Kołodziejska et al. (2020)
Clindamycin-modified polymer-ceramic hybrid composite	Słota et al. (2024)
Titanium-protein nanocomposites	Floriano et al. (2023)
HA/PCL	Yao et al. (2024)
Mono-layer of halloysite nanotube-magnesium oxide/ β-tricalcium phosphate composite	Chozhanath-misra et al. (2024)
Poly(l-lactic acid)/Cellulose Composite	Chen et al. (2024)
PVA-based bioplastic film incorporated with keratin	Habib et al. (2025)
PCL-PLA/ HA scaffolds	Kareem et al. (2019)
Poly(N-isopropyl acrylamide)-co-acrylic acid nanogels	Rana and la Hoz Siegler (2024)

nanotechnology, 3D printing, and bio-fabrication. The combination of biomaterials with cells and bioactive molecules enables the creation of more sophisticated, patient-specific tissues, which can be used for clinical applications such as skin, bone, cartilage, vascular, and neural tissue regeneration (Agrawal et al. 2023). The optimum biomaterial characteristics for complex tissues are still difficult to achieve, due to some issues related to immunogenicity, biomaterial degradation, mechanical strength, and vascularization, despite the tremendous promise. A schematic representation of biomaterials in tissue engineering applications is given in Fig. 3.

Application of Biomaterials in Drug Delivery

The process, which is utilized to administer a pharmaceutical product to the body in a manner that ensures its therapeutic effects, refers to drug delivery, including the formulation of drugs, and control of the release, absorption, and targeting of drugs. The objective of drug delivery is to mitigate adverse effects while optimizing the drug's efficacy. Due to the limited effectiveness of conventional medications, new and improved drug delivery systems have evolved. Biomaterials show great potential, particularly in the area of drug delivery, where the design of materials with specific properties has enabled more efficient, controlled, and targeted therapeutic approaches (Voci et al. 2021). Drug delivery application of biomaterials is shown in Table 5.

Because of the increasing demand for biomaterials, several natural, synthetic, hybrid, nanoparticle, hydrogel, and composite biomaterials have been developed, which offer unique advantages in drug delivery due to their biocompatibility, biodegradability, and ability to be tailored for specific delivery purposes. Natural polymers such as collagen, hyaluronic acid (HA), alginate, and chitosan possess inherent biocompatibility and biodegradability, which are of extreme importance when considering a material for biomedical applications. On the other hand, synthetic polymers provide us with control over the molecular weight, incorporation of a variety of chemical functional groups, adjustable mechanical properties, and reproducibility (Sood et al. 2021).

By using biomaterials, drug delivery systems can enhance drug stability, control release rates, minimize side effects, and target disease sites more effectively, especially in complex conditions like cancer, diabetes, neurological disorders, autoimmune diseases, and genome editing (Shown in Fig. 4) (Fenton et al. 2018; Alvi et al. 2022).

Application of Biomaterials in Wound Healing

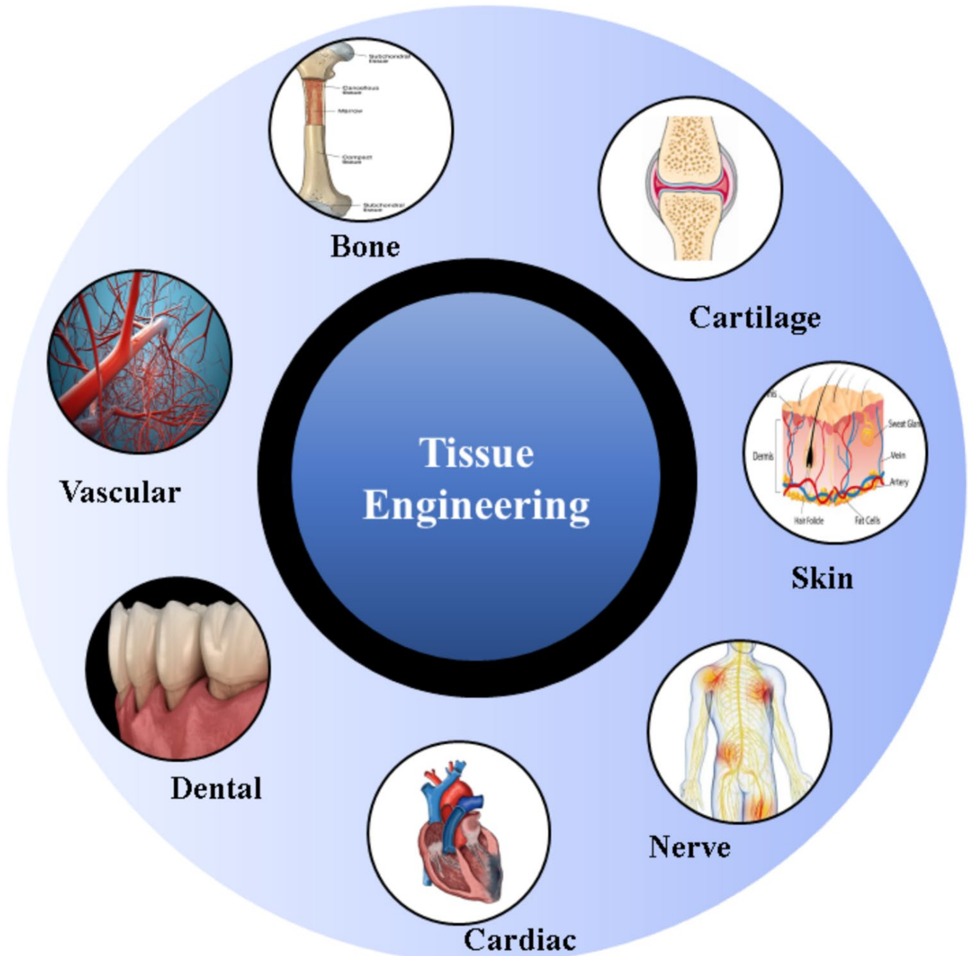
Wound healing is an intricate, dynamic process encompassing cellular responses, tissue regeneration, and extracellular matrix remodeling (Table 6). The healing process is hampered in cases of chronic wounds, such as diabetic ulcers or burns, resulting in prolonged recovery periods and significant healthcare burdens. Biomaterials have become a major advancement in wound healing treatments, offering

Table 4 Application of biomaterials in tissue engineering

Biomaterials system	Application discussion	References
Peptide	Bone tissue engineering	Li et al. (2025)
Fibrin		Farmani et al. (2021)
SMC-chitosan- n-hydroxyapatite		Ullah and Chen (2020)
Chitosan-hydroxyapatite		Nazeer et al. (2017)
Marine-derived fucoidan		Anupama et al. (2023)
PEGDA-CS		Jin et al. (2021)
Silk fibroin-silica aerogel		Maleki et al. (2019)
Chitosan-alginate		Sahoo and Biswal (2021)
Chitosan	Bone and nerve tissue engineering	Amiryaghoubi et al. (2021)
PHA		Kaniuk and Stachewicz (2021)
Keratin		Soleymani Eil Bakhtiari and Karbasi (2024)
Laminin/fibrin/HA	Brain tissue engineering.	Arulmoli et al. 2016)
PEDOT-agarose	Cartilage tissue engineering	Zarrintaj et al. (2018)
Chitosan-polyethyleneimine		Khan and Tanaka (2017)
Alginate		Lee et al. (2017)
Hydrogels		
Silk/gelatin		Ullah and Chen (2020)
Alginate hydrogels		Wang et al. (2018)
PEO-PPO-PEO		Khan and Tanaka (2017)
Cellulose acetate	Cardiac tissue engineering	Chainoglou et al. (2016)
PEUU		Rodríguez-Soto et al. (2023)
P4HB		Yuan et al. (2021)
Polyglycolic acid	Genitourinary tissue reconstruction	Budak et al. (2020)
PLA		Liu et al. (2020b)
PLGA		Webster et al. (2013)
Silk fibroin	Nerve tissue engineering	Lee et al. (2017)
Poly (polyol sebacate)		Saudi et al. (2022)
PPy-PLGA	Neural tissue engineering	Liang and Goh (2020)
PEDOT		Gajendiran et al. (2017)
PEDOT-HA-PLA		Wang et al. (2017a)
Cellulose-ceramic	Osteoblast cell regeneration	Kim et al. (2018)
Collagen/hyaluronate	Respiratory tract engineering	O'Leary et al. (2016)
Dextran	Skin tissue engineering	Lee et al. (2017)
Gelatin-chitosan-PCL		Gomes et al. (2017)
Gelatine- PCL		
Gelatin	Skin and cartilage tissue engineering	Poursamar et al. (2016)
Elastin		Stojic et al. (2021)
HA		Saravanakumar et al. (2022)
PCL-gelatin	Soft tissue engineering	Moazzami Goudarzi et al. (2021)
Dextran-PEG		Wang et al. (2017b)
Poly (ethylene glycol)- poly (acrylate)	Stem cell growth	Khan and Tanaka (2017)
Collagen-graphene oxide	Vascular and nerve tissue engineering	Liu et al. (2018b)
Silk fibroin/keratin/gelatin	Urinary tissue engineering	Lv et al. (2016)
PGA-PHB		Yadav et al. (2019)

cutting-edge ways to enhance tissue regeneration, mitigate infection, and speed up the recovery process (Downer et al. 2023). Natural, synthetic, and hybrid materials are all examples of biomaterials, which are designed to imitate natural tissue and collaborate with biological systems to facilitate the healing process. Biomaterials can be utilized as wound dressings, scaffolds for cell growth, antibacterial agents, and delivery systems for medications or growth hormones.

Fig. 3 Schematic representation of tissue engineering applications



Improvements in recent years have been concentrated on developing materials with increased biocompatibility, controlled degradation rates, and the ability to stimulate cellular responses that accelerate tissue repair (Bianchera et al. 2020).

Several natural or synthetic polymers are advantageous for wound healing due to their properties, like immunogenicity as well as flexibility, mechanical strength, elasticity, and controlled degradation rate, while nanomaterials are being used for their antimicrobial properties and ability to enhance cellular signaling pathways. Moreover, collagen-based materials are also used for healing as they possess qualities like non-cytotoxicity, enhanced biocompatibility, and bioactivity in body cells. The incorporation of growth factors or stem cells within biomaterials is also being investigated for their ability to accelerate tissue regeneration in chronic wounds. Biomaterials play a pivotal role in improving wound healing outcomes, with ongoing research focused on optimizing their properties for better integration and effectiveness in clinical applications (Sharma et al. 2022). A schematic representation of the biomaterials system in wound healing application is shown in Fig. 5.

Application of Biomaterials in Water Purification

In recent decades, the rise in industrial activity and water usage worldwide has led to the release of various pollutants into aquatic environments, including toxic heavy metals, dyes, and pesticides, among other harmful contaminants. Rapid industrialization and urbanization have had a significant negative impact on water bodies due to the discharge of industrial and domestic wastewater (Harripersadth et al. 2020). Industries such as textiles, pulp and paper, and steel produce large amounts of wastewater containing diverse contaminants, which can severely harm living organisms due to their toxic nature (Boakye et al. 2022). For example, textile industry effluents are often dye-laden, which not only affects the aesthetic quality of water even at low concentrations but also contains toxic chemicals that are slow to degrade and are carcinogenic or mutagenic to various organisms. Moreover, organic pollutants like phenols, surfactants, humic substances, and monoaromatic compounds released from pesticides, fertilizers, plasticizers, oils, detergents, and pharmaceuticals are also highly concerning due to their carcinogenic properties (Issabayeva et al. 2017; Siyal et

Table 5 Biomaterials system for drug delivery application

Biomaterials system	Application discussion	References
Alginate	Controlled drug release, biological barrier absorption	Trucillo (2024)
HA	Create an ideal environment for drug release	How et al. (2020)
Silk fibroin	Breast cancer treatment, high encapsulation, and sustained release	Drabczyk et al. (2024)
Soy protein	Bacterial infections, cancer treatment	
Zein protein	Treatment of intestinal inflammation, treatment of acute promyelocytic leukemia, and skin diseases	Drabczyk et al. (2024)
Cyclodextrins	Increase drug solubility and encapsulation	Haimhoffer et al. (2019)
Sericin	Anti-aging therapy	Shankar et al. (2023)
Chitosan	Oral drug delivery	Tao et al. (2021)
Legumin	Hydrophilic drug delivery	Drabczyk et al. (2024)
Poly(lactic-co-glycolic acid) (PLGA)	Sustained drug release, antigen entrapment for enhanced delivery, and slow biodegradation for sustained antigen release	Perinelli et al. (2019)
PHB	PHB nanospheres releasing plasmonic NPs (Silver and gold NPs) and showed bactericidal activity against *E. coli* and *S. aureus*	Grajales-Velázquez et al. (2025)
Polyethylene Glycol (PEG)	Improve drug solubility	Sun et al. (2023)
PLA	Enables sustained release with controlled degradation, and reduces dosing frequency and side effects	Trucillo (2024)
Dendrimers	Targeted drug delivery, gene therapy	Wang et al. (2022)
Polymeric Micelles	Solubilizing and delivering hydrophobic drugs	Chaudhuri et al. (2022)
Lipid nanomaterials	Enhance chemotherapeutic agent delivery, increase solubility, reduce systemic toxicity, and improve selectivity for cancer cells	Trucillo (2024)
Gold nanoparticles (AuNPs)	Maximizing efficacy while minimizing tissue damage enhanced osteoinduction in dental implants	
Silver nanoparticles (AgNPs)	Targeted drug-delivery vehicles and infection-control agents	Trucillo (2024)
Hydrogels	Provide a drug-releasing environment, and control drug-release capabilities	
Liposomes	Targeted drug delivery, gene therapy, and enhancing the solubility and stability of therapeutic agents	Trucillo (2024)
Hydroxyapatite	Slow release of antibiotics loaded	Khamkongkaeo et al. (2023)
Calcium phosphate	Improve control of drug release	Chen et al. (2023b)
Carbon dot nanospheres with folic acid and chitosan	Anticancer doxorubicin hydrochloride drug delivery system	Ghosh et al. (2025)
Chitosan and hydroxypropyl methylcellulose (HPMC)	Enhanced drug release control with optimal adhesion and strength	Timur et al. (2019)
Fibrin-based nanoscale	Anti-inflammatory, antioxidant, antidiabetic, and slows down cancer cell proliferation	Kaparekar et al. (2020)
DNA-doxorubicin complexes	Develop a drug carrier for improved anticancer efficacy	Drabczyk et al. (2024)
DNA-modified liposomes	Create innovative drug carriers and targeted delivery of active substances	

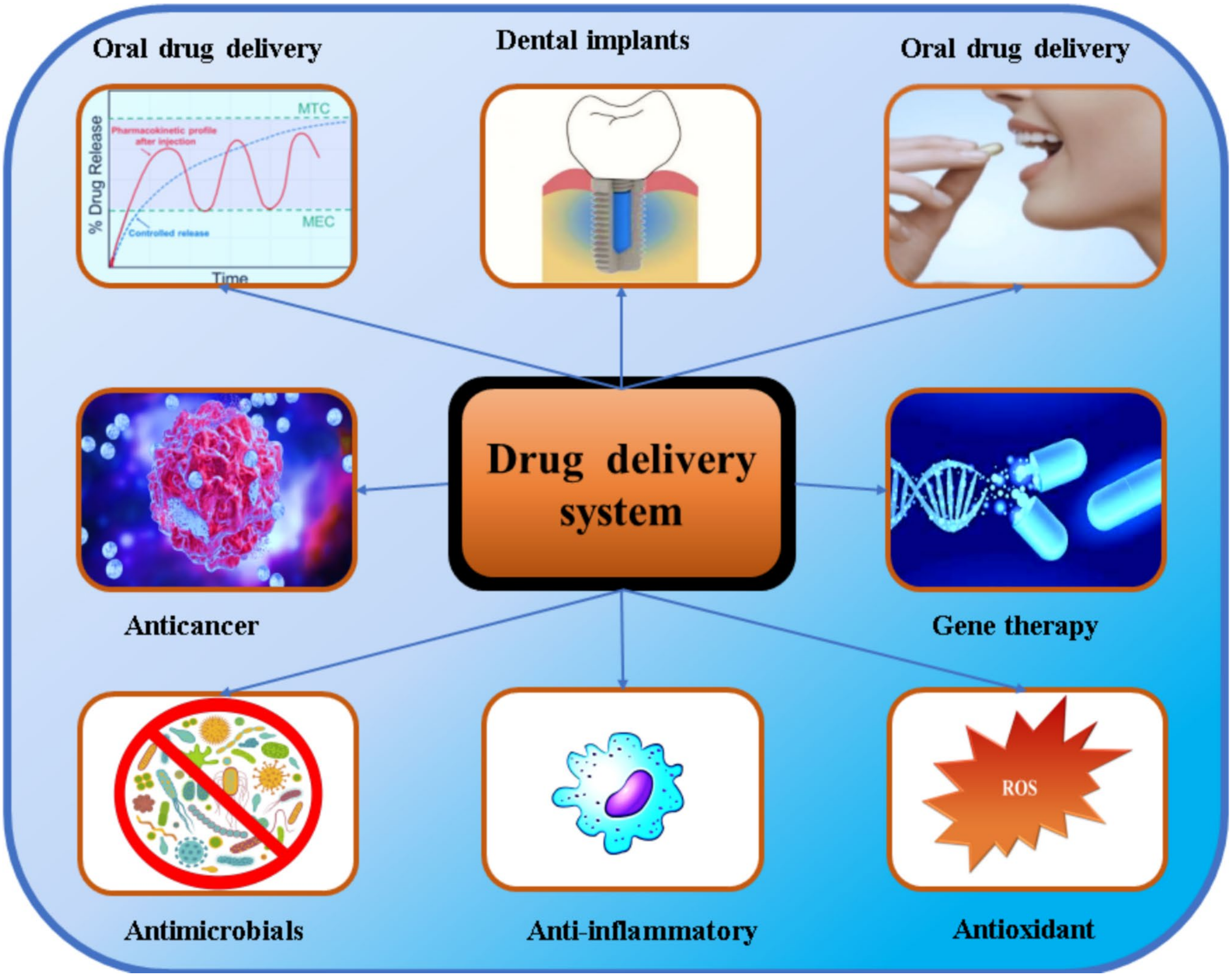


Fig. 4 Biomaterials in a drug delivery system

al. 2020). Industrial, municipal, and agricultural activities, including the use of fertilizers and pesticides, have directly or indirectly contributed to the increasing concentrations of pollutants such as dyes and heavy metals in our environment, particularly in water bodies (Boakye et al. 2022). Given the growing global population and the fact that one-third of the world's population lives in water-stressed areas, the need for affordable, accessible, efficient, and sustainable water treatment methods is more critical than ever.

Various water treatment techniques have been explored, including filtration and membrane technologies, ion exchange, catalysis, coagulation and flocculation, reverse osmosis, electrochemical treatment, evaporation recovery, and sorption processes. Several biomaterials are used in the aforementioned water treatment techniques. Among these, two readily available and low-cost adsorbents are natural soil components and biomass materials (Fig. 6). These include substances such as clays and soil minerals (e.g., kaolinite, bentonite, feldspar) as well as agricultural and industrial waste products (e.g., pine cones, Carica papaya seeds, rice husks, maize cobs, moss biomasses). These materials are considered low-cost because they are inexpensive, easily accessible, and generally do not pose environmental harm (Diagboya et al. 2020). A detailed summary of biomaterials in water purification applications is shown in Table 7.

Application of Biomaterials in Soil Remediation and Agriculture

Table 8 shows the application of biomaterials in soil remediation and agriculture. Some problems, including expanding populations, limited resources, and environmental concerns, are driving the need for sustainable agriculture. Traditional agricultural practices frequently involve the use of agricultural chemicals, excessive water use, and soil degradation, all of which are detrimental to ecosystems and public health. Food security is guaranteed, the consequences of climate change are lessened, and a healthy ecosystem is promoted

Table 6 Different biomaterial systems in wound healing

Biomaterials system	Application	References
Collagen	Promotes cell adhesion, migration, and angiogenesis in wound healing	Bagheri Miyab et al. (2020)
Chitosan	Chitosan aids platelet adhesion and activation, and chitosan has antimicrobial and anti-inflammatory effects	Xu et al. (2024)
	Strong adhesion with improved mechanical and swelling properties, preventing infection	Ali Khan et al. (2019)
Bacterial cellulose	Remarkable swelling properties, absorb wound exudate	Insuasti-Cruz et al. (2021), Jankau et al. (2022)
Starch	Suitable for bone implants and bone cement, used in drug delivery and tissue scaffolds	
β-glucans	Significantly reduced skin irritation versus cotton gauze, strongly inhibited adipogenic differentiation	
Chitin	Enhance immunity and wound healing	
Pectin	Occlusive and semi-occlusive dressings for wound care	
Fibrin	Natural scaffold for wound healing and cell transplantation	
HA	Tissue regeneration, a scaffold component for wound healing	Raza et al. (2023)
Calcium alginic	Adhesion and proliferation in wound healing	He et al. (2019)
Gelatin	Aids in wound matrix formation, useful for skin grafts and burn wounds, and wound dressings	Cao et al. (2024)
Aloe Vera	Anti-inflammatory, hydrating, and promotes collagen synthesis and wound healing	Liang et al. (2021)
Honey-based gels	Antibacterial, promotes healing by creating a moist wound environment	Nezhad-Mokhtari et al. (2021)
PEG	Used as a hydrogel in wound healing, wound dressings, and stable activity	Prete et al. (2023)
Polyethylene oxide (PEO)	Wound exudate absorption and contact with EpiDerm tissue confirmed the material's non-irritating nature	
PVA	Accelerate the healing process, better blood compatibility, and enhance cell migration and proliferation	Neres Santos et al. (2019), Shitole et al. (2019)
Polyvinyl pyrrolidone	Effectively curbing infection rates and accelerating the healing process creates a suitable micro-environment for healing	Prete et al. (2023)
PGA	Neo-epithelium formation and inflammation prevent delayed perforation and wound surface closure	Zha et al. (2022)
Polyurethane	Foam or film maintains a moist microenvironment, including decubitus ulcers, granulating wounds	Kapukaya and Ciloglu (2020)
AgNPs	Promotes healing by preventing infection and reducing inflammation, embedded dressings. Also, showing photothermal bactericidal action	Nethi et al. (2019, Grisoli et al. (2021)
ZnONPs	Antibacterial wound dressings for infection control and healing	Nethi et al. (2019)
AuNPs	Delivery of antibiotics, tissue adhesive, and laser-activated wound healing. Plasmonic AuNPs are the best photothermal candidates	
Copper nanoparticles (CuNPs)	Promotion of VEGF (growth factor) and upregulates the integrin expression, assists in stabilizing extracellular matrix proteins, fibrinogen, and collagen, aiding wound healing	
Gelatin-silverNp	Suitable as a wound dressing material	Ninan et al. (2015)
Epigallocatechin	Accelerates diabetic wound healing via increased angiogenesis and anti-inflammatory activity	
Gallate-goldNp		
Chitosan-MMT (montmorillonite)	Mucoadhesive wound healing ability	
Chitin-bentonite nano clay	Enhance tensile properties and wound healing ability	
Chitosan-titanium dioxide NPs	Anti-inflammatory activity	Halawa et al. (2025)
Sulfobetaine and p-coumaric acid incorporated chitosan-based nanogel	Accelerated wound closure and reduced inflammation	Basak et al. (2025)
Silk fibroin-collagen	Supports cell growth and proliferation, a hybrid scaffold supports cell adhesion, promotes blood vessel maturation, and accelerates healing	Naomi et al. (2020)
Nanocomposite matrix of chitosan	Release of melatonin to improve wound healing	Ali Khan et al. (2019)
Chitosan-ethylene diaminetetraacetic acid	Produced wound-healing fibrous mats.	
Gel@fMLP/ SiO_2-FasL	Accelerated wound healing in diabetic cutaneous defects	Liu et al. (2022)

Fig. 5 Biomaterials for wound healing

by sustainable agriculture, an ecological method of producing food that seeks to limit the impact on the environment, conserve natural resources, and preserve biodiversity over the long run (Saberi Riseh et al. 2024). Due to inefficient agrochemical delivery and usage, excessive fertilizer and pesticide application are still a common agricultural practice used to boost crop output. By providing new ways to regulate crop production, food handling, and food quality, biomaterials can provide enormous technical prospects to improve food security while reducing environmental consequences (Sun et al. 2022). Different biomaterials have recently been used in crop protection, seed coatings, and fertilizer encapsulation, among other uses. Similarly, the goal of these applications is to boost crop output by reducing nutrient losses and shielding seeds and/or seedlings from pests and unfavorable weather conditions (Dingley et al. 2024). Figure 7 shows the approaches of biomaterials in agriculture and soil remediation.

Application of Biomaterials in Air Pollution Control

The use of biomaterials in air pollution control systems is described in detail in Table 9. Air pollution is the introduction of any particle, biological molecule, or toxic gas, liquid, or solid into the atmosphere that endangers the system, damages or infects living things, or alters the local ecology (Aghababai Beni and Jabbari 2022). The largest threat to the environment is air pollution. Almost every nation in the world is impacted by ambient air pollution, which has been designated as a global health issue in the Sustainable Development Agenda. Air pollution is responsible for almost one out of every nine fatalities each year (Lv et al. 2018). One of the serious problems of modern life is air pollution, which harms the ecosystem. Numerous pollutants are carcinogenic, meaning they may cause tumors and cancer, which can harm both the environment and human health (Sheoran et al. 2022). Air pollution is a significant global issue that includes a wide range of hazardous substances that are harmful to all kinds of lifeforms (Cetin et al. 2023). Heavy metals are a particularly important component of air pollution in terms of both environmental and human health since they bioaccumulate in living organisms. Even at low doses, many of these can be poisonous, carcinogenic, or fatal (Cetin and Jawed 2022; Zeren Cetin 2024). Proper tracking and control of heavy metal levels, particularly in the atmosphere, is critical. Direct monitoring of air pollution is not generally recommended because it is costly and its immediate impacts on the environment are unpredictable (Cesur et al. 2022). Particulate matter of different sizes, chemical fumes and vapors, germs and viruses, and other substances are typically found in polluted air. Numerous illnesses or discomforts in people and other living things have been

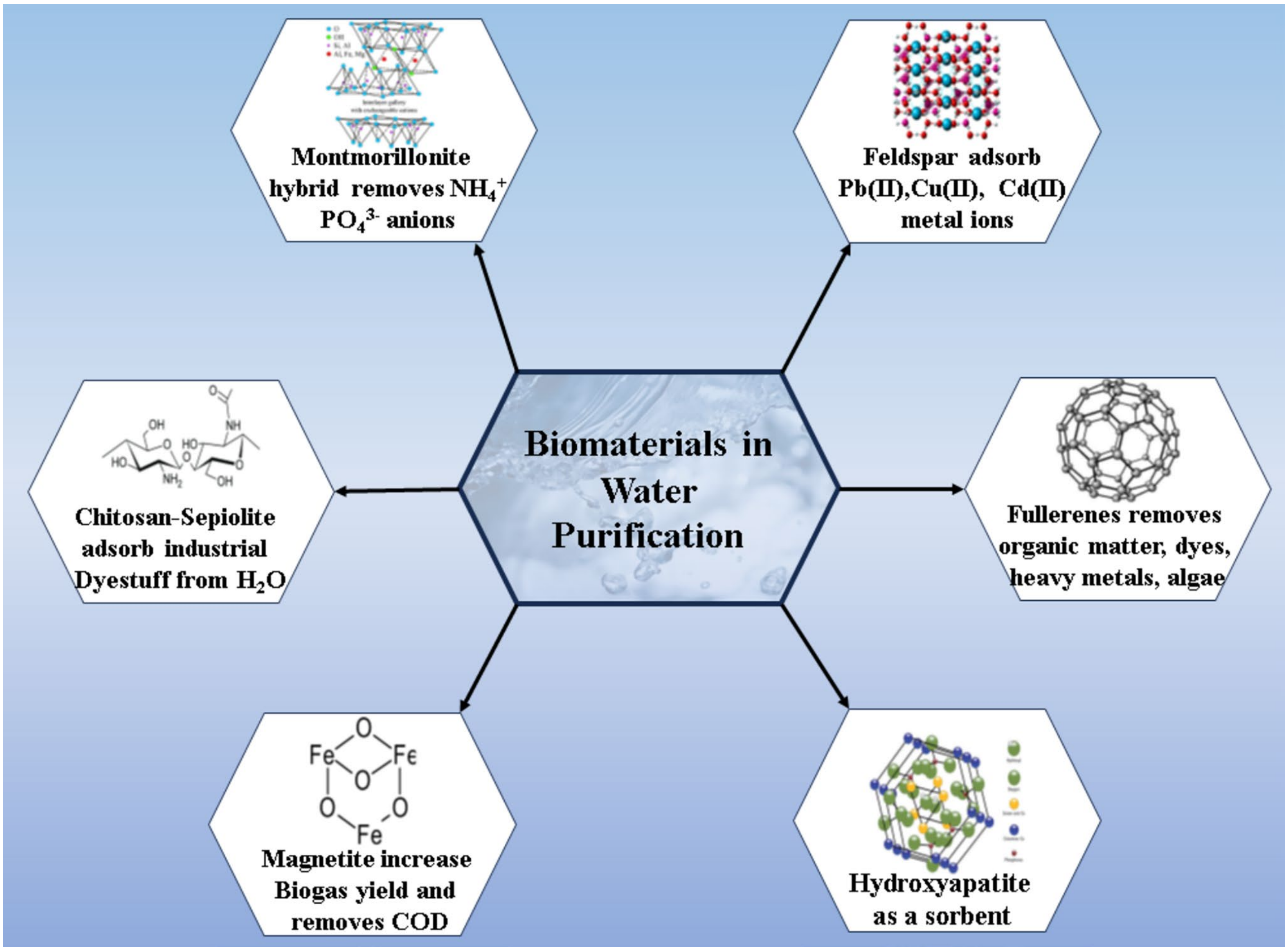


Fig. 6 Schematic diagram of various biomaterials in water purification

linked to the combination of the abovementioned harmful substances. Bacteria, viruses, and fungi are examples of bioaerosols, a class of main pollutants that significantly raise public health concerns due to their ease and speed of disease transmission through contaminated air (Souzandeh et al. 2019). Continuous air pollution monitoring is one of the most crucial and fundamental requirements for environmental pollution control. Certain plant species act as efficient bio-monitors, tracking and reducing heavy metal contents in heavily polluted regions. Monitoring the concentration of heavy metals in metropolitan areas with leaf-bearing species of trees as bio-monitors can provide useful information and insights into air pollution. These plants can help limit human exposure to air pollution by capturing it on their surfaces. Unlike other technical solutions for reducing air pollution, this strategy is both cost-effective and environmentally beneficial (Cebi Kilicoglu and Zeren Cetin 2024; Yucedag et al. 2025). Remarkable progress has been achieved in reducing air pollution through the use of nanosensors. According to the researchers, these sensors will be used to identify air pollutants, combat biological gases, and even detect organic substances in space (Aghababai Beni and Jabbari 2022).

The application area of biomaterials in air pollution systems is illustrated in Fig. 8.

Application of Biomaterials in Sensing and Detection

A sensor is a tool that can measure one or more variables, generally electrically, and translate the measurement into a signal. To monitor the surroundings and use the information for various reasons, sensors must have the following essential qualities: stability, selectivity, variety, sensitivity, and accuracy of information gathered (Noah 2020). There are many different kinds of sensors, including calorimeters, electrochemistry, optics, piezoelectricity, and acoustics (Zhou et al. 2020). Over the last 10 years, biosensors, i.e., bio-based electronics and analytical tools, have attracted a lot of academic attention because of their enormous potential for use in the fields of sports, biological sciences, healthcare, and environmental studies (Kaushik et al. 2020). Biosensors are analytical instruments or devices that may

Table 7 Application of biomaterials in water purification

Biomaterial used	Application area	References
Hydroxyapatite	Hydroxyapatite makes for a perfect choice of sorbent for water pollutants, which demonstrates the attractiveness as a heavy metal immobilizer through a dissolution-precipitation mechanism	Ibrahim et al. (2020)
Feldspar and Carica papaya or pine cone seeds	They are used for aqueous adsorption of Pb(II), Cu(II), and Cd(II) metal ions	Olu-Owolabi et al. (2018)
Bentonite-Carica papaya seeds and Bentonite-pine cone seeds	They are also used for aqueous adsorption of Pb(II), Cu(II), and Cd(II) metal ions	Diagboya et al. (2020)
Kaolinite clay-Carica papaya	This hybrid is used for the adsorption of aqueous metal ions like Cd(II), Ni(II), and Pb(II)	
Kaolinite-Carica papaya seeds-$ZnCl_2$ or Kaolinite-Plantain peels-$ZnCl_2$	The hybrids use clay, biomass, and a metal cation was applied to study the adsorption of phosphates in aqueous solution	Unuabonah et al. (2017)
Montmorillonite–bamboo hybrid	It's used for the removal of ammonium and phosphate anions in aqueous solutions	Chen et al. (2017)
Kaolinite-Carica papaya hybrid	The metal and surfactant-doped kaolinite clay–Carica papaya seeds hybrid adsorbents are responsible for the sorption of aqueous fluoride, nitrate, and phosphate	Omorogie et al. (2017)
Carboxymethyl cellulose-montmorillonite	It is applied for the adsorption of the methylene blue dye	Yang et al. (2018)
Montmorillonite/wheat straw biochar	This hybrid material has been used as an adsorbent for norfloxacin–fluoroquinolone antibiotics	Zhang et al. (2018)
CNTs /Zeolitic imidazolate frameworks	CNTs /Zeolitic imidazolate frameworks were incorporated to remove malachite green (MG) dyes efficiently	Abdi et al. (2017)
MWCNT-polyamidoamine	This hybrid was synthesized for the removal of Co(II) from polluted water	Hayati et al. (2016)
Polyamidoamine /CNT	It was also employed for the removal of Ni, As, and Zn metals from an aqueous medium	
Reduced graphene oxide	Reduced graphene oxide was used for the removal of malachite green dyes from aqueous solution	Gupta and Khatri (2017)
ZnO nano-rod/reduced graphene oxide	Some heavy metals/radioactive elements, such as Sr (II), Cd (II), and U (VI), were removed using the adsorbents	Ranjith et al. (2017)
Eggshells	Eggshells can be used for removing Pb (II) and Cd (II) from aqueous solutions	Harripersadth et al. (2020)
Sugarcane bagasse	Sugarcane bagasse, a biomaterial, can also be used for removing aqueous Pb (II) and Cd (II)	
Copper/Activated carbon	It acts as an effective catalyst for remediating dyeing wastewater from various textile industries	Biswal et al. (2020)
Microcrystalline cellulose /TiO_2	This nanocomposite can reduce methylene blue photo-catalytically from water	
Magnetite NPs /pine cone	This material can be used for the removal of As (III) from water	Pholosi et al. (2018)
Bentonite modified with quaternary ammonium salt	This material can be used for the removal of carbon tetrachloride contaminants from an aqueous medium	Tomar and Kumar (2017)
Bentonite clay modified using magnesium chloride	These materials were used for the removal of fluoride from water	
Bentonite- kaolin hybrid	This hybrid can be used for the removal of salicylic acid	
Biochar from banana peels	The process had the highest removal of copper (93.52%) and lead (87.44%)	Amo-Duodu et al. (2021)
Magnetite (Fe_3O_4)	There was a 28% increase in biogas yield and COD removal	
Calcinated eggshell	The removal of toxic heavy metals, i.e., Cd and Cr, in synthetic wastewater was much enhanced when calcined eggshell was added	
Rice husk	Adsorbent for the removal of dyes such as Congo red (CR) and heavy metals such as Ni^{2+}, Zn^{2+}, Cd^{2+}, and Cr^{6+}, as well as organic pollutants such as phenol	Boakye et al. (2022)
Cashew nut shell	It has been studied for the removal of dyes such as CR dye and metal ions such as Cu^{2+}, Cd^{2+}, Pb^{2+}, and Cr^{2+} from an aqueous solution	
NaOH-treated *Michelia figo* wood sawdust	Effective for the removal of Pb^{2+}	
Orange peel modified with xanthate	Used for the removal of heavy metals $Pb^{2+}>Cu^{2+}>Cd^{2+}>Zn^{2+}>Ni^{2+}$	Khodakarami and Bagheri (2021)
Apple waste	Removal of Cu^{2+} from water	
Fullerenes	Removes organic matter, dyes, heavy metals, and algae	

Table 8 Application of biomaterials in soil remediation and agriculture

Biomaterial used	Application area	References
Polyacrylamide-based superabsorbent	They are used in pest management in aquatic and terrestrial regions by controlling the release of pests	Behera and Mahanwar (2019)
Agar and starch-based hydrogels	They are used for the controlled release of herbicides and to improve soil health. Agar and starch act as soil conditioners and thus enhance plant growth	
Polyacrylate-based superabsorbent	They are used as soil conditioners to promote plant growth in drought-prone areas	
Xanthan gum	It is commonly used in the agricultural industry as a suspending agent to improve the flowability and spray characteristics of insoluble fungicides, herbicides, and insecticides	Das and Dalei (2023)
	Xanthan gum was found to have extremely promising applications in sustainable soil stabilization	Bagheri et al. (2023)
	As a seed coating, it is mostly used as a biocontrol encapsulant due to its favorable properties in preserving the viability and functionality of biocontrol agents	Dingley et al. (2024)
Alginate microparticles incorporated with seaweed	It was used to improve biomass and chlorophyll content in tomato plants, along with improved abundance of microorganisms, providing a healthier soil system	Merino et al. (2021)
Alginate microparticles/limestone	These are applied within the soil as a fertilizer release agent and a pH controlling agent	van der Merwe et al. (2022)
CMC hydrogel/biochar	They are used for improving water retention and aggregate stability in desert soils	Shao et al. (2023)
Carboxymethyl cellulose	It's used as a suspending agent in pesticide and herbicide sprays due to its high viscosity at low concentrations	Dingley et al. (2024)
Carboxymethyl cellulose	It is effective in fertilizer encapsulation applications due to its capacity for controlled release, high water retention, and ability to adhere to fertilizer particles	
Pleurotus sajor-caju	This was used for reducing the level of heavy metals in the soil due to biosorption. Thus, it can enhance the nutrient content of polluted soils and can be used as a remediator of heavy metal-polluted environments	Bukola et al. (2023)
Arabic gum / ferrous sulfate	It's utilized for increasing water retention capacity, controlled release of actives, antibacterial activity, and heavy metal ions adsorption	Li et al. (2021)
Chitosan/ PVA supramolecular polymer	Applied for controlled release of actives	Elhassani et al. (2023)
Rice husk and sawdust	These biomaterials were used to decrease the pH, organic carbon, phosphorus, and potassium values of the contaminated soil. Moreover, the nitrogen content increased significantly after remediation using these two biomaterials	Biswal et al. (2020)
Microalgae	They have been found in agricultural applications due to their plant biostimulation benefits in the form of soil amendments and biofertilizers	Orejuela-Escobar et al. (2021)

provide quantitative biological data through a biological identification element that is in direct or spatial contact with a transducer element. A biosensor is widely used in biosensing to identify biomolecules. Sweat, saliva, and other essential physiological fluids are biological components that are combined with a physicochemical detector in these biosensors. A larger number of functional groups may be introduced and organized into the surface area of biosensors thanks to the use of nanomaterials. By improving the composite's physical and chemical characteristics, the sensors' sensitivity and specificity are further increased (Subhedar et al. 2021). New materials and cutting-edge applications have emerged quickly and are widely utilized in a variety of sectors, including sensors, medical devices, and conventional materials. For instance, Graphene oxide (GO) and its oxygen-containing groups make it easier to modify, assemble, and synthesize novel composite materials that may be utilized as biosensor electrodes because of its huge specific surface area, strong electrical and thermal conductivity, and exceptional hydrophilicity. Due to their organic-inorganic hybrid nature, high specific surface area, tunable aperture and shape, and controlled functional

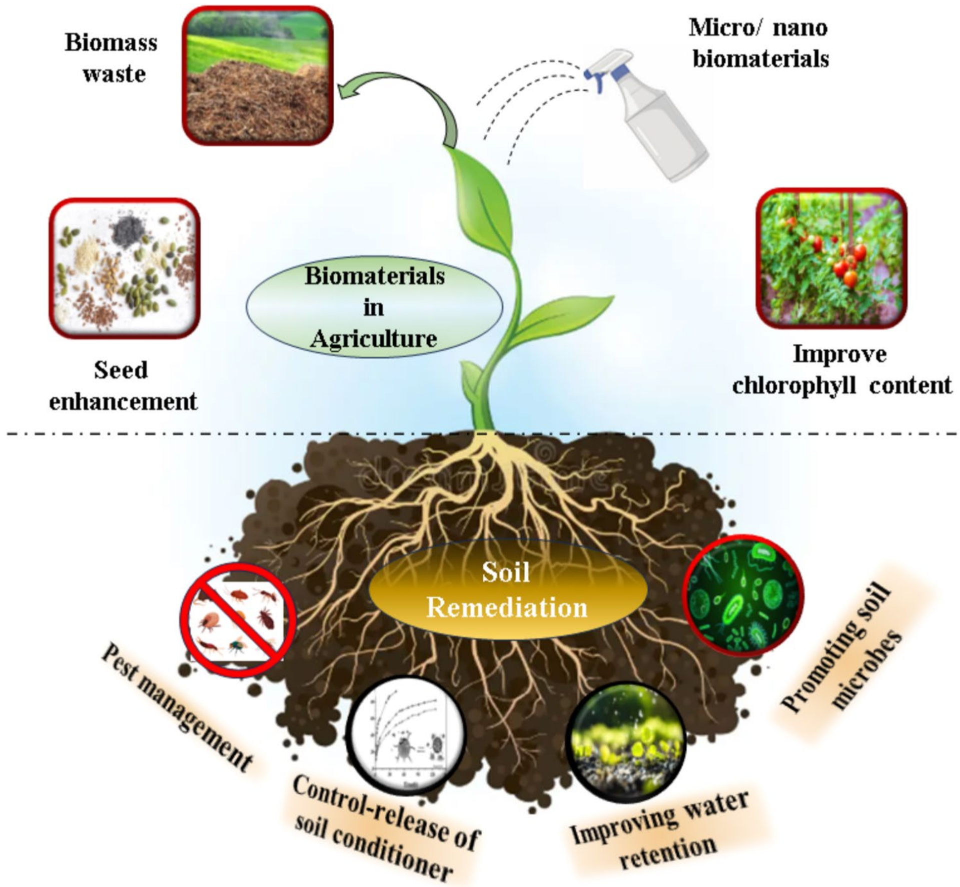


Fig. 7 Applications of biomaterials-based approaches and platforms in agriculture and soil remediation

characteristics, metal-organic matrix materials have also found extensive usage in sensing applications (Zhou et al. 2020). The application area of biomaterials in sensing and detection is shown in Table 10.

Application of Biomaterials in Biofertilizers and Biopesticides

Table 11 shows the application of Biomaterials in Biofertilizers and Biopesticides. Climate change, nutritional shortages, and decreased agricultural output are some of the major issues agricultural experts face today. To meet present and future food needs, it is thus estimated that current agricultural output has to be raised by as much as 50–70% (Hemathilake and Gunathilake 2022). The main causes of greenhouse gas emissions, which contribute significantly to climate change, include the use of fossil fuels, heavy fertilization of agricultural soils, tillage techniques, and livestock waste. Therefore, because of their ease of use, effectiveness, and environmental friendliness, biopesticides, biofertilizers, and genetic material-mediated plant enhancement initiatives have gradually gained recognition (Yu et al. 2021). Biofertilizers are economical and environmentally beneficial. Soil fertility is increased via consistent application of these fertilizers. Through a variety of processes, including nitrogen fixation, P-solubilization, P-mobilization, K-solubilization, micronutrient solubilization, organic matter enhancement, and growth hormone excretion, the use of biofertilizers in crop production systems greatly increases crop yields.

Using biofertilizers is one way to promote sustainable agricultural production without harming the environment or public health. This approach helps mitigate the negative impacts of inorganic fertilizers on soil quality and crop productivity. Pesticides have long been a key tool for pest control in industrialized nations. Various pests, such as *Acalitus vaccinia* (blueberry bud mite), *Acrobasis vaccinia* (cranberry fruit worm), *Acrosternum hilare* (green stink bug), *Agrotis ipsilon* (black cutworm), *Altica Sylvia* (blueberry flea beetle), *Aphis gossypii* (cotton aphid), and *Bemisia tabaci* (sweet potato whitefly), are harmful to crops due to their high nutritional demands. Pesticides, which are chemical substances or mixtures, are used to kill, repel, or control these pests (Hazafa et al. 2022). However, pesticides and fungicides are potentially hazardous and can significantly harm the environment by contaminating water sources and disrupting soil microbiota (Singh et al. 2022). Figure 9 shows some advantages of biofertilizers and biopesticides.

Table 9 Application of biomaterials in air pollution control

Biomaterial used	Application area	References
Chlorine oxide	Chlorine oxide has drawn attention to air pollution control, especially oxides of nitrogen control. The simultaneous removal of oxides of nitrogen and sulfur using chlorine oxide oxidation has gained interest in flue gas cleaning	Chen et al. (2020)
Chitosan	Chitosan is used as a suitable alternative amino-functionalized polymer for CO_2 recovery from industrial waste gases	Bakshi et al. (2020)
Activated carbon	Dioxin can be removed by using an activated carbon adsorbent	Aghababai Beni and Jabbari (2022)
Zeolite-CNTs	Zeolite-CNTs are one of the common adsorbents used to remove nitrogen oxides at low temperatures	
Single-walled carbon nanotubes/multi-walled carbon nanotubes with AuNPs	Carbon nanotubes and AuNPs have the most important uses as an adsorbent of poisonous gases in the atmosphere	Rahman et al. (2023)
Metal-organic frameworks-based nanowire filters	These filters are used for *E. Coli* destruction, CO_2 level reduction, and particulate matter removal	Bian et al. (2018)
Copper-copper oxide NPs	These nanocomposites are used for the reduction of oxygen	Mohamed (2017)
Gold-titanium oxide NPs	These nanocomposites are used for NO oxidation to NO_3 and NO_2	
Brominated flame retarded plastic/biomass biochar	They can remove elementary mercury with 40% removal efficiency	Xu et al. (2018)
Biochar	Significant quantities of toxic emissions such as HCl, SO_2, and nitrogen oxides can be mitigated using biochar as filter materials	Ma et al. (2019)
Biochar-based filters	They may be developed for the removal of metals and organic contaminants in gaseous emissions	Gwenzi et al. (2021)
Hydroxyapatite	It demonstrates good catalytic performance when it comes to formaldehyde oxidation under ambient conditions	Ibrahim et al. (2020)
Protein-based nanofilters	The bacterial filtration efficiency of soy protein-based nanofilters against Escherichia coli (E. coli) is significant	Souzandeh et al. (2019)
Cellulose acetate nanofibers	They are applied as heat-resistant air filtration materials	Souzandeh et al. (2019)
Chitosan/PEO filter	The chitosan/PEO filter showed about 70% removal efficiency for the generated aerosol	
Microalgae	Microalgae are considered a promising way to recycle atmospheric CO_2 and can remove CO_2 from industrial flue gases released during chemical processing	Orejuela-Escobar et al. (2021)
Stumpwood chips-bark-compost bed	The compost bed was used for the removal of volatile organic compounds, ammonia, and hydrogen sulphide gases emitted by municipal waste treatment and the food industry	Rolewicz-Kalińska et al. (2021)
Fungi	They can treat hydrophobic volatile organic compound emissions in the air	Sheoran et al. (2022)
Thiobacillus thioparus (Bacteria)	It is the only species of bacteria that can degrade carbon disulfide to CO_2 and H_2S by growing on it	
Calcium oxides	Usually used at higher temperatures to capture carbon dioxide gas	Khine et al. (2022)
Sodium alginate, calcium iodate, and silica fume	It's used as a coating to purify the air in urban areas by adsorbing air particulates with dimensions lower than 1 µm	Zanoletti et al. (2018)
Konjac glucomannan-based aerogel	These biobased materials are widely applied in air filtration applications	Wang et al. (2019)
Ag/PAN nanofiber membranes	This membrane is widely applied in air filtration applications to remove Nps from the air and also efficiently deactivate bacteria	Bortolassi et al. (2019)

Biopesticides, sometimes referred to as biological pesticides, are pesticides made from natural materials or microorganisms. Microbial biopesticides, botanical biopesticides, and plant-incorporated protectants are the three types of biopesticides. Biopesticides have lately attracted a lot of interest as an alternative to traditional insecticidal techniques because of their high effectiveness, possible target specificity, low risk of negative side effects, and ability to

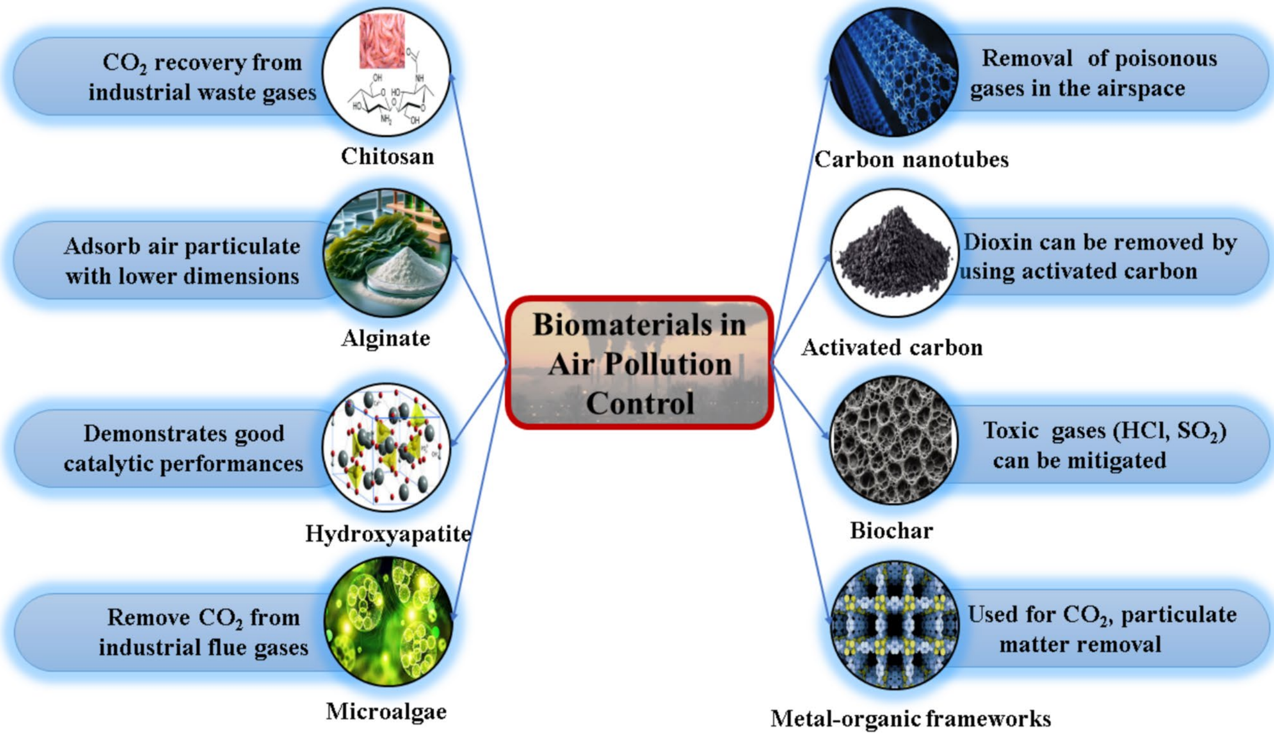


Fig. 8 Applications of biomaterials in air pollution control

dissolve quickly (Hazafa et al. 2022). Plant compounds such as alkaloids, phenolics, terpenoids, and some secondary chemicals are examples of biopesticides. Their physiology and behavior are affected by their biological activity against nematodes, fungi, and insects. Pyrethrum, Nicotine, Neem, Margosa, Rotenone, *Trichoderma virideae*, *T. harazianum*, and *Pseudomonas fluorescence* are examples of common pesticides (Rajput et al. 2020). By proving effectiveness in controlling pests and diseases, the creation of biopesticides from waste offers safe, natural alternatives to synthetic pesticides. Because nanoparticle-based pesticide formulations can overcome the drawbacks of traditional pesticides, they are garnering a lot of interest as potentially useful tools for pest management. In the long run, these innovations could be the best way to lessen negative environmental consequences. Numerous studies have connected pesticide nanoformulations to the emergence of systemic acquired resistance in plants.

Advantages and Current Challenges of Biomaterials

In recent years, the field of biomaterials has advanced significantly, with a wide range of applications. The main advantage of biomaterials is their availability in nature and as by-products of different industries. Furthermore, biomaterials exhibit high biocompatibility and are frequently eliminated from the body after metabolism without triggering immunological responses or other adverse consequences. Thus, biomaterials have been suggested as parts of a wide range of biomedical products, such as pharmaceuticals, implants, and medical equipment (Kashirina et al. 2019; Graça et al. 2020; Udayakumar et al. 2021). The use of biomaterials in developing packaging materials (biopolymers) is a promising area of research, as it comprehensively minimizes plastic waste and reduces greenhouse gas emissions (Roy et al. 2022). One of the most common examples of natural biomaterials is chitosan and alginate, which show excellent biocompatibility and biodegradability, making them the best candidates for wound healing and drug delivery applications (Hakim et al. 2021).

Although the usage of biopolymers has several benefits, including addressing food safety issues, there are still several drawbacks when compared to their counterparts that must be addressed to satisfy the demands of synthetic plastics (very flexible, inexpensive, and easy to handle) (Taherimehr et al. 2021). For example, high production cost and limited scalability of polyhydroxyalkanoates are the most significant challenges that hinder their industrial application (Gautam et al. 2024). Therefore, improving hydrophobicity, cost minimization, and scale-up production could solve the drawbacks of biomaterials. The challenges are to develop biocompatible biomaterials that can respond

Table 10 Application of biomaterials in sensing and detection

Biomaterial used	Application area	References
Alginate coated with polyelectrolyte nanofilms.	Used in the continuous monitoring of glucose and oxygen	Pradhan et al. (2024)
Silk fibroin /cellulose nanocrystals (CNC)	Showed excellent sensing of small tactile signals resulting from the dynamic reversible network between SCNCs and silk fibroin molecular chains	Zhu et al. (2020)
Genetically engineered *E. Coli* in agar hydrogels, sandwiched between polystyrene and nanoporous polycarbonate membranes.	Used as a living biosensor for detecting isopropyl-β-d-1-thiogalactopyranoside (IPTG), lactose, or galactose in milk	Rodrigo-Navarro et al. (2021)
E. Coli bacterial electronic capsule encased in acrylonitrile butadiene styrene (ABS) chamber	Has application in sensing gastrointestinal bleeding	
Phenylboronic acid (PBA)	Applied as sensors for the in vitro detection of sialic acid, glucose, and adenosine triphosphate (ATP)	Chen et al. (2020)
Poly-dimethyl siloxane microfluidic network	Used for the detection of pH, lactate, glucose, and chloride in sweat	Bandodkar et al. (2019)
Organic polymers containing N-benzyl carbazole, N-benzyl dibromocarbazole, and N-benzyl dimethoxycarbazole groups	The polymers show different fluorescent responses toward detecting the pesticides, including trifluralin, isopropalin, glyphosate, fenitrothion, imidacloprid, and cyfluothrin	Zhang et al. (2020)
Graphene-based biosensors	Has shown the ability to detect nucleic materials (DNA/RNA), antibodies, enzymes, or even pathogens	Pal et al. (2021)
Pani/CNC nanocomposite with a layer of ionic liquid	Has been developed as a sensitive biosensor for detecting enzymatic cholesterol	Abdi et al. (2019)
Platinum NPs	They have been used in sensors developed for the detection of hydrogen peroxide	Song et al. (2018b)
Palladium NPs	Have sensor applications for gases, biomolecules, and hazardous toxic molecules	Abdel-Karim et al. (2020)
CuNPs capped with cetyltrimethylammonium bromide.	They have been used as a colorimetric probe for the detection of dithiocarbamate pesticides	Ghoto et al. (2019)
Nickel oxide-zinc oxide p-n semiconductors	These have been applied for the chemical sensing of volatile organic compounds	Chen et al. (2018)
$In_2O_{3/}Sno_2$ core-shell nanofiber	They have been tested for the sensing performance of formaldehyde (HCHO)	Wan et al. (2019)
Perovskite/carbon nanotube	This was used to develop a photo sensor to distinguish between ultraviolet, visible, and infrared spectra	Wu et al. (2018)
Conductive network of functionalized carbon nanotubes	They have been used to develop a pressure sensor	Doshi and Thostenson (2018)
Graphene plasmonic biosensor	Has been applied to detect colorless biomaterials, including Chlorobenzene, Quinoline, Ether, and Ethylene glycol	Farmani et al. (2020)
Reduced graphene oxide-Chitosan-glassy carbon coupled with amino-functionalized HER2-specific aptamer	The aptasensor was developed as a key prognostic biomarker for breast cancer by detecting human epidermal growth factor receptor 2 protein (HER2)	Tabasi et al. (2017)

to external signals and be applied in drug delivery, tissue engineering, and immunological engineering. Creating a smart biomaterial with the optimal chemical and mechanical qualities without compromising its biological qualities can be difficult. In this regard, the material should not only be degradable, but the degradation substances must be biocompatible and nontoxic (Basak et al. 2021). At the same time, biomaterials frequently have short half-lives in the biological environments and poor mechanical properties like low compressive or tensile strength that are necessary for some applications, like bone or ligament prostheses (Shiroud Heidari et al. 2023). To overcome these limitations, biomaterials can be chemically altered to reduce their degradation rate and enhance their mechanical properties. Additional drawbacks include variation of characteristics according to the source, geographical and seasonal considerations, the isolation technique, and possible contamination with pathogens and traces of immunogenic substances such as proteins. Nevertheless, additional study is still

Table 11 Application of biomaterials in biofertilizers and biopesticides

Biomaterial used	Application area	References
Poly (epsilon caprolactone) nanocapsules	They are commonly used as a nano-formulation for enclosing atrazine. In addition, these nanocapsules can be used with environmentally safe neem oil as a pesticide	Suresh et al. (2019)
ZnONPs	These NPs are used to increase the seed yield of soybeans	Yusefi-Tanha et al. (2020)
CuONPs	They are used to increase the total yield of pigeon peas.	Feng et al. (2019)
ZnO	Used for the improvement in the growth of photosynthetic pigments and antioxidants in maize	Azam et al. (2022)
Cu-Chitosan NPs	This nanocomposite is used in plant growth and has a bactericidal effect	Swati and Joshi (2022)
Chitosan NPs -Piper nigrum essential oil	This biomaterial is used as an insecticide for the stored grain	Rajkumar et al. (2020)
Bacillus firmus and *Bacillus sphaericus*	They are used against diamondback moths	Hazafa et al. (2022)
Trichoderma harzianum and *Trichoderma viride*	They are used against root rots and wilts	
Beauveria bassiana	They are used against mango hoppers.	
Neem-based nano-biopesticides	They are used as biopesticides against whiteflies	
Acidic solution of chitosan	It was tested against Botrytis cinerea as a biopesticide in grapevines.	De Bona et al. (2021)
Methylobacterium oryzae cross-linked with sodium alginate and chitosan	This hybrid material is used for seed germination and the promotion of tomato plant growth	Chanratana et al. (2018)
Azospirillum brasilense in sodium alginate beads combined with humic acid, trehalose, and peat	It can be used for the plant growth promotion of wheat.	Zago et al. (2019)
Streptomyces fulvissimus encapsulated with Chitosan and gellan gum	It was used for biocontrol against Gaeumannomyces graminis along with the growth promotion of root and branch systems in wheat plants	Saberi-Riseh and Moradi-Pour (2021)
Bacillus licheniformis encapsulated with alginate and chitosan	It can be used for plant growth promotion of capsicum and biocontrol against Sclerotium rolfsii	Panichikkal et al. (2021)
Potassium-solubilizing microbes	The application of the PSMs as biofertilizers has been proven to positively affect the leaf nutrient content (N, P, and K) of Chinese fir, and increase the total N, P, and K, as well as available P and K content in the soil	Sattar et al. (2019)
Wood sawdust and maize stalk biochar	This biomaterial has applications in enhancing soil fertility by mitigating salt-affected soils	Mahmoud et al. (2019)
Anabaena variabilis	It could act as a biofertilizer in rice fields, promote the growth of rice plants, increase yield, and also act as a biopesticide against rice sheath blight and bacterial blight	Bao et al. (2021)
ZnO and SiNPs	They have applications as biofertilizers for high plant growth of *Mangifera indica* L.	Elsheery et al. (2020)
Dried powder of *Anabaena sp.*, *Nostoc sp.*, *Aulosira sp.*, and *Tolypothrix sp.*	It's used as a biofertilizer for a high yield of rice	Mahapatra et al. (2022)
Xanthan gum with glycerol acid	They are used to increase the lotus root storage stability.	Lara et al. (2020)
Chitosan and tripolyphosphate	This hybrid biomaterial can be used as a fungicide against *Rhizoctonia solani*	Chauhan et al. (2017)

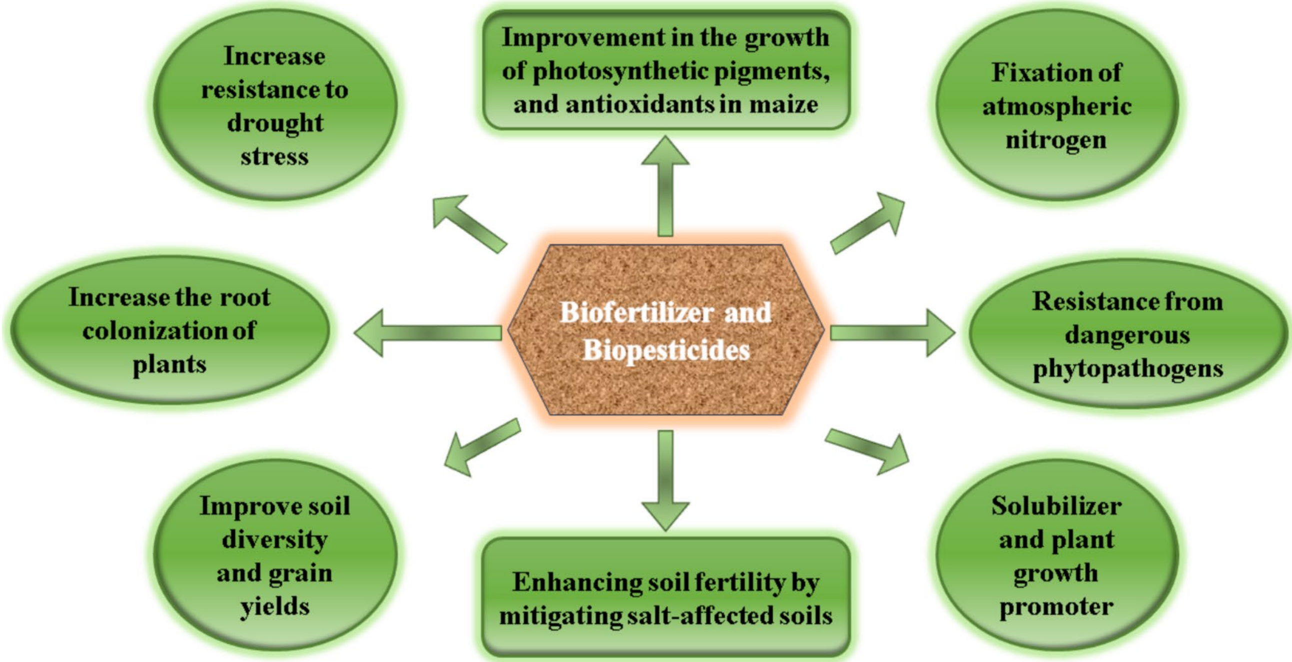


Fig. 9 Advantages of biofertilizers and biopesticides

needed to address the challenges related to biomaterials for their viability as a potential material.

Future Perspective of Biomaterials

In order to create better immunoprotected biocompatible materials, future research should focus on better understanding how biomaterials interact with the body. Additionally, biomaterial design should incorporate natural or biocompatible building blocks and degradability features (Capasso Palmiero et al. 2018). Regulatory and manufacturing constraints (e.g., reproducibility, complexity, ease of scalability), consistency in material performance, and its biocompatibility over time are some of the factors that should be taken into account to ensure better translation of preclinical studies (Basak et al. 2024).

Future research will also focus on the development of bioinspired, "smart," multifunctional biomaterials for health monitoring and prevention of biological crises. Identifying these materials as templates derived from biopolymers and organisms will be a critical step toward designing and synthesizing active, multifunctional devices. Additionally, economic and social impacts will be reduced by lowering the costs associated with manufacturing existing chemicals and medications. This progress will require the integration of techniques from various disciplines, including biology, engineering, and the physical and chemical sciences. This review provides an overview of biomaterials and their versatile applications, setting the stage for further elaboration and exploration in the field (Kowalski et al. 2018; Basak and Das 2025b).

Conclusion

Biomaterials have become a transformative tool in modern society by revolutionizing numerous aspects of life. Their applications have expanded across a wide range of fields, including diagnostics, tissue engineering, biofertilizers, water treatment, medical equipment, therapeutic medications, and emerging regenerative technologies. The definition of biomaterials has evolved in response to new research and innovations, and it is expected to continue expanding with further advancements in medical science and biotechnology. The biomaterials represent the most interesting class of materials for delicate areas such as biomedical applications and tissue engineering. Due to their unique physical and chemical properties, they have the potential to be used in various applications. With the rapid progression of science and technology, they demonstrate immense potential and vast opportunities for advancing their employment in other application fields as well. This work incorporates insights from recent research on biomaterials to provide a comprehensive overview of current trends in innovative applications. It includes practical findings of biomaterials focusing on multifaceted application areas such as tissue engineering, drug delivery, wound healing, water purification, soil remediation, and air pollution etc. This combined accumulation of diverse application areas emphasizes the novelty of this work. Biomaterials, broadly categorized into natural, synthetic, and composite classes, were assessed for their efficacy, and their application areas were explored. Looking ahead, the development of more functional medical biomaterials and their application in novel fields will be a significant focus. Advances in understanding the chemistry of biomaterials are expected to provide valuable insights into how these materials interact with biological systems and influence clinical performance. The future may also present an opportunity to reimagine how natural science can inspire and motivate innovation.

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Declarations

Conflict of interest The author(s) declared no potential conflicts of interest to the research, authorship, and/or publication of this article.

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