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REVIEW

An overview of sustainable biopolymer composites in sensor manufacturing and smart cities

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Abstract

Biopolymer composites are emerging as promising materials for smart sensors in the fields of civil engineering and intelligent cities. With enhanced mechanical properties, tailored sensitivity, and versatile fabrication methods, biopolymer composites provide a compelling solution for sustainable sensing technologies. The versatility of biopolymer composites with different electrical properties enables their applications in resistive, capacitive, and piezoelectric sensors, thus enhancing their potentials in healthcare, environmental monitoring, and consumer electronics. Here, we review an advancement of biopolymer composites in sensor technology, such as piezoresistive strain sensors used in structural health monitoring and a novel biochemical oxygen demand (BOD) biosensor for water monitoring. Integrating biopolymer composites into electrical biosensors has demonstrated promising results in detecting various substances, including moisture content in soil and model pollutants. Furthermore, their utilization in biopolymer-bound soil composites for building materials holds potential implications for sustainable construction practices. In summary, the incorporation of biopolymer composites in sensing applications paves the pathway towards developing smart and sustainable cities. As research continues, these materials are expected to play an increasingly significant role in sensor technology, providing eco-friendly solutions for challenges in civil engineering, environmental monitoring, and beyond. Furthermore, the potential for biopolymer composites to contribute to a more sustainable and interconnected world is considerable, making them a promising avenue for future sensor manufacturing and Internet of Things (IoT) applications.

Keywords Biopolymer · Sensing · Sustainable · Construction

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1 Introduction

Sensors are widely utilized in civil engineering for environmental monitoring [1–3], structural health assessment [4–7], healthcare [8–10], and human motion [11, 12]. They can detect pollutants, heavy metals, and contaminants in water, air, and soil, providing real-time data on environmental quality [13–15] and working conditions [16]. Additionally, sensors integrated into structures aid in assessing their health by detecting stress and potential failures [17]. Soil monitoring benefits from sensors measuring parameters like pH and moisture content [18]. Smart materials with such sensors can self-detect and repair damage [19]. It also aids disaster monitoring and early warning systems [20]. Such sensors could be manufactured in variety of technics. However, looking at the Sustainable Development Goals, particularly the application of SDG 12 (responsible consumption and production) for SDG 11 (sustainable cities and communities), it is essential to use raw material, which is part of the ecology and environment for implementation in sustainable technologies [21]. One such possibility is in the use of biopolymer composites, which offers several advantages in sensor manufacturing process and applications. They can be combined with reinforcing fillers or nanoparticles to improve mechanical properties, sensitivity, and fabrication methods. Their biocompatibility, eco-friendliness, and cost-effectiveness make them suitable for diverse sensor applications with reduced environmental impact [22, 23].

In sectors such as healthcare [24, 25], environmental monitoring [26, 27], and consumer electronics [28, 29], biopolymer composites are opening new possibilities [30]. Their resistance to chemicals enables deployment in harsh environments, while their mechanical strength and flexibility enhance durability [31]. As research progresses, the role of biopolymer composites in sensor technology is poised to expand, providing sustainable and innovative solutions to sensor manufacturing challenges. Biopolymer composites can be fine-tuned to detect specific analytics, making them ideal for various sensing needs and healthcare applications [32]. Their biodegradability and renewable sourcing reduce environmental impact, making them suitable for disposable or environmental monitoring sensors [33]. Biopolymer composites can be engineered to exhibit different electrical properties, making them applicable in resistive, capacitive, and piezoelectric sensors. There are a few review papers regarding biopolymers for environmental, medical applications [34, 35], humidity sensing [36], and electrochemical sensing [37]. However, there are no review yet for the biopolymers and their composites for their applications in sensor manufacturing and smart cities. In this paper, firstly, biopolymers and their composites utilized in smart and sustainable cities are described in detail. Research questions are formulated for a search of suitable literature and all the literature corresponding to the existing technologies and their advantages are explained further.

2 Background

Different from petro-based polymers [38] such as epoxy [39], polyurethane [40], polystyrene [41], acrylic resin [42], polyimide [43, 44], polypropylene [45–51], polyethylene [52, 53], conjugated polymers [54], and polyvinyl alcohol [55], biopolymers are a distinctive and diverse family of materials with potential uses in almost every industry. While the terms “biopolymer” and “biodegradable polymer” are sometimes used interchangeably in the literature, there is a significant distinction between these two types of polymers [56]. Biodegradable polymers are characterized as materials, whose chemical and physical properties deteriorate and completely disintegrate when subjected to microbes, aerobic, and anaerobic processes [57]. The term “biobased” is used when referring to polymers developed from renewable sources to emphasize the raw materials’ basis. Materials are considered renewable if natural processes regenerate raw resources at rates equal to or faster than their rate of use.

The two main factors that define a “biopolymer” are (1) the origin of the raw materials and (2) the polymer’s biodegradability. Biopolymers can be categorized as follows: (A) biopolymers that are both biodegradable and manufactured from renewable source materials (biobased); (B) biopolymers that are not biodegradable and are derived from sustainable raw materials (biobased); and (C) biopolymers that are both biodegradable and manufactured from fossil fuels.

Biopolymers such as polysaccharide can be created chemically from natural starting materials (such as starch, sugar, and maize) or by biological systems (microorganisms, plants, and animals) [58, 59]. Biodegradable biobased biopolymers include (1) synthetic polymers made from renewable resources, such as poly(lactic acid) (PLA); (2) biopolymers produced by microorganisms, such as PHAs; (3) naturally occurring biopolymers, such as proteins and starch.

Natural polymers are, by definition, those produced through various biosynthetic pathways in the biosphere. The majority of biobased polymers used worldwide come from first-generation feedstock, including non-consumable sources like natural rubber and edible biomass like starch, sugar, and plant oils [60–63]. Natural rubber was one of the first biopolymers employed, but the goal of moving away from resources centered on food and significant

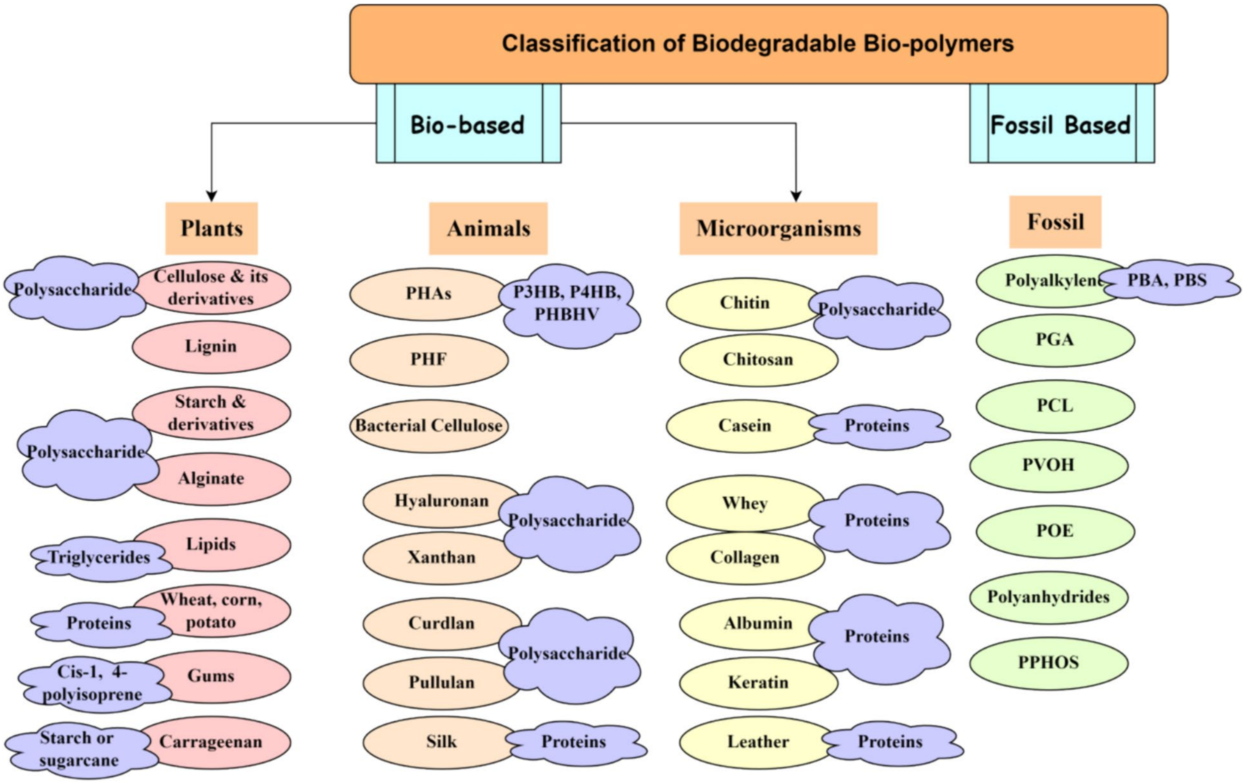


Fig. 1 Schematic diagram representing the classification of biodegradable biopolymers. The abbreviations are as follows: P3HB, poly(3-hydroxybutyrate); PBA, poly(butylene adipate); PBS, poly(butylene succinate); PGA, poly(glycolic acid); PCL, poly(ε-caprolactone); PHA, polyhydroxyalkanoate; PHF, polyhydroxy fatty acid; PLA, poly(lactic acid); POE, poly(propylene fumarate); PPHOS, polyphosphazenes; PVOH, poly(vinyl alcohol); P4HB, poly(4-hydroxybutyrate); PHBHV, poly(3-hydroxybutyrate-co-3-hydroxyvalerate)

advancements in biotechnology has caused a subsequent shift in focus. Biobased polymers that resemble conventional polymers are produced by bacterial fermentation through the synthesis of monomers from sustainable sources, especially lignocellulosic biomass (starch and cellulose), fatty acids, and organic waste (Fig. 1). Another category of biobased polymers is known as natural biobased polymers, which include polysaccharides [64–69], cellulose [70, 71], collagen [72], and chitosan [73, 74], as well as proteins and nucleic acids [75, 76]. These biobased polymers have seen significant growth in recent years in terms of technological advancements and practical uses. The three primary approaches to produce biobased polymers from renewable resources are as follows: firstly, using natural biobased polymers that have undergone some modification to meet specific requirements (e.g., starch); secondly, producing polymerized biobased monomers through fermentation or conventional chemistry, such as polylactic acid; and thirdly, the direct bacterial synthesis of biobased polymers, such as polyhydroxyalkanoates.

3 Methodology

Once the background of the variety of biopolymers is understood, it is essential to formulate specific research questions

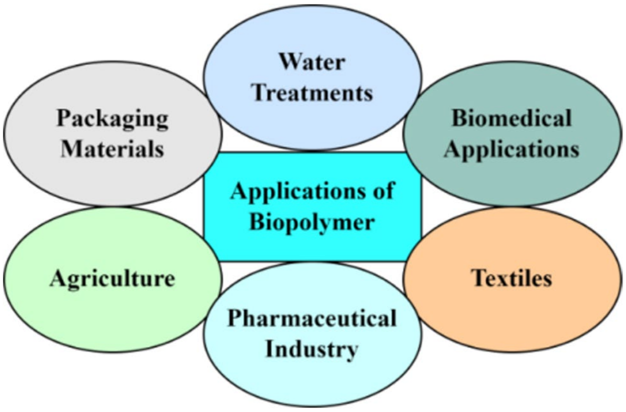


Fig. 2 Schematic diagram of the applications of biopolymers in general

to determine the applicability in smart cities. To progress with the search, it is essential to narrow down the applications to smart and sustainable cities. Others acquire special qualities that could open up a variety of new commercial opportunities, while some biopolymers can directly replace synthetically created materials in typical uses. Established agricultural and chemical corporations as well as small biotechnology companies are researching new biopolymer molecules (Fig. 2). To find the most up-to-date literature on biopolymer composite sensors, academic databases like PubMed, IEEE Xplore, and Google Scholar were used. Here are the six keywords used and named as K1, K2, K3, K4, K5, and K6, respectively, and details are given as follows: K1, biopolymer composite sensors; K2, biopolymer-based sensors; K3, biopolymer nanocomposite sensors; and K4, smart materials for sensing.

The relevant papers out of all keywords together were found to be 80. The biopolymer composites that are utilized for civil engineering applications are shown in Table 1.

Based on the application purpose, the following research questions have been formulated for the literature review.

1. Research Question 1: "How can biopolymer composites be further optimized to enhance sensitivity and selectivity in biosensors for air quality monitoring in smart cities?"
2. Research Question 2: "What are the potential applications and performance improvements of biopolymer composite-based soil sensors in precision agriculture for optimizing irrigation and nutrient management?""
3. Research Question 3: "How can biopolymer composite sensors be tailored and integrated into structural health monitoring systems to ensure resilient and sustainable smart infrastructure in urban environments?"

These research questions explore different aspects of biopolymer composite sensors, their applications in smart cities, and potential areas for further development and optimization. Addressing these questions can contribute to advancements in sensor technology, environmental monitoring, and urban sustainability. The composites can be formed by integrating with various nanostructural materials such as silver nanoparticles [77–83], gold nanoparticles [84, 85], carbon nanospecies [86–88], and Mxene [89–93].

Biopolymer composite sensors have been extensively studied for various applications, including environmental monitoring, biomedical sensing, and smart materials. They offer advantages such as biocompatibility, renewable nature, and potentially lower environmental impact compared to traditional sensor materials. Biopolymer-based nanocomposites usually show excellent stability, maximum accessibility, and even fascinating advantages caused by the interaction of nanoparticles and matrix, in addition to their inherent properties. They are frequently utilized as biosensors [36], antioxidant [93], antibacterial [94, 95], antifouling [96], and drug delivery agents [97]. They are also commonly used as adsorbents for the removal of organic and inorganic pollutants from effluent water solutions [98–100] and energy materials [101].

4 Mechanism of the sensors

Biopolymer composites serve as sensor materials in various applications [102, 103]. The actual mechanism of sensors using biopolymer composites can vary depending on the specific type of sensor and the intended purpose. However, a general overview of how biopolymer composites function as sensors is provided below:

Biopolymer composites can exhibit changes in their physical, chemical, or electrical properties in response to a specific stimulus. This stimulus could be temperature, pressure, humidity, pH, chemical analytes, or biological molecules [104, 105]. The composite's matrix material is biopolymer. Typical biopolymers found in sensor applications are collagen, chitosan, cellulose, starch, and gelatin. The ideal qualities and compatibility with the sensing application determine which biopolymer to be used [106].

A biomolecule, conductive filler, or dye can be used as the composite's sensing agent. The target stimulus must be detected and converted into a measurable signal by the sensing agent [107]. The structure, morphology, or chemical

Table 1 The biopolymer composites that are utilized for civil engineering applications

Biopolymer composite	Source	Purpose
Chitosan-based	Chitin from crustacean shells	Environmental monitoring for detecting pollutants such as heavy metals and pathogens
Alginate-based	Seaweed	Water quality monitoring to detect pH levels, metal ions, and organic pollutants
Cellulose-based	Plant cell walls	Environmental biosensors for detecting pollutants like volatile organic compounds (VOCs) and heavy metals
Gelatin-based	Collagen	Pathogen detection and environmental monitoring of specific bacteria and chemical pollutants
DNA-based	Genetic material	Disease surveillance and pathogen identification in environmental samples

properties of the biopolymer composite are altered when a stimulus interacts with it. Depending on the particular application, these modifications can be irreversible or reversible [108]. A measurable signal is produced by the stimulus-induced modifications in the biopolymer composite. Depending on the kind of sensor, the signal transduction mechanism may use mechanical, optical, or electrical techniques [109]. The presence, strength, or other properties of the stimulus can be ascertained by reading and interpreting the measurable signal that the sensor produces. For analysis or control purposes, this data may be recorded, viewed, or subjected to additional processing [110]. Depending on the needs for sensing, various kinds of biopolymer composites, sensing agents, and signal transduction mechanisms are used [111]. Spectrophotometers or colorimeters can be used to measure the absorbance, fluorescence intensity, or color change of the biopolymer composite [112]. Prior to using any sensor like the pH sensor, calibration is of utmost importance for developing a relationship between the measured signal and the actual values for reliability [113]. The pH value is then ascertained by comparing the measured signal to the calibration curve or reference standards. Depending on how the sensor is designed, the pH data may be shown numerically or understood using color-coded indicators [114]. Sensors can utilize various common sensing mechanisms to detect and measure different physical, chemical, or biological parameters. Some of the commonly used sensing mechanisms in sensors are electrical, optical, piezoelectric, magnetic, thermal, and electrochemical [115].

Electrical sensors measure changes in electrical properties such as resistance, capacitance, or conductivity [116, 117]. Examples include thermistors (temperature sensors), strain gauges (measuring deformation), pH electrodes [118, 119], and humidity [120]. Sensors that use optics can identify variations in polarization in light, wavelength, or intensity by use of concepts of fluorescence, reflection, refraction, or absorption [121, 122]. Optical fiber sensors, spectrometers, and photodiodes are a few examples of the same [123]. Due to chemical reactions at electrode interfaces, electrochemical sensors measure changes in electrical current or potential. Examples are biosensors, pH sensors, and gas sensors (like oxygen or carbon monoxide sensors) [124]. When mechanical stress or pressure is applied, piezoelectric sensors produce an electrical signal [125]. They use materials which generate an electric charge when mechanically distorted, for example: accelerometers, pressure sensors, and ultrasonic sensors [126, 127].

Magnetic sensors use the Hall effect or magnetic materials to detect changes in magnetic fields. They are capable of measuring current, position, and proximity. For example, compasses, magnetic encoders, and magnetic field sensors [128]. Thermal sensors are used in tracking the variation in heat flow or temperature. The concept of infrared radiation, resistance, and other temperature-dependent characteristics are utilized for the same. Infrared sensors, thermistors, and thermocouples are a few examples. Acoustic sensors pick up vibrations or sound waves. They take measurements of variables like phase, amplitude, and frequency. Microphones, vibration sensors, and ultrasonic sensors are a few examples [129].

Biological sensors, also known as biosensors, detect and measure biological or biochemical interactions. They often utilize biomolecules or biological receptors to selectively interact with target analytes. Examples include enzyme-based sensors, immune-sensors, and DNA sensors [130, 131].

Table 2 shows a few examples of the common sensing mechanisms used in sensors in smart city application. Each sensing mechanism has its own principles, advantages, and limitations. The choice of sensing mechanism depends on the specific application and the parameter to be measured. Sensor technologies often combine multiple sensing mechanisms to enhance sensitivity, selectivity, and accuracy in detecting and measuring various parameters [132, 133].

Table 2 Examples of sensing mechanisms used in sensors

Sensing mechanism	Description	Examples
Electrical	Measures changes in electrical properties	Thermistors, strain gauges, pH electrodes
Optical	Detects changes in light intensity, wavelength, or polarization	Photodiodes, spectrometers, optical fiber sensors
Electrochemical	Measures changes in electrical current or potential resulting from chemical reactions	pH sensors, gas sensors, biosensors
Piezoelectric	Generates an electrical signal in response to mechanical stress or pressure	Accelerometers, pressure sensors, ultrasonic sensors
Magnetic	Detects changes in magnetic fields	Compasses, magnetic encoders, magnetic field sensors
Thermal	Measures changes in temperature or heat flow	Thermocouples, thermistors, infrared sensors
Acoustic	Detects sound waves or vibrations	Microphones, ultrasonic sensors, vibration sensors
Biological	Detects and measures biological or biochemical interactions	Enzyme-based sensors, Immunosensors, DNA sensors

5 Use of biopolymer sensors in smart cities

Biopolymer sensors hold significant potential in revolutionizing smart cities by enhancing sustainability and efficiency. These sensors, constructed from renewable materials, offer a greener alternative to conventional plastic-based counterparts. Their integration into urban environments allows for real-time monitoring of crucial parameters like air and water quality, noise levels, and temperature. This data empowers cities to make informed decisions, improving environmental conditions and public well-being. Biopolymer sensors also contribute to waste management, structural integrity monitoring, and energy conservation efforts, thereby optimizing resource allocation. By incorporating these eco-friendly sensors, smart cities demonstrate a commitment to environmentally responsible practices, aligning with broader sustainability goals and fostering a more resilient urban landscape. There are some key points that highlight the role of biopolymer sensors in smart cities and the schematic diagram is shown in Fig. 3.

Biopolymer sensors have the capacity to measure key parameters like air and water quality, noise levels, and temperature. This data is instrumental in the effective management and enhancement of the overall environmental conditions within a city. By providing real-time information on these vital aspects, biopolymer sensors enable timely interventions and informed decision-making to address issues related to pollution, noise levels, and temperature variations. This, in turn, contributes to creating a healthier and more sustainable urban environment for residents and ecosystems alike [134–136].

Integration of biopolymer sensors with IoT (Internet of Things) systems offers a seamless connection that enables the collection and transmission of real-time data. Therefore, these sensors can communicate with other devices and systems within a network which is highly of use for smart city application. It allows for the continuous monitoring of environmental conditions, such as air quality or noise levels, and transmits this data instantly. As a result, city officials and decision-makers have access to up-to-date information which empowers them to make well-informed choices about urban planning and management in changing environmental conditions, contributing to a more adaptive and efficient urban environment [137–139]. Biopolymer sensors play a pivotal role in revolutionizing waste management systems. They are adept at optimizing collection routes and keeping tabs on the fill levels of waste bins. Additionally, these sensors excel in identifying hazardous materials within the waste stream. This integration leads to a marked improvement in the efficiency and sustainability of waste management practices. By utilizing biopolymer sensors, cities can streamline their waste collection processes, ensuring that resources are allocated efficiently. Moreover, the ability to detect hazardous materials enhances safety measures and promotes responsible waste handling. Ultimately, the implementation of biopolymer sensors in waste management systems represents a significant step towards creating cleaner, more environmentally conscious urban environments [134, 135, 140, 141]. By integrating these sensors, cities can take proactive measures to curb wastage and minimize energy expenditure. For instance swiftly detect and rectify any inefficiencies in building systems, ensuring that energy is utilized judiciously. This not only leads to significant cost savings but also aligns with broader sustainability goals by reducing the environmental impact associated with excessive energy consumption [100, 106, 142–154]. Biopolymer sensors can be seamlessly integrated into critical structures such as bridges, roads, and buildings. Their primary function is to meticulously oversee the structural integrity of these constructions. This involves the continuous analysis of various factors that may affect their stability, including signs of wear and tear, stress points, or indications of potential safety hazards [134, 135, 140, 141, 155–160]. By providing real-time data on the condition of these infrastructures, biopolymer sensors empower city planners and engineers to take proactive measures to address any potential issues before they escalate. This not only enhances overall safety but also prolongs the lifespan of vital urban structures, ultimately contributing to the creation of more resilient and reliable urban environments.

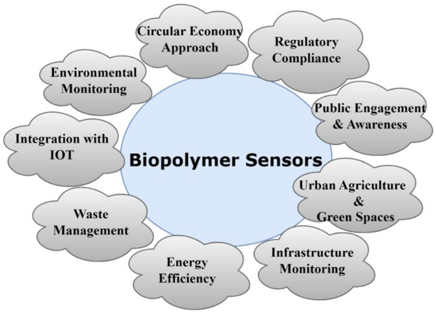


Fig. 3 Role of biopolymer sensors in various applications of smart cities

In urban agriculture and green spaces, the incorporation of biopolymer sensors represents a significant advancement. These sensors are adept at monitoring crucial parameters such as soil conditions, humidity levels, and the overall health of plants. By continuously collecting and analyzing this data, biopolymer sensors provide invaluable insights for optimizing agricultural practices in urban settings. This includes making informed decisions about irrigation schedules, selecting appropriate plant varieties, and applying fertilizers or nutrients as needed [106, 137, 142–144, 146, 147, 161].

Data gathered through biopolymer sensors serves as a powerful tool for fostering public engagement and environmental awareness. By sharing this information with the community, citizens gain valuable insights into the current state of their environment, including factors like air quality, noise levels, and temperature. This transparency not only educates the public about the conditions in their city but also empowers them to take an active role in sustainability efforts. Citizens are more likely to participate in initiatives aimed at reducing environmental impact and improving overall urban well-being.

Biopolymer sensors are invaluable tools in ensuring that cities adhere to regulatory standards for environmental monitoring and reporting. They provide accurate and reliable data on various environmental parameters, such as air and water quality. This information is essential for demonstrating compliance with legal requirements set forth by governing bodies. By utilizing biopolymer sensors, cities can efficiently gather the necessary data and maintain documentation to demonstrate their adherence to environmental regulations [162, 163]. This proactive approach not only helps avoid potential legal issues but also reinforces the city's commitment to responsible environmental stewardship.

Biopolymer sensors play a pivotal role in fostering a circular economy. Their design takes into account what happens at the end of their lifespan. This means that they are intentionally created to be either recyclable or biodegradable. In the context of a circular economy, this approach ensures that once a biopolymer sensor reaches the end of its useful life, it can be reintegrated into the production cycle in an environmentally sustainable manner. Recyclable sensors can be processed and reused in the manufacturing of new products, conserving valuable resources. Meanwhile, biodegradable sensors can naturally decompose, minimizing waste, and environmental impact. This thoughtful design not only aligns with the principles of a circular economy but also contributes to a more sustainable and responsible approach to sensor production and disposal.

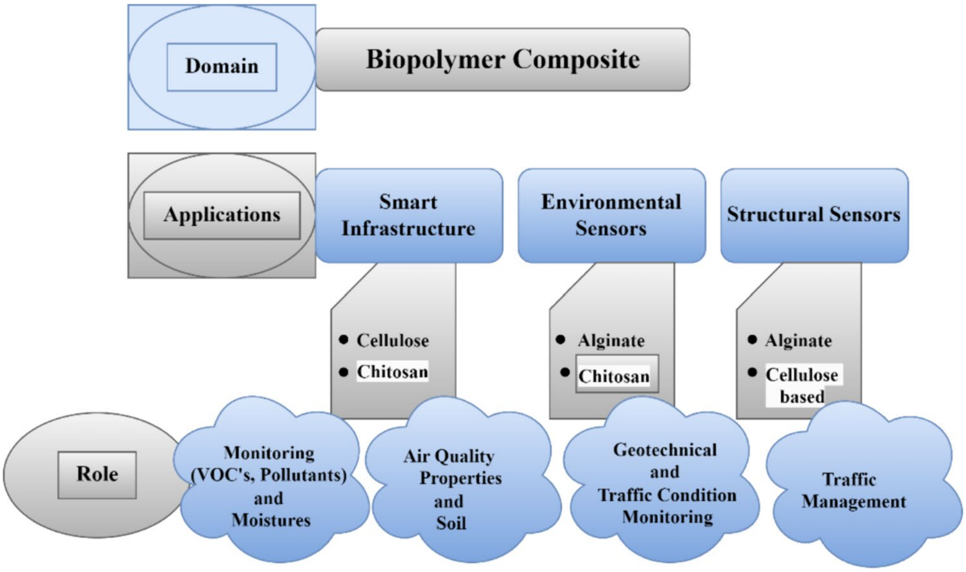
To understand further the usage of these biopolymer composites in smart cities, the role and the mechanism of the different sensors used in the civil engineering application are characterized in Fig. 4.

Further, Fig. 5 describes the different aspects in smart and sustainable cities wherein biopolymer composites are utilized.

6 Specific use of biopolymer in sensors

The choice of biopolymer for a specific sensor application depends on the required properties, target analytes, and environmental conditions of the intended application. Biopolymer composites can be tailored to meet the unique needs of each sensor, making them versatile materials for various smart city applications. As research continues, new biopolymer composites and sensor designs may further expand the possibilities for sustainable and efficient sensor technology in smart cities and related fields [164]. In 2004, M. Rayan and colleagues developed an electronic nose that uses an array of about 32 polymers–carbon black composite sensors. They claimed to have constructed a capable array for identifying and quantifying a broad range of target compounds, including alcohols, aromatics, and isomers. Additionally, a model of the interaction between target molecules and the polymer–carbon black composite sensors is under development. In 2011, Evgeni and co-workers recognized that a significant portion of the population spends most of their time

Fig. 4 Types of sensors based on applications in infrastructure sector



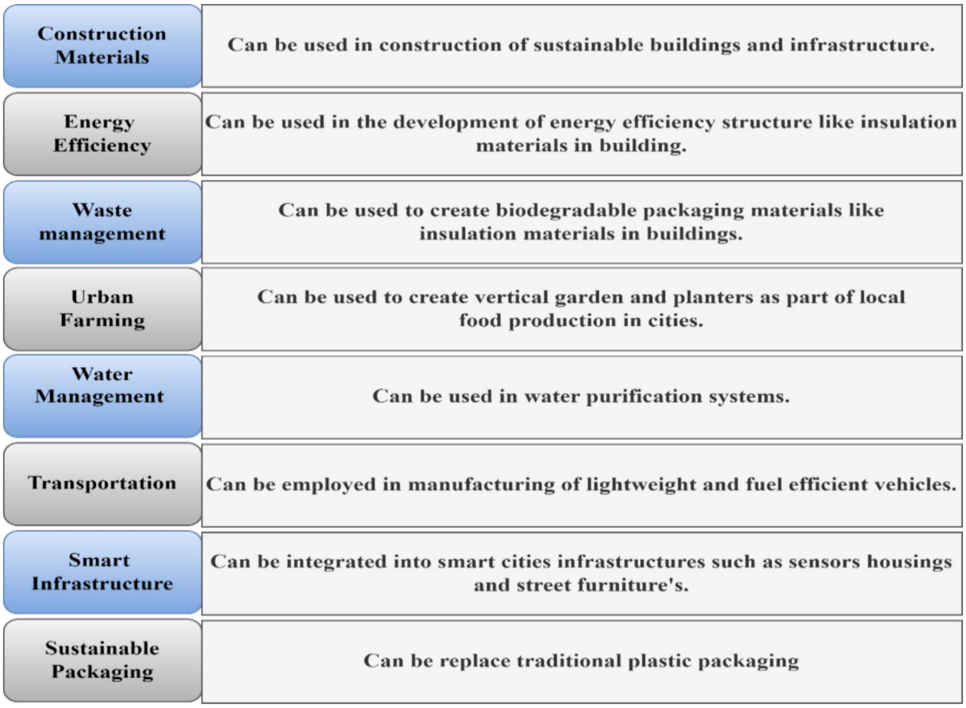


Fig. 5 Multifaceted applications of biopolymer composites in smart and sustainable cities

Construction Materials	**Can be used in construction of sustainable buildings and infrastructure.**
Energy Efficiency	**Can be used in the development of energy efficiency structure like insulation materials in building.**
Waste management	**Can be used to create biodegradable packaging materials like insulation materials in buildings.**
Urban Farming	**Can be used to create vertical garden and planters as part of local food production in cities.**
Water Management	**Can be used in water purification systems.**
Transportation	**Can be employed in manufacturing of lightweight and fuel efficient vehicles.**
Smart Infrastructure	**Can be integrated into smart cities infrastructures such as sensors housings and street furniture's.**
Sustainable Packaging	**Can be replace traditional plastic packaging**

indoors, making indoor air quality crucial. To address this issue, they proposed a sensor for monitoring indoor pollution using bioluminescent bacteria as bioreporters. The authors suggested the use of this system as a portable fiber optic biosensor, which could be part of indoor air pollution alert systems [165].

In 2017, M. Abhilash and his team highlighted the implementation of biopolymers from renewable resources in the fields of science and industry. They emphasized the potential of bionanocomposites made of biopolymers in the creation of chemical sensors, offering enhanced biocompatibility, sensitivity, and selectivity. The coupling of polymers with carbon nanomaterials opens up new avenues for research [166]. A quaternized and crosslinked poly(4-vinylpyridine) and polyaniline and polyaniline bilayer-structured composite humidity sensor was created by Krebsz M. and colleagues that same year. As low as 1% relative humidity could be detected with great sensitivity by this sensor. The concentration of PANI and poly(4-vinylpyridine) as well as the order in which the sensitive layers were deposited affected the composite's ability to sense humidity. Researchers used a carbon nanotube polymer material to create a piezoresistive strain sensor for use in structural health monitoring applications. They improved strain transfer, reproducibility, and linearity by employing the polymer to improve the interfacial connection between the nanotubes. An electrical model for the nanotube strain sensor was developed as a result of this sensor's foundation in electrochemical impedance spectroscopy and strain testing [34]. A unique biochemical oxygen demand (BOD) biosensor for water monitoring was created in 2003 by Jianbo et al. The biosensor made use of co-immobilized *Bacillus subtilis* and *Trichosporon cutaneum* in a composite material derived from sol–gel that included silica and a grafting copolymer of 4-vinylpyridine and poly(vinyl alcohol). When measuring BOD in water samples, the biosensor showed outstanding long-term stability and repeatability [167]. J. Gobet and associates developed a flexible microelectrode array sensor for water quality monitoring that same year. The construction of the array was based on batch microelectronic techniques, which allowed for high-pressure operation for online water quality monitoring and stable passivation of the silicon chip surface. The sensor was used to track the levels of ozone, dissolved chlorine, and dissolved oxygen in different water samples. An overview of electrochemical sensors for the detection of various water contaminants, such as pesticides, nitrates, nitrites, phosphorus, water hardeners, disinfectants, and emerging contaminants, was presented by Kanoun et al. in 2021. They also talked about the effects of using imprinted polymers, metallic nanostructures, and carbon nanomaterials to modify the surface of working electrodes [168]. A moisture microsensor based on the conductive polymer poly(3,4-ethylenedioxythiophene-poly(styrene-sulfonate)) was created in 2008 by Jie Liu and his colleagues. This sensor was capable of detecting gravimetric water content in highly plastic soil samples. The sensor's sensitivity was attributed to changes in the electrical properties of the PEDOT-PSS film in response to moisture content [169]. In 2022, a fully biodegradable paper substrate with enhanced surface properties through cellulose nanofibril (CNF) infiltration was used to create a capacitive moisture sensor. The authors demonstrated that CNF infiltration improved the substrate's moisture response and its suitability for RF passive wireless sensing systems [170]. In the same year, Madhur Atreya and colleagues introduced an electronic soil decomposition sensor using the biopolymer poly(3-hydroxybutyrate/co-3-hydroxyvalerate) as a binder. The sensor relied on the degradation of a printed conductive composite trace and showed a correlation between sensor response and the intensity of microbial decomposition activity in soil [171]. Biological recognition components, such as enzymes, nucleic acids, cells, and tissues, are primarily used in biosensors. Biopolymers are commonly employed as matrices for immobilizing these components due to their biocompatibility and ability to swell in an aqueous environment. Combining biopolymers with various functional components, such as conducting polymers, metal nanoparticles, and carbon-based nanomaterials, enhances their bioanalytical performance in biosensors, particularly electrical biosensors [164]. In 2014, Sheetal Patil and her team developed a small and low-cost piezoresistive microcantilever sensor for measuring soil moisture and relative humidity. The sensor was realized using a nanocomposite made of SU-8 and carbon black and showed sensitivity to humidity changes [172]. In 2003, J. Artigas described the development of a thick-film sensor for soil analysis. This sensor had probes at different depths and a copper plate as a reference electrode. The sensors were calibrated on-site with soil samples, and their results were compared to extracts of soil samples analyzed using the Kjeldahl method. In 2020, Jin Woo Bae prepared an optical biosensor module for detecting soil contamination using bioluminescent bacterial bioreporters encapsulated in poly-dopamine-coated alginate microbeads. The biosensor module demonstrated the potential for monitoring soil contamination, especially in areas with suspected chemical pollution [152]. In 2019, Henning Roedel presented a damage-based model for estimating the compressive strength of biopolymer-bound soil composites. This model predicted the behavior of BSC materials under uniaxial compression and explored various mixture designs with different biopolymer solution contents [144]. In the study of Varma and colleagues, a new capacitive sensor known as "DQN-70," covered with a polymer material, was employed to measure soil moisture content. The performance of the sensor was calibrated using a thermogravimetric method, and the probe's capacitance variations were observed at various moisture levels. Vinay and his associates talked about the effects of MEMS and NEMS technology on integrated agricultural and environmental monitoring systems in 2013. They provide a summary of inexpensive polymers that are utilized in sensing devices to capture environmental factors and soil-related variables [145]. A self-sensing carbon nanotube/cement composite for traffic monitoring was created in 2009 by Han Yu and his colleagues. This composite showed promise for a range of traffic monitoring applications and revealed sensitivity to mechanical stresses caused by traffic flow [149]. A cement composite containing carbon black filler was used as a piezoresistive sensor for traffic monitoring by A.O. Monteiro and associates in 2017. The composite showed reversible and linear pressure-sensing capabilities and was responsive to different compressive loadings that mimicked traffic situations [146]. In the same year, A.O. Monteiro and his team investigated the piezoresistivity of a cement composite with conductive carbon black filler for traffic monitoring. The results demonstrated the potential of such composites as stress-sensitive materials for various traffic monitoring applications [147]. In 2017, Sadasivuni and associates explored biocomposites-based proximity and touch sensors, providing insights into their ambient stimulus detection capabilities [143]. In 2022, Vasudevan and colleagues conducted a review of biopolymers in biosensor applications, focusing on their enhanced properties when combined with various functional components, particularly in electrical biosensors. The review inspired new possibilities in medical diagnostic tests [142].

6.1 Biopolymer composites for civil engineering applications

The research questions formulated provided a wide range of opportunities for the utilization of biodegradable materials, including natural fibers from plant and animal sources, as well as natural and/or synthetic biopolymers. These materials, when combined as composites, are commonly referred to as "biopolymer composites" [106, 150]. The inclusion of natural fibers as reinforcement agents in the discontinuous phase of the continuous biopolymer matrix enhances the stiffness and tensile strength of the resulting composite. The primary objective of such composites is to create products with high mechanical performance and durability by utilizing natural fibers and biopolymers [153]. Biocomposites typically exhibit maximum stiffness and tensile strengths within the ranges of 1–4 GPa and 20–200 MPa, respectively [151]. The adoption of biopolymer composites offers several notable benefits, such as sustainability, economic viability, lightweight characteristics, exceptional specific strength, biodegradability, environmental friendliness through the use of renewable resources, and safety for both manufacturers and consumers [148]. The properties of biopolymer composites are influenced by various factors, including the type of fiber, the percentage of fiber content, moisture absorption of the fiber, surface modification techniques, composite structure, interfacial adhesion between the fiber and matrix, presence of voids, and the incorporation of additives like plasticizers, compatibilizers, nanofillers, and binding agents [138, 161]. The density, water sensitivity, gas permeability, degradability, and shelf life of biopolymer composites are also affected by the reinforcing elements and plasticizers employed. Moreover, the chemical enhancement of biopolymer composite performance depends on the processing methods, specific processing requirements, and environmental conditions [137].

6.2 Biopolymer composites for energy applications

Biopolymers have emerged as a class of materials characterized by their biodegradability, renewable sourcing, and compatibility with various renewable energy sources. The material usage highlights their transformative potential in mitigating greenhouse gas emissions and advancing energy technologies. By offering a sustainable alternative to conventional materials, biopolymers present a pathway toward more environmentally conscious energy solutions. It is imperative to acknowledge the existence of challenges and impediments on the path to mainstream biopolymer integration. These include increasing manufacturing scale, doing in-depth research, and improving economic viability. Overcoming these obstacles will be made possible by the synergy of multidisciplinary collaboration including scientists, engineers, policymakers, and industry stakeholders.

6.3 Biopolymer composites for geotechnical engineering applications

Biopolymer composites are gaining traction in geotechnical engineering due to their potential to provide sustainable, eco-friendly alternatives to traditional materials. There are few key points about the use of biopolymer composites in geotechnical applications as illustrated in Fig. 6.

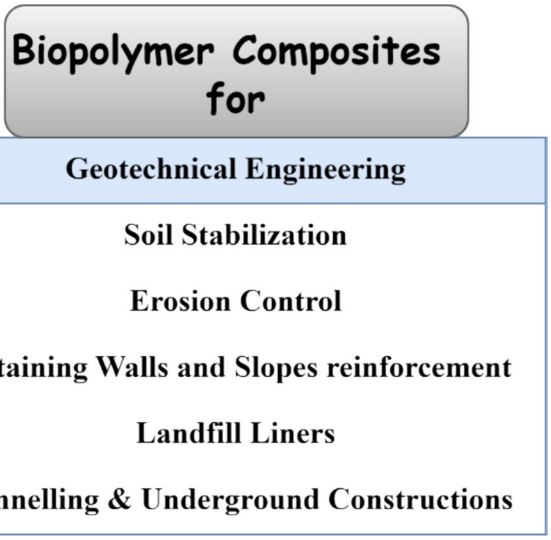


Fig. 6 Use of biopolymer composites in geotechnical engineering

Soil stabilization Biopolymer composites serve as a valuable solution for soil stabilization in geotechnical applications. When integrated with soil, these composite materials work to enhance the soil's load-bearing capacity and overall stability. By effectively blending biopolymer composites with soil, reinforced layers are created that exhibit increased resistance to common issues like erosion and settlement. This reinforcement mitigates the potential for structural failure and instability, making it particularly beneficial in construction projects where strong, stable soil foundations are crucial. This approach not only improves the overall performance and longevity of the engineered structure but also aligns with sustainable practices, as biopolymer composites are derived from renewable resources [139].

Biopolymer composites offer an effective solution for erosion control in areas susceptible to soil erosion. Few examples could be embankments, slopes, and riverbanks. Post application, these composite materials act as a protective barrier against the forces of water flow and wind action. By creating a stable and resilient surface, they effectively impede the loss of soil, safeguarding the integrity of critical landscapes. This application is especially crucial in regions where natural erosion processes can lead to environmental degradation, property damage, and compromised infrastructure. Biopolymer composites provide a sustainable approach towards mitigating erosion since these materials are derived from renewable resources [159].

Biopolymer-based materials present an innovative and eco-friendly option for constructing retaining walls and reinforcing slopes. These materials, derived from renewable sources, offer a sustainable alternative to conventional options such as concrete or steel. When employed in the construction of retaining walls, biopolymer-based materials provide a robust and stable support structure, effectively preventing soil erosion and retaining the integrity of landscapes. Similarly, in slope reinforcement, they bolster the stability of inclines, reducing the risk of landslides or slope failure [155]. This application not only enhances the structural integrity of the landscape but also aligns with environmentally conscious practices, as biopolymer-based materials have a lower environmental impact compared to traditional alternatives. In essence, incorporating biopolymer-based materials in these construction projects represents a significant step towards more sustainable and resilient infrastructure solutions.

Biopolymer composites offer a valuable solution for landfill liners, playing a crucial role in preventing the contamination of surrounding soil and groundwater. These composite materials serve as an impermeable barrier, effectively containing leachate, which is the liquid that results from the decomposition of waste within landfills. What sets biopolymer composites apart is their biodegradability, which can be advantageous in specific applications. Unlike traditional liners made from non-biodegradable materials, biopolymer composites have the potential to naturally break down over time, reducing the long-term environmental impact of landfills. This feature aligns with sustainable waste management practices, making biopolymer-based liners a promising option for more environmentally responsible landfill containment systems.

Tunnelling and under-ground constructions Biopolymer-based materials offer a valuable solution for tunnelling and underground construction endeavors. When applied in these projects, these materials provide essential reinforcement and support for excavated areas. Their inherent strength and stability make them effective in fortifying the surrounding soil or rock, reducing the risk of collapses or structural failures during the construction process. Additionally, biopolymer-based materials offer the advantage of being derived from renewable resources, aligning with sustainable practices [158]. This means that they not only enhance the safety and stability of tunneling and underground construction projects, but also contribute to a more environmentally conscious approach to infrastructure development. In essence, incorporating biopolymer-based materials in these applications represents a significant advancement towards more resilient and sustainable underground structures.

6.4 Biopolymer composites in hydraulics

Biopolymer composites have emerged as a promising choice for crafting essential components in hydraulic systems, including valves, pumps, and actuators. Their mechanical characteristics, including strength, durability, and resistance to wear and tear, render them well-suited for these critical applications. By utilizing biopolymer composites in the production of hydraulic components, manufacturers can benefit from materials that exhibit the necessary performance attributes, while also contributing to sustainability efforts due to their renewable and eco-friendly nature. This integration of biopolymer composites not only enhances the operational efficiency of hydraulic systems but also aligns with the broader industry trend towards more environmentally conscious engineering solutions. The use of biopolymer composites in various fields of hydraulics is explained below and represented in the schematic Fig. 7.

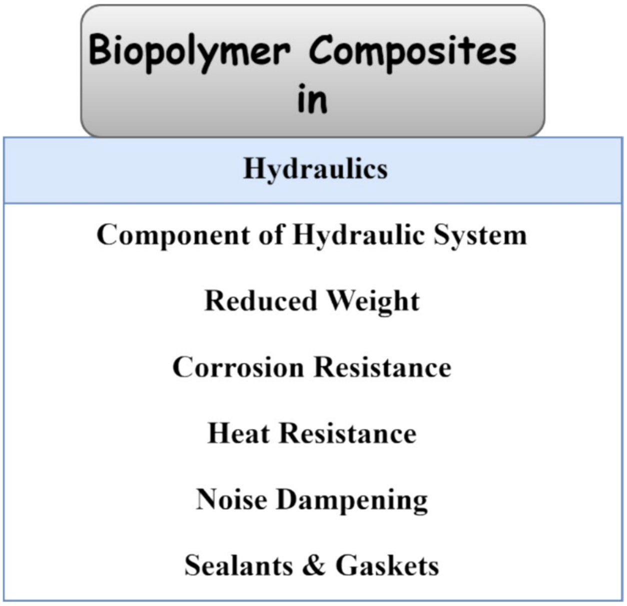


Fig. 7 Schematic diagram representing the use of biopolymer composite in various fields of hydraulics

Biopolymer composites offer a distinct advantage in terms of weight reduction compared to conventional materials such as metals or alloys. Their inherent lightweight nature translates to a significant decrease in the overall weight of hydraulic components. This characteristic is particularly advantageous in applications where minimizing weight is a critical consideration. Lighter components not only facilitate easier handling and installation but also contribute to improved overall system efficiency. Additionally, in sectors like aerospace or automotive industries, where fuel efficiency and payload capacity are paramount, the use of biopolymer composites can lead to notable gains in performance and resource utilization [134]. Thus, the adoption of biopolymer composites for their reduced weight properties presents a practical and impactful advancement in hydraulic system design and engineering.

The resistance of biopolymer composites to corrosion stands as a notable advantage, particularly in hydraulic systems that are frequently exposed to moisture or corrosive fluids. Unlike traditional materials like metals, which can degrade over time when in contact with corrosive elements, biopolymer composites exhibit a high level of resistance to such chemical deterioration. This property ensures that the structural integrity and functionality of hydraulic components remain preserved, even in harsh environmental conditions. By incorporating corrosion-resistant biopolymer composites, manufacturers can extend the lifespan of hydraulic systems and reduce maintenance requirements [135]. This not only enhances the reliability and longevity of the equipment but also contributes to cost savings and overall operational efficiency. In essence, the corrosion-resistant nature of biopolymer composites represents a significant benefit for hydraulic systems operating in challenging and corrosive environments.

Biopolymer composites demonstrate commendable heat resistance, a trait that proves invaluable in hydraulic systems subject to varying temperature conditions. This characteristic ensures that these composite materials maintain their structural integrity and functionality even when exposed to elevated temperatures. In hydraulic systems, where temperature fluctuations are commonplace, having components that can withstand these conditions is crucial for consistent and reliable performance [141]. The heat-resistant nature of biopolymer composites safeguards against deformation, degradation, or loss of mechanical properties, ultimately contributing to the longevity and efficiency of the hydraulic system.

Biopolymer composites offer a valuable feature in hydraulic systems—the ability to contribute to noise reduction. Their unique damping properties play a crucial role in mitigating vibrations and noise generated by the movement of various components. This is especially important in environments where noise levels need to be controlled, such as in industrial settings or applications where sound pollution is a concern. By incorporating biopolymer composites, hydraulic systems can operate with reduced noise emissions, creating a more comfortable and quieter working environment. Additionally, this noise-dampening effect can also lead to enhanced overall system performance, as excessive vibrations and noise can sometimes lead to wear and tear on components. In essence, the inclusion of biopolymer composites for their noise reduction capabilities not only improves the working conditions but also contributes to the efficiency and longevity of hydraulic systems [140].

Biopolymer composites offer a compelling solution for crafting seals and gaskets within hydraulic systems. These critical components play a vital role in preventing fluid leakage and ensuring the proper functioning of the system. Biopolymer composites, known for their robust mechanical properties, provide an effective and reliable sealing solution. Additionally, their environmentally friendly nature sets them apart from conventional sealant materials. Derived from renewable resources, biopolymer composites align with sustainability objectives, reducing reliance on non-renewable resources and minimizing the environmental impact associated with sealant production. This dual advantage of effective sealing performance and environmental friendliness positions biopolymer composites as a highly favorable choice for seals and gaskets in hydraulic systems.

6.5 Biopolymer sensors in construction management

Structural health monitoring Structural health monitoring (SHM) involves the use of specialized sensors to assess the condition and performance of construction elements within buildings, bridges, or other structures. Biopolymer sensors, with their unique properties, offer a novel approach to SHM. They can be seamlessly integrated into building materials, such as concrete or steel, to provide continuous and real-time data on critical structural parameters. This includes information on stresses, strains, and other relevant indicators. This real-time monitoring capability is invaluable as it enables early detection of potential structural issues or deterioration [156]. By embedding biopolymer sensors, construction managers and engineers can stay proactive in addressing any emerging problems, thereby enhancing the safety, durability, and longevity of the structure. Figure 8 represents the use of biopolymer composites in various fields of construction management. This advanced monitoring technique represents a significant advancement in construction practices, facilitating a more sustainable and resilient built environment. Additionally, the use of biopolymer sensors aligns with eco-friendly construction approaches, as they are derived from renewable resources, further emphasizing their contribution to sustainable construction management.

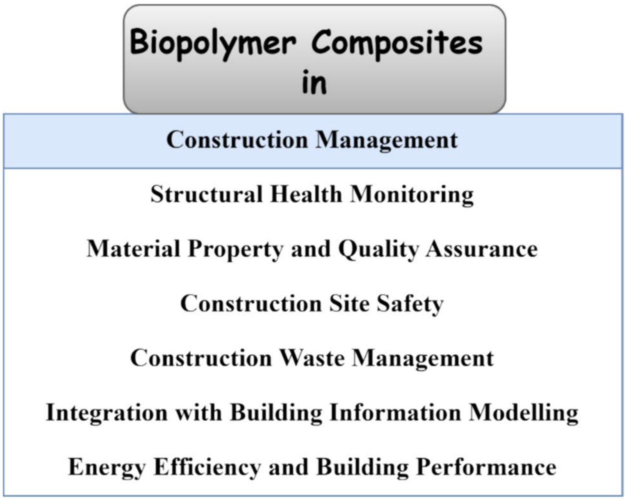


Fig. 8 Schematic diagram representing the use of biopolymer sensors in construction management

Material property and quality assurance The incorporation of biopolymer sensors into construction materials marks a significant leap in quality assurance and material evaluation processes. These sensors, due to their specialized properties, have the capacity to provide detailed assessments of the material properties and overall quality. By embedding these sensors within construction materials, engineers and quality control personnel can conduct on-site evaluations, gaining real-time insights into crucial characteristics like strength, density, and composition. This enables immediate identification of any deviations from specified standards, allowing for timely adjustments or replacements as needed. This proactive approach to quality control greatly reduces the risk of structural failures, ensuring that the final constructed product meets the highest standards of safety and performance. The integration of biopolymer sensors in material assessments not only enhances the reliability of construction projects but also contributes to a more streamlined and efficient quality assurance process in the field of construction management.

Construction site safety Biopolymer sensors play a crucial role in bolstering safety protocols on construction sites. These specialized sensors, when strategically deployed, serve as vigilant monitors for potential hazards. For instance, they can swiftly detect hazardous gas levels, providing an early warning system that enables workers to take immediate action. This early detection capability is paramount in ensuring the well-being of personnel on-site, as it allows for timely evacuation or implementation of safety measures. Additionally, biopolymer sensors can be programmed to alert workers to various dangers, such as unstable structures or unsafe conditions, further fortifying overall safety protocols [157, 163]. By integrating these sensors into construction site operations, companies demonstrate a commitment to prioritizing the welfare and security of their workforce. This proactive approach not only safeguards the lives and health of workers but also contributes to a culture of safety excellence within the construction industry.

Construction waste management Biopolymer sensors introduce a forward-thinking approach to construction waste management. By strategically deploying these sensors, construction sites gain the capability to monitor waste levels in real time. This data provides valuable insights into the volume and types of waste being generated during the construction process. Armed with this information, construction managers can implement more effective waste management strategies, optimizing collection schedules and resource allocation. Moreover, the use of biopolymer sensors supports sustainability goals by reducing the environmental impact associated with waste production. It enables construction sites to minimize the amount of material sent to landfills and promotes recycling efforts by identifying opportunities for material reuse or repurposing. This integrated approach not only improves the efficiency of waste management practices but also aligns with broader environmental conservation initiatives, ultimately contributing to a more sustainable construction industry [173].

Integration with building information modeling (BIM) The integration of biopolymer sensors with building information modeling (BIM) systems represents a significant advancement in construction management. BIM serves as a digital representation of a construction project, incorporating detailed information about its various elements. By integrating biopolymer sensors into this system, construction managers gain a powerful tool for real-time monitoring of structural parameters. This includes data on stresses, strains, and other critical indicators provided by the sensors. This combined approach offers a comprehensive view of construction progress and performance, allowing for accurate assessments of the project's status. The real-time data from biopolymer sensors, when integrated with BIM, enables construction managers to make informed decisions about planning, scheduling, and resource allocation. They can identify potential issues or deviations from the original plan early on, facilitating timely adjustments to maintain project timelines. Additionally, the integration enhances the ability to allocate resources efficiently, ensuring that materials and labor are deployed where they are most needed. Overall, the integration of biopolymer sensors with BIM systems enhances the precision and effectiveness of construction management. It empowers construction professionals to proactively address challenges, optimize resource utilization, and ultimately deliver projects with higher levels of accuracy and efficiency. This integrated approach is a testament to the ongoing technological advancements in the construction industry, driving improvements in project management and execution.

Energy efficiency and building performance The integration of biopolymer sensors into construction materials introduces a ground-breaking approach to enhancing energy efficiency and overall building performance. These specialized sensors have the capability to monitor and collect data on energy usage within constructed spaces. By embedding them within the building materials, engineers and construction professionals can gain real-time insights into how energy is being consumed and utilized. This data serves as a valuable resource for making informed decisions about optimizing energy-efficient practices. For instance, it can reveal areas where energy is being wasted or identify opportunities for implementing more efficient technologies or practices. By leveraging this information, construction teams can make targeted adjustments to improve the building's energy performance. Furthermore, the use of biopolymer sensors supports the broader goal of sustainability in constructed buildings. It allows for the implementation of measures that reduce energy consumption, lower environmental impact, and enhance the overall ecological footprint of the structure [174]. This integrated approach aligns with the global movement towards more sustainable and environmentally conscious construction practices. In essence, the incorporation of biopolymer sensors into construction materials represents a significant step towards creating buildings that not only meet high-performance standards but also contribute to a more energy-efficient and sustainable built environment. This innovative approach stands as a testament to the evolving technology-driven solutions in the construction industry [162, 175].

7 Conclusion and perspectives

There is a lot of potential in using biopolymer composites in the production of sensors for civil engineering and smart city sensing applications. Biopolymer composites are ideal for these kinds of applications because they have a number of special benefits. These benefits include enhanced mechanical qualities, customized sensitivity, and adaptability in manufacturing techniques. In addition, the composites are economical, ecologically friendly, and biocompatible, all of which are in line with the rising need for sustainable methods in IoT and civil engineering. Biopolymer composites are perfect for a variety of sensing applications since they can be precisely adjusted to detect particular analytics. They are appropriate for disposable or environmental monitoring sensors due to their biodegradability and renewable supply, which also lessen their influence on the environment. These composites' potential uses in industries including consumer electronics, healthcare [176], and environmental monitoring are increased by their capacity to be engineered to show various electrical characteristics, which enable them to be used in resistive, capacitive, and piezoelectric sensors. The study described in this paper demonstrates a number of fascinating developments and uses of biopolymer composites in sensor technology. For example, piezo-resistive strain sensors for structural health monitoring have been developed by combining carbon nanotubes with biopolymer composites, which provide enhanced linearity, repeatability, and strain transmission. Additionally, a novel BOD biosensor was developed using co-immobilized microorganisms in a sol–gel-derived composite material, demonstrating excellent repeatability and long-term stability for water monitoring.

The advancement of novel biopolymeric materials with improved properties, such as enhanced thermal stability and electrical conductivity, is directly related to the development of smart cities. These materials can be applied in various smart city infrastructure components, such as energy-efficient buildings, sensors, and renewable energy systems, contributing to improved sustainability and resource efficiency. Additionally, conducting rigorous environmental assessments of biopolymeric energy solutions aligns with the smart city concept's focus on environmental sustainability and the reduction of ecological footprints, making it essential for the development of eco-friendly and resilient urban environments.

Moreover, the integration of biopolymer composites in electrical biosensors has shown promising results for detecting various substances, including moisture content in soil and toluene in soil as a model pollutant. These sensors exhibited reliable responses and could be employed in soil contamination tracking applications. Another notable development includes the use of biopolymer-bound soil composites for building materials, with damage-based models predicting their compressive strength, which could have potential implications for sustainable construction practices. Overall, the utilization of biopolymer composites in sensing applications offers a path towards smart, sustainable cities and infrastructure. As research continues, these materials are expected to play an increasingly significant role in sensor technology, providing innovative, eco-friendly solutions to address various challenges in civil engineering, environmental monitoring, and beyond. The potential for biopolymer composites to contribute to a more sustainable and interconnected world is considerable, making them a promising avenue for future sensor manufacturing and IoT applications.

Author contribution Xingkui Guo and Hua Hou conceived and supervised the research. Xingkui Guo, Hua Hou, and Duo Pan built the framework and organized the figures. Bingkun Liu, Anjana S. Desai, Xiaolu Sun, Juanna Ren, Neeru Bhagat, Habib M. Pathan, Vaishnavi Dabir, and Aparna Ashok wrote the initial manuscript under the guidance of Xingkui Guo, Hua Hou and Neeru Bhagat. All authors have provided feedback and contributed to the manuscript writing.

Data availability The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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