

Real-Time Monitoring in Polymer Composites: Internet of Things Integration for Enhanced Performance and Sustainability — A Review

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This review article critically examines the integration of Internet of Things (IoT) sensors and wireless technology into polymer composites, highlighting its transformative potential in materials science. The focus is on real-time monitoring of key parameters such as temperature, stress, strain, humidity, and environmental exposure, which are essential for predictive maintenance and performance optimization. This review covers existing research and technological developments in IoT-enabled polymer composites, including sensor technologies, data transmission, cloud-based analysis, and digital twin creation for rapid design optimization and troubleshooting. The scope of this review does not extend to experimental procedures for sensor integration, detailed material property enhancements unrelated to IoT technologies, or the development of new composite materials without IoT integration. Key challenges such as standardization, data security, and system interoperability are discussed, and future research directions are proposed. By defining the scope and boundaries of the discussion, this review provides a comprehensive overview of how IoT integration is advancing the performance, reliability, and sustainability of polymer composites across industries such as aerospace, automotive, and infrastructure.

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INTRODUCTION

As industries increasingly require advanced materials with superior properties, lignocellulose-based polymer composites have emerged as a key solution due to their unique combination of sustainability, strength, lightness, and versatility (Manickaraj *et al.* 2024b; Palaniappan *et al.* 2024a). Lignocellulosic materials composed of cellulose, hemicellulose, and lignin are abundant in natural fibers and are obtained from agricultural and forestry residues as well. Their renewable and biodegradable nature makes them highly attractive as reinforcing agents in polymer composites, especially in an era where environmentally friendly solutions are in high demand. By combining polymer matrices with lignocellulosic fibers or particles, these composites can be tailored to meet specific performance requirements in a wide range of applications, from automotive and construction to consumer products and packaging. This adaptability makes them invaluable in industries where performance, weight, and sustainability are paramount (Vasoya 2023; Velrani *et al.* 2025).

The necessity of automation, detection, and control systems has recently grown in many chemical processes within the polymer composite industry. However, the life cycle management of lignocellulosic-based composites presents significant challenges, particularly due to their heterogeneous structure and sensitivity to environmental conditions. The integration of the Internet of Things (IoT) and machine learning (ML) offers innovative solutions to these challenges and enhances the functionality and reliability of polymer composites throughout their life cycle. An IoT involves the interconnection of physical devices equipped with sensors, software, and other technologies that enable them to collect and exchange data. When applied to lignocellulosic polymer composites, IoT technology enables real-time monitoring of performance metrics such as temperature, humidity, stress, and strain (Ammar *et al.* 2022; Vasoya 2023). By embedding IoT sensors into these bio-composites, manufacturers gain continuous insight into material behavior under varying conditions, which improves the understanding of durability and structural integrity.

Real-time monitoring is critical in environments where lignocellulosic composites are exposed to fluctuating or extreme conditions, such as automotive and outdoor applications. For instance, structural health monitoring in such settings ensures early detection of material degradation, minimizing risks and enhancing safety (Manickaraj *et al.* 2024a; Ramasubbu *et al.* 2024). Data collected *via* IoT sensors can be transmitted to cloud platforms for further analysis, allowing engineers to evaluate long-term performance trends. Leveraging this data, organizations can make informed decisions regarding maintenance schedules, design optimization, and operational practices to extend material lifespan. Additionally, ML plays a vital role in processing and analyzing IoT-generated data. ML algorithms are capable of identifying patterns and correlations in large datasets that manual methods may miss (Chinchanikar and Shaikh 2022). When trained on historical performance data, these algorithms can predict future behavior under specific environmental and mechanical conditions. This predictive capability is particularly useful for maintenance planning, enabling proactive repairs and reducing downtime and unplanned costs (Baduge *et al.* 2022).

The synergy between IoT and ML is also transforming the manufacturing process of lignocellulosic polymer composites. Smart manufacturing systems equipped with IoT can continuously monitor parameters such as temperature, pressure, and resin flow during processing. ML algorithms analyze this data in real time to optimize conditions for

preserving fiber integrity and ensuring desired composite properties (Bin Abu Sofian *et al.* 2024). For example, in additive or compression molding techniques, adjusting processing variables on-the-fly can lead to better surface finishes, mechanical strength, and reduced material waste. This dynamic control not only improves product quality but also enhances overall manufacturing efficiency (Aruchamy *et al.* 2024; Ramakrishnan *et al.* 2024). Natural fiber composites are complex and heterogeneous, making it challenging to monitor their structural integrity and accurately predict potential failures. For this reason, the integration of the IoT sensors to the process of natural fiber composites will be useful for the manufacturing process and service life quality of these composites. Given the complex and heterogeneous nature of natural fiber composites, real-time structural monitoring using IoT has potential benefits for both the production and service life stages of the material.

Sustainability is a growing concern across all industries, and the integration of IoT and ML supports more sustainable lifecycle management of polymer composites. IoT devices can track environmental impacts from production to disposal, including resource consumption, emissions, and waste generation (Nair *et al.* 2013; Azad *et al.* 2024). These insights help organizations make responsible decisions to minimize environmental footprints. Moreover, ML can improve recycling processes for lignocellulosic composites, which are often difficult to separate due to their mixed organic and synthetic nature (Kurien *et al.* 2023; Sathish *et al.* 2024a). By analyzing material composition and degradation patterns, ML can guide the development of more effective recycling methods, thus supporting circular economy initiatives within the composites industry (Gomez *et al.* 2022).

Despite their many advantages, the integration of IoT and ML into lignocellulosic composites faces several challenges. Effective ML models require high-quality and diverse datasets, which are often hard to obtain in experimental materials science (Gurusamy *et al.* 2024). Integrating IoT systems into traditional manufacturing setups can also be complex, involving sensor embedding, data communication, and cybersecurity considerations. Furthermore, the success of these technologies depends on the availability of skilled professionals—from data scientists to materials engineers—who can bridge the gap between physical composites and digital systems (Manickaraj *et al.* 2022). Specialized knowledge is essential to ensure that embedded sensors do not compromise the composite's mechanical performance or structural integrity. Moreover, managing the vast amount of data generated by IoT devices is a significant hurdle. Looking ahead, the adoption of IoT and ML in lignocellulose composites is expected to increase, driven by technological progress and the growing need for efficiency and sustainability. This encompasses data scientists, who are capable of developing and refining algorithms, as well as engineers who possess a comprehensive understanding of both materials and digital technologies. As industries continue to evolve, it is imperative to invest in education and training to leverage the full potential of these advanced technologies (Palanisamy *et al.* n.d.; Sathesh Babu *et al.* n.d.). The integration of the IoT devices with polymer composites is a complex process, requiring specialized knowledge and expertise. Moreover, technical challenges related to integrating devices into polymer composites in a manner that does not affect their performance or integrity. Effective administration and analysis can be challenging due to the enormous volume of data generated by IoT devices. In the future, it is anticipated that there will be an increased integration of the IoT and ML in polymer composites, driven by technological advancements and a growing emphasis on sustainability and efficiency (Janeliukstis and

Mironovs 2021). Research will likely focus on robust sensor systems, efficient data processing, and intelligent algorithm design, as well as the creation of protocols and standards for secure data sharing and system interoperability. Furthermore, the establishment of standards and protocols for data sharing and security is anticipated to be pivotal in fostering collaboration across diverse sectors and ensuring the safe utilization of these technologies (Sathish *et al.* 2024b).

The current body of research on polymer composites has focused extensively on enhancing mechanical, thermal, and environmental properties through the incorporation of advanced fibers and fillers. A notable area of development has been the integration of sensors, particularly fiber Bragg grating (FBG) sensors, to monitor strain and temperature changes in composite materials (Zhou *et al.* 2016; Kakei and Epaarachchi 2018). These efforts have demonstrated the feasibility of embedding sensors within composites for real-time monitoring, but their application has often been restricted to controlled laboratory environments, limiting scalability and industrial adoption (Zhang *et al.* 2011). Studies have highlighted the use of polymer-based FBG sensors for measuring humidity and strain, revealing promising potential for structural health monitoring (Rajan *et al.* 2014). However, challenges related to the standardization of sensor integration methods, data management, and energy efficiency remain unresolved (Luyckx *et al.* 2009). Environmental sensors have also been employed to assess exposure conditions and detect material degradation in composites (Zhang *et al.* 2015), though most research has focused on the recyclability and eco-friendliness of composite materials rather than leveraging real-time monitoring data (Leng and Asundi 2002). Despite these advancements, the literature indicates a gap in developing fully integrated, scalable systems for predictive maintenance and data-driven decision-making in polymer composites.

The integration of IoT and machine learning into the lifecycle management of lignocellulosic polymer composites presents significant opportunities to enhance material performance, manufacturing efficiency, and sustainability (Ahmed *et al.* 2021). Through real-time monitoring, predictive analytics, and data-driven optimization, these technologies empower manufacturers to improve reliability and resource efficiency. As industries increasingly embrace bio-based materials and digital innovation, the synergy of IoT and ML will be a driving force in shaping the future of sustainable composite applications across various sectors (Gokul *et al.* 2024).

IoT Sensors in Polymer Composites

The integration of IoT sensors within polymer composites represents a transformative advancement in the domains of material science and engineering. By integrating these sensors directly into composite structures, manufacturers can achieve continuous monitoring of critical parameters that influence performance and durability (Senthilkumar *et al.* 2021). This real-time data collection is essential for understanding how materials behave under varying operational conditions, leading to improved safety, reliability, and overall performance.

Types of IoT sensors

The sensors utilized in polymer composites can be classified according to the parameters they measure. Each sensor plays a crucial role in the monitoring of material performance and the assurance of longevity. The IOT sensors are displayed in Fig. 1.

Temperature sensors

Temperature is one of the most fundamental and significant factors in analyzing and controlling a variety of technical processes in the manufacture and processing of polymer composites. Particularly, thermal sensing is essential for controlling the thermal degradation temperature of natural fillers, melting, and rheology of the polymer matrix. In numerous cases, direct contact measurements are not feasible due to the examined movement of the material, distance, or temperature (Chen *et al.* 2016; Everton *et al.* 2016).

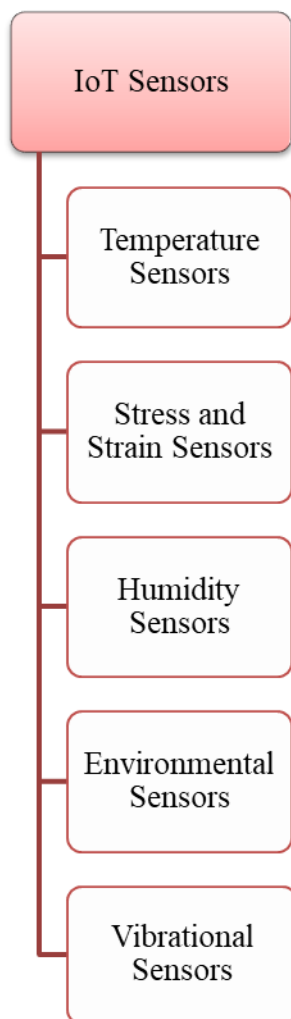


Fig. 1. Various IOT sensors used for real-time monitoring in polymer composites

Accurate and automated temperature determination is required for complex heat-treatment procedures, along with quick correction and error management. Fiber optic sensors may be the most suitable choice as temperature meters in many situations for several reasons such as unfavorable conditions including electromagnetic or ionizing radiation, excessively high or low pressure, and a chemically aggressive environment (Ramakrishnan *et al.* 2016).

Temperature sensors are integral for the monitoring of the thermal conditions that polymer composites experience throughout their lifecycle (Nielsen *et al.* 2014; Duan and Liu 2024). Temperature fluctuations can significantly affect the properties of polymers, such as viscosity during processing and mechanical strength post-curing. For instance,

excessive heat can lead to thermal degradation, altering the composite's structural integrity. By providing continuous temperature data, these sensors enable engineers to optimize processing conditions and maintain quality control. This capability is particularly vital in high-performance applications like aerospace, where even minor temperature fluctuations can have a significant impact on safety and functionality. Different types of temperature sensors can be utilized for the real-time monitoring of composite materials. Common properties, values, and parameters of different sensors are given in Table 1. Thermocouples are a popular option due to their broad temperature range and availability in various types. While they do have some drawbacks, such as potential drift and sensitivity issues, they are well-regarded for their high accuracy (Lu *et al.* 2018).

Table 1. Various Temperature Sensors Used for Real-Time Monitoring of Composites (Arockiasamy *et al.* 2023; Ge *et al.* 2023)

Temperature Sensor	Properties	Values	Parameters
Thermocouples	Such as type K, J, T, E	-200 to 1750 °C	Response time, accuracy, drift, sensitivity
Resistance Temperature Detectors (RTDs)	Such as platinum, nickel, copper	-200 to 850 °C	Resistance, α -value, linearity, hysteresis
Thermistors	NTC, PTC	-100 to 300 °C	Resistance, β -value, accuracy, interchangeability
Infrared Thermometers	-	-50 to 3000 °C	Emissivity, wavelength, distance-to-spot ratio, ambient temperature
Fiber Optic Sensors	Such as Bragg grating, Fabry-Perot-	-200 to 1000 °C	Strain, temperature, accuracy, resolution, bandwidth
Surface-mounted Temperature Sensors	Diodes, ICs	-55 to 150 °C	Response time, accuracy, stability, package type

Stress and strain sensors

Stress and strain sensors, including strain gauges and piezoelectric sensors, are imperative for the assessment of polymer composite deformation under load. These sensors offer real-time insights into the mechanical behavior of the material during operational conditions (Zhao *et al.* 2023). This data is critical for applications where structural integrity is paramount, such as in aerospace and automotive components. Understanding how materials respond to dynamic loads allows engineers to design components that can withstand expected stresses, enhancing safety and performance. Moreover, continuous monitoring enables the identification of potential failure points before they lead to catastrophic failures, facilitating predictive maintenance strategies.

Strain sensors are essential for the real-time monitoring of composite materials, as they provide important information about the loads and stresses applied to these materials (Ramakrishnan *et al.* 2016; Qureshi *et al.* 2020). The most commonly used types of strain sensors in composites include electrical resistance strain gauges, optical strain sensors, and piezoelectric sensors.

Humidity sensors

Humidity sensors measure moisture levels within and around polymer composites. High humidity can significantly impact the properties of these materials,

leading to issues such as hydrolysis or degradation of the polymer matrix (Ma *et al.* 2023; Qian *et al.* 2024). These changes in turn affect the mechanical properties and durability of the materials. It is therefore vital to monitor humidity levels in environments where composites are exposed to varying moisture conditions, such as in construction or marine applications. The integration of humidity sensors within the manufacturing process enables manufacturers to develop a more profound understanding of the environmental factors that influence composite performance (Ogunleye *et al.* 2024). This, in turn, facilitates informed decisions regarding material selection and the implementation of effective maintenance practices.

Environmental sensors

Environmental sensors are designed to detect exposure to various external factors, including chemicals, extreme temperatures, and UV radiation. These sensors assess how such conditions influence the longevity and reliability of polymer composites. For example, exposure to harsh chemicals can lead to chemical degradation, while UV radiation can cause surface damage over time (Butt *et al.* 2022). Continuous monitoring of these environmental parameters enables manufacturers to gain insights into the material's behavior and performance under real-world conditions. This information is invaluable in the development of more resilient materials and the improvement of the overall lifecycle management of polymer composites, ultimately enhancing product reliability, and safety in demanding applications. Each type of IoT sensor contributes uniquely to the comprehensive monitoring and management of polymer composites, ensuring that these materials meet the rigorous demands of various industrial applications (Gangwar and Pathak 2021; Vasoya 2023).

Vibration sensors

Vibration sensors are crucial for real-time monitoring of composites to evaluate the dynamic loads and vibrations that the material encounters. Accelerometers and piezoelectric sensors are the two primary types of vibration sensors used in composite materials (Ogunleye *et al.* 2024). Accelerometers measure the acceleration of a material and convert it into an electrical signal. This provides insights into both the frequency and magnitude of the vibrations. Piezoelectric sensors utilize the piezoelectric effect to generate an electrical voltage that is proportional to the mechanical stress applied. This enables the measurement of vibration and dynamic loads on composite materials. The primary benefits of using vibration sensors for composites are their ability to monitor in real-time and their precision. They deliver real-time information on dynamic loads and vibrations, allowing for the early detection of potential issues and enhancing predictive maintenance. For example, Chen *et al.* (2016) investigated the application of IoT sensors to cement bonded natural fiber composites, allowing for the real-time data collection and communication. It enables buildings to adapt to changing conditions and efficiently utilize data resources for self-optimization (Mishra and Tyagi 2022). In another study, Dinesh *et al.* (2023a,b) developed a self-sensing cement composite that includes carbon fibers, which can be used for structural health monitoring. This innovation demonstrates the potential of using sensor-embedded fiber concrete for infrastructure monitoring.

Real-Time Monitoring

The integration of IoT sensors into polymer composites offers a range of significant benefits that enhance material performance, safety, and efficiency across

various applications (Karuppiah *et al.* 2022; Nithyanandhan *et al.* 2022). The most prevalent applications of the real-time monitoring system are illustrated in Fig. 2.

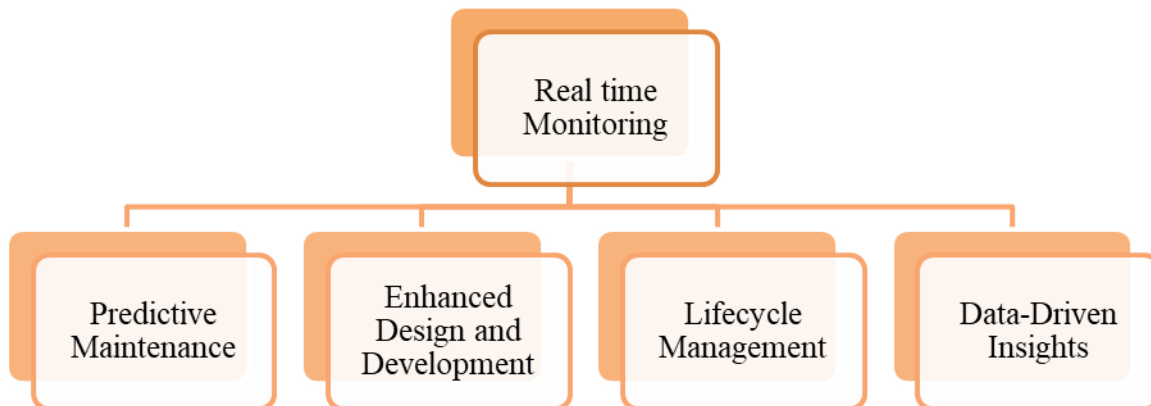


Fig. 2. Various IoT sensors for real-time monitoring in polymer composites

Predictive maintenance

Continuous monitoring through IoT sensors enables the early detection of potential failures in polymer composites. This proactive approach is crucial in industries such as aerospace and automotive, where material integrity is paramount for safety (Ranasinghe *et al.* 2022). By identifying signs of wear or stress before they lead to catastrophic failures, manufacturers can schedule maintenance more effectively, minimizing downtime and reducing the risk of accidents.

Enhanced design and development

Real-time data feedback from IoT sensors aids engineers and researchers in refining material formulations and processing techniques. This allows for more precise tailoring of material properties to meet specific application needs, leading to the development of high-performance composites that can better withstand the demands of their intended use (Vasoya 2023; Parekh and Mitchell 2024). For instance, real-time insights can inform adjustments in the mixing ratios of polymers and additives, optimizing the final product's mechanical and thermal properties.

Lifecycle management

By continuously monitoring the health of polymer composites throughout their lifecycle, manufacturers can optimize maintenance schedules and improve resource efficiency. This holistic view of material performance enables better planning for repairs or replacements, ultimately extending the lifespan of components and reducing overall operational costs (Roy *et al.* 2016; Kabashkin *et al.* 2024). For example, in construction, understanding how materials perform over time can inform decisions on maintenance interventions, preventing premature failures, and ensuring safety.

Data-driven insights

The aggregation of data from multiple sensors allows for advanced analytics and the development of predictive models. These models can forecast material performance under various environmental and operational conditions, enabling manufacturers to make informed decisions about material selection, design modifications, and process improvements (Krishnamurthi *et al.* 2020). This data-driven approach not only enhances

the reliability of polymer composites but also supports continuous innovation in material science. In summary, the integration of IoT sensors in polymer composites provides a wealth of benefits that lead to improved safety, enhanced product performance, and greater efficiency in manufacturing and lifecycle management. This transformative technology is paving the way for smarter, more resilient materials capable of meeting the evolving demands of modern industries (Aheleroff *et al.* 2022).

Environmental Monitoring in Real-time

Environmental sensors are essential for monitoring the conditions surrounding polymer composites, providing critical insights into factors that can significantly influence their performance and durability (Palanisamy *et al.* n.d.; Yang *et al.* 2017). Various external conditions, such as humidity, temperature fluctuations, and exposure to chemicals, can alter the properties of polymer materials. By integrating these sensors into composite structures, manufacturers can continuously assess the environmental factors impacting their products (Roy Choudhury 2014; Mamun and Yuce 2020; Chithra *et al.* 2024). The environmental monitoring is shown in Fig. 3.

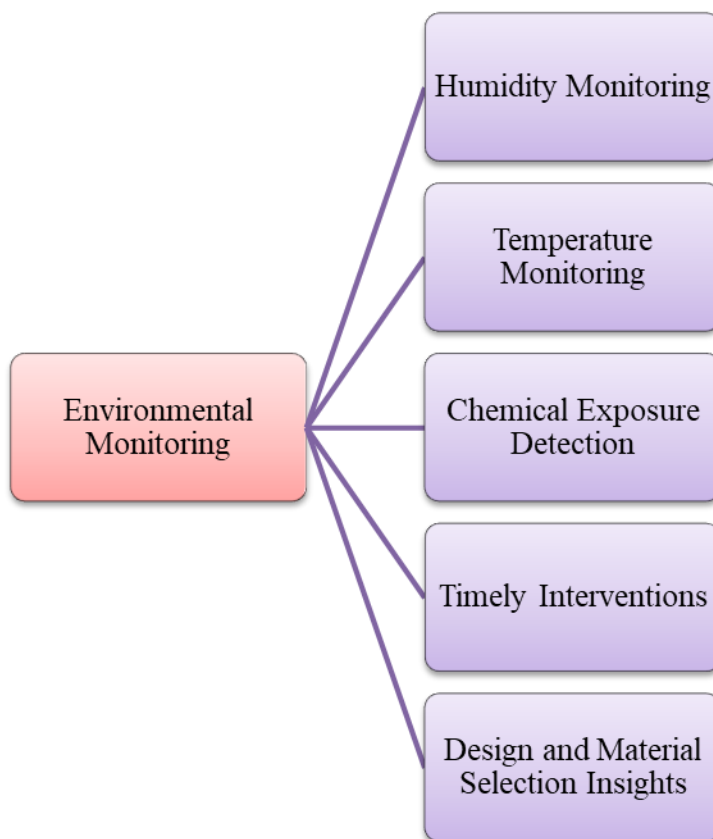


Fig. 3. Real-time environmental monitoring

Humidity monitoring

One key role of environmental sensors is to measure humidity levels, which are crucial for understanding moisture absorption in polymer composites. High humidity can lead to hydrolysis, weakening the polymer matrix and compromising its mechanical strength. Continuous humidity monitoring enables manufacturers to detect rising moisture levels and take preventive measures (Barreira-Pinto *et al.* 2023). This could

include applying moisture barriers or using desiccants in storage areas to reduce exposure. By managing humidity effectively, manufacturers can prolong the life of the composites and ensure consistent performance under varying environmental conditions.

Temperature monitoring

Environmental sensors also track temperature extremes, which can cause thermal expansion or contraction in polymer composites. These fluctuations can lead to stress fractures or warping, significantly impacting the material's structural integrity. By monitoring temperature in real time, manufacturers can identify potential risks associated with thermal cycling. This information allows for better design choices and the implementation of thermal protection strategies, such as insulation or temperature control systems. Ultimately, effective temperature management enhances the reliability and longevity of composite materials in demanding applications (Cai *et al.* 2022; Yang *et al.* 2023).

Chemical exposure detection

Exposure to chemicals is a significant concern in many industries that utilize polymer composites. Environmental sensors can detect harmful substances or corrosive agents that may degrade the composite over time. This capability is particularly important in sectors like construction and manufacturing, where materials may be exposed to solvents, acids, or other reactive compounds (Al-Okby *et al.* 2021). By monitoring chemical exposure continuously, manufacturers can implement protective measures, such as selecting more resistant materials or applying protective coatings. This proactive approach minimizes the risk of degradation and ensures that the composites maintain their intended properties.

Timely interventions

Real-time monitoring facilitated by environmental sensors allows for timely interventions to address potential issues before they escalate. For example, if sensor data indicates that humidity levels are rising to a threshold that could lead to degradation, manufacturers can take proactive measures, such as adjusting ventilation systems or applying protective coatings, to mitigate potential damage. This not only helps maintain the integrity of the materials but also extends their lifespan, resulting in cost savings, and enhanced performance (Alrashdi and Alqazzaz 2024; Bhardwaj and Joshi 2024).

Design and material selection insights

Furthermore, the insights gained from environmental monitoring can inform the design and selection of materials that are better suited for specific applications. Understanding how different environmental conditions affect material behavior enables engineers to make informed decisions regarding composite formulations. By selecting polymers that exhibit greater resistance to humidity, temperature fluctuations, or chemical exposure, manufacturers can enhance the durability and reliability of their products (Kangishwar *et al.* 2023). This knowledge ultimately leads to more robust designs that can withstand the rigors of real-world applications. In summary, environmental sensors play a pivotal role in monitoring the conditions affecting polymer composites. Through humidity, temperature, and chemical exposure monitoring, manufacturers can ensure material integrity and make informed decisions that enhance the performance and longevity of their products (Liang 2021; Pajic *et al.* 2024).

IoT-Enabled Polymer Composites: Technologies and Applications

The integration of Internet of Things (IoT) technologies into polymer composites represents a significant leap in materials science and engineering. IoT sensors embedded within composites enable real-time monitoring of critical parameters, offering unprecedented insights into their performance and behavior under various environmental and mechanical conditions (Davim 2017).

Technologies in polymer composites

Modern IoT sensors are miniaturized devices capable of detecting a variety of parameters such as temperature, strain, stress, humidity, vibration, and environmental exposure. These sensors can be embedded directly into polymer matrices or surface-mounted, enabling seamless data collection without compromising material integrity. The choice of sensors depends on the targeted application and the operational environment. For example, fiber optic sensors are commonly used for strain monitoring due to their high sensitivity and durability, while capacitive and resistive sensors are employed for moisture and temperature sensing (Solanki *et al.* 2019).

Wireless technologies, such as Bluetooth Low Energy (BLE), ZigBee, LoRaWAN, and emerging 5G networks, facilitate the transmission of collected data to cloud-based platforms for further analysis. These protocols are selected based on required data rates, range, power consumption, and environmental constraints. For instance, BLE and ZigBee are favored in localized environments due to their low energy consumption and moderate range, while LoRaWAN and cellular networks are suitable for long-range data transmission in infrastructure and remote monitoring applications (Davim 2024a).

Current industrial applications

The integration of Internet of Things (IoT) technologies into polymer composites has gained considerable traction across various industrial sectors, enabling enhanced performance monitoring, predictive maintenance, and improved safety (Davim 2025b).

Aerospace

In aerospace, IoT-enabled polymer composites are extensively used for structural health monitoring of critical airframe components such as wings, fuselage sections, and control surfaces. Embedded sensors continuously track parameters including strain, temperature, and vibration, enabling early detection of issues such as micro-cracks, delamination, or impact damage. This real-time monitoring helps prevent catastrophic failures, reduces maintenance costs, and extends the service life of aircraft components. The data collected also supports the development of digital twins, virtual replicas of physical structures, that allow engineers to simulate various flight scenarios and predict material behavior under different stress conditions.

Automotive

Within the automotive industry, IoT sensors integrated into polymer composites monitor body panels, chassis components, and under-the-hood parts exposed to harsh mechanical and thermal conditions. These sensors enable continuous assessment of fatigue, wear, and thermal cycling effects on composite materials. This leads to enhanced vehicle safety, better quality control during manufacturing, and proactive maintenance scheduling. Moreover, the data generated facilitates optimization of composite design for

weight reduction and fuel efficiency, aligning with industry trends toward electrification and sustainability.

Infrastructure and Civil Engineering

IoT-enabled composites are increasingly utilized in infrastructure applications, including bridges, pipelines, and wind turbine blades. Sensors embedded within these structures monitor stress accumulation, corrosion, temperature fluctuations, and environmental exposure in real time. Early detection of structural fatigue or environmental degradation allows timely repairs, reducing the risk of catastrophic failures and costly downtime. This continuous health monitoring supports asset management strategies, improving the longevity and safety of critical infrastructure while reducing maintenance expenditures.

Energy Sector

In renewable energy systems, polymer composites equipped with IoT sensors are deployed in wind turbine blades and solar panel components. These sensors monitor operational parameters such as strain, temperature, and vibration to optimize performance and facilitate predictive maintenance. Continuous condition monitoring helps identify potential failures before they occur, enhancing reliability and reducing operational costs. Data-driven insights also support design improvements to increase energy capture efficiency and material durability, contributing to the overall sustainability of energy infrastructure.

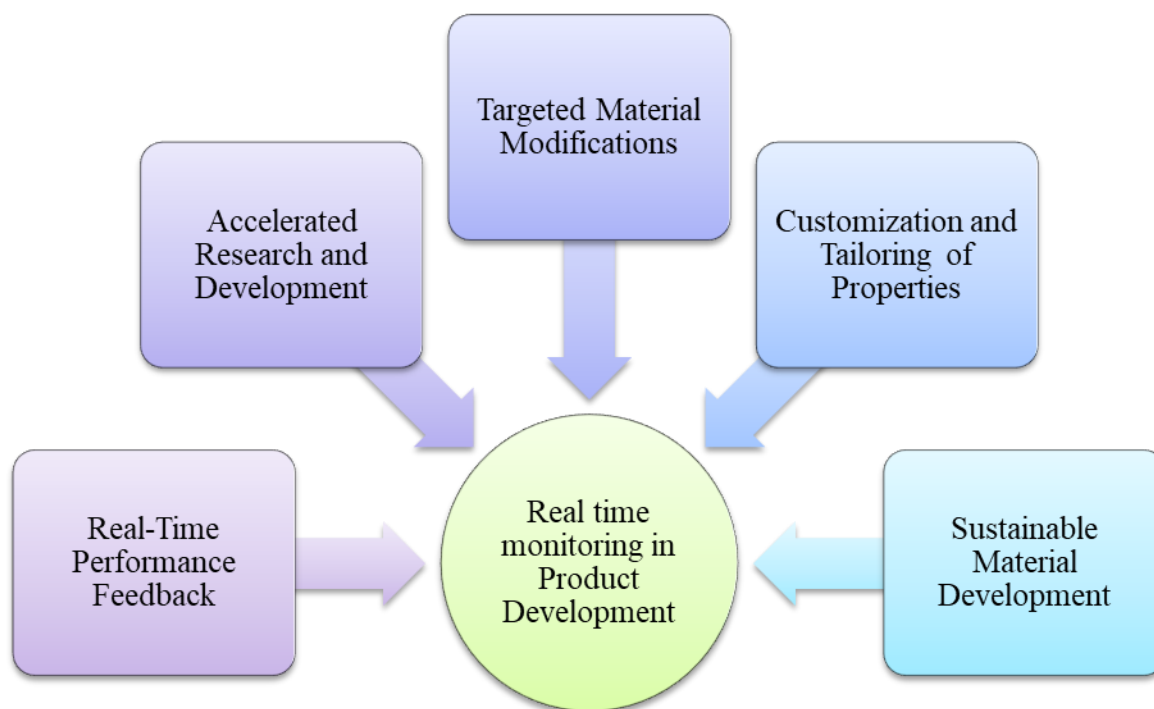


Fig. 4. Real time monitoring innovation in product development

Innovation in Product Development

The integration of IoT sensors in polymer composites is driving significant innovation in product development (Moinudeen *et al.* 2017). By providing real-time

feedback on material performance during actual use, these sensors enable researchers and engineers to gain valuable insights that can inform design improvements and the creation of advanced materials (Manickaraj *et al.* 2024c; Mohankumar *et al.* 2024). This capability fosters a more agile approach to product development, allowing for rapid iterations, and enhancements based on empirical data. Figure 4 shows real-time monitoring in the innovation of product development.

Real-time performance feedback

Real-time performance feedback from IoT sensors allows manufacturers to monitor how polymer composites behave under various operational conditions (Al Mamun and Yuce 2019). For example, sensors can track mechanical properties, temperature variations, and environmental exposure during the lifecycle of the product. This continuous stream of data helps identify specific weaknesses or failure points, allowing engineers to make informed adjustments. By understanding the actual performance of materials in real-world scenarios, researchers can refine their designs and formulations to optimize durability and functionality, ensuring that products meet or exceed industry standards (Manickaraj *et al.* 2023).

Targeted material modifications

With detailed insights into material behavior, targeted modifications can be implemented to enhance the performance of polymer composites. If a particular composite consistently underperforms in specific environmental conditions—such as high humidity or exposure to chemicals—engineers can analyze sensor data to pinpoint the root causes of the issue (Jain *et al.* 2020). This information can lead to targeted changes in the composite formulation, such as adjusting the ratios of polymers and additives or selecting more resistant materials. Such modifications not only improve the material's performance but also ensure that it meets the unique demands of its intended application.

Accelerated research and development

The integration of IoT sensors also accelerates the research and development (R&D) process. By providing instant feedback on material performance, engineers can quickly evaluate the effectiveness of different formulations and processing techniques. This rapid prototyping and testing process shortens development cycles, allowing companies to bring innovative products to market faster (Cooper 2021). The ability to iterate based on real-time data reduces the reliance on time-consuming traditional testing methods, enabling a more dynamic and responsive approach to product development.

Customization and tailoring of properties

IoT sensors facilitate the customization of polymer composites to meet specific application needs. With the ability to monitor performance in real time, manufacturers can tailor the properties of composites based on their intended use (Gogineni *et al.* 2022; Hammad *et al.* 2023). For instance, in the automotive industry, sensors can help develop lightweight composites that maintain high strength while improving fuel efficiency. Similarly, in the medical field, composites can be engineered for biocompatibility and mechanical properties that suit specific surgical applications. This level of customization leads to innovative products that are better aligned with the demands of various industries.

Sustainable material development

Moreover, the insights gained from IoT-enabled monitoring contribute to the development of more sustainable materials. By understanding how polymer composites respond to environmental factors, manufacturers can optimize formulations to reduce waste and improve recyclability (Palanisamy *et al.* 2023; Palaniappan *et al.* 2024b; Yousaf *et al.* 2024). For instance, sensors can help identify the most effective ways to incorporate recycled materials without compromising performance. This focus on sustainability not only meets regulatory requirements but also addresses consumer demand for environmentally friendly products. In conclusion, the integration of IoT sensors in polymer composites is revolutionizing product development. Through real-time performance feedback, targeted modifications, accelerated R&D, customization, and sustainable practices, manufacturers can create advanced materials that meet the evolving needs of various industries (Davis *et al.* 2012; Ninduwezuor-Ehiobu *et al.* 2023). This innovation not only enhances product quality but also drives competitiveness in the market, positioning companies for future success.

Data Management and Analytics in IoT-Integrated Composites

The real-time data generated by IoT sensors embedded in polymer composites needs to be effectively managed, transmitted, and analyzed to derive actionable insights. This section discusses the data lifecycle from acquisition to advanced analytics (Davim 2025a).

Data acquisition, transmission, and cloud-based storage

IoT sensors embedded in composites continuously generate streams of data capturing the material's response to operational stresses and environmental conditions. Data acquisition systems (DAQs) are designed to collect, preprocess, and digitize sensor signals. Modern DAQs integrate seamlessly with IoT networks, supporting wireless data transmission to edge devices or cloud servers for centralized storage (Davim 2024b). Cloud-based storage solutions provide scalable and secure repositories for vast amounts of sensor data. These platforms enable long-term data retention, access control, and integration with advanced analytics tools. Edge computing is also emerging as a solution to preprocess data near the source, reducing bandwidth requirements and latency in critical applications (Pervez *et al.* 2024).

Use of machine learning (ML) and digital twins for performance prediction

Machine Learning (ML) algorithms play a pivotal role in extracting insights from large datasets generated by IoT-enabled composites. ML models can identify hidden patterns and correlations between sensor signals and material degradation or failure modes, enabling predictive maintenance and early intervention. Supervised learning approaches such as neural networks and decision trees are commonly used to predict composite behavior under various scenarios, while unsupervised learning techniques aid in anomaly detection and clustering of performance data (Rai *et al.* 2024).

Digital twins—virtual replicas of physical composites—are constructed using real-time sensor data and historical performance records. These digital models simulate the behavior of composite structures under diverse conditions, enabling rapid design optimization, failure analysis, and operational troubleshooting. Engineers can test hypothetical changes or new design configurations within the digital twin environment,

significantly accelerating the development cycle and enhancing performance reliability (Song *et al.* 2019).

Challenges in data security and interoperability

The vast and sensitive data generated by IoT-enabled composites necessitate robust cybersecurity measures to prevent unauthorized access and data breaches. Encryption protocols, secure authentication mechanisms, and blockchain technologies are increasingly applied to safeguard data integrity and confidentiality (Zhuang *et al.* 2023).

Interoperability remains a challenge due to the diversity of sensors, communication protocols, and data formats used across different manufacturers and applications. The development of standardized interfaces and data exchange protocols is essential to enable seamless integration of IoT systems within existing composite manufacturing and monitoring infrastructures. Standardization efforts, such as those led by industry consortia and international organizations, are crucial to ensuring system compatibility, scalability, and long-term sustainability (Santhosh *et al.* 2020).

Challenges and Limitations of IoT Integration in Polymer Composites

While the integration of Internet of Things (IoT) technologies into polymer composites offers promising benefits, it also raises several critical challenges and limitations that warrant careful consideration.

Security and privacy risks

Embedding IoT sensors into composites introduces vulnerabilities that could be exploited by hackers or unauthorized entities. These security breaches may compromise sensitive data or even control over structural components, posing risks particularly in critical sectors such as aerospace and infrastructure (Smith *et al.* 2021; Kumar and Singh 2023). Ensuring robust cybersecurity measures and encryption protocols is essential to mitigate these threats.

Increased costs and economic considerations

The addition of sensors, wireless communication modules, and associated data management infrastructure inevitably increases the production cost of composites. These expenses are likely to be passed on to end users, potentially limiting the adoption of IoT-enabled composites in cost-sensitive markets (Johnson and Lee 2022). Additionally, maintenance and replacement of IoT components add to lifecycle costs.

Questionable immediate benefits for end users

Although IoT integration promises long-term advantages through predictive maintenance and enhanced performance monitoring, the tangible benefits for owners and operators may be limited in the short term. For many applications, especially where failure risks are low or routine maintenance is sufficient, the value proposition may not justify the added complexity and cost (Garcia *et al.* 2022).

Electromagnetic interference and system compatibility

IoT devices emit electronic signals that could interfere with other communication or electronic systems within households or industrial environments. This electromagnetic interference (EMI) can affect the performance of nearby devices, necessitating rigorous testing and compliance with EMI standards (Wang *et al.* 2020).

In summary, while IoT integration enhances polymer composite capabilities, these challenges must be addressed through ongoing research and development. A balanced approach that weighs benefits against costs and risks will be crucial for widespread acceptance and success.

Potential Overestimation of IoT Benefits: The “Echo-Chamber” Effect and Trend-Driven Hype

The Internet of Things (IoT) has captured significant attention in the realm of polymer composites due to promises of real-time monitoring, predictive maintenance, and enhanced performance. However, it is essential to recognize the potential overestimation of IoT’s benefits, driven by the “echo-chamber” effect and the desire to stay trendy. The echo-chamber effect amplifies positive narratives within closed groups, often overlooking critical challenges such as sensor durability, power constraints, and cybersecurity risks. Meanwhile, the urge to align with emerging technologies such as AI and Industry 4.0 leads researchers and organizations to emphasize IoT’s potential benefits while downplaying practical limitations. This selective focus creates a distorted perception of IoT’s readiness and effectiveness, with a risk of inflating expectations beyond what current evidence supports. Addressing these dynamics is crucial to maintaining a balanced perspective, ensuring that IoT’s integration into polymer composites is both evidence-based and realistically assessed.

Impact on research and industry

The echo-chamber effect and trend-driven hype can influence various aspects of research and industry related to IoT-enabled polymer composites:

1. **Research Priorities:** Funding agencies and academic institutions might prioritize projects aligned with IoT integration, sometimes at the expense of foundational research addressing core challenges such as sensor reliability, material compatibility, and data security. This could slow the development of necessary supporting technologies.
2. **Technology Deployment:** Industries eager to capitalize on IoT may invest prematurely in integration efforts that lack robust validation, leading to costly failures or suboptimal products. Without clear standards and guidelines, inconsistent implementations can reduce user confidence.
3. **User Expectations:** End-users, whether manufacturers, engineers, or consumers, may expect immediate and significant improvements from IoT-enabled composites. When these expectations are not met due to practical limitations or delays in technology maturation, dissatisfaction and skepticism can increase.
4. **Policy and Regulation:** Policymakers and regulators might struggle to keep pace with the technology, making it difficult to develop effective safety, privacy, and interoperability standards. An environment dominated by hype can obscure the need for careful oversight.

Balancing optimism with realism

Recognizing the potential for overestimation does not imply rejecting the value of IoT in polymer composites. Instead, it calls for a more balanced, critical approach that openly discusses both benefits and limitations. A few recommendations to achieve this balance include:

- **Transparent Reporting:** Researchers and developers should document and publish not only successes but also challenges, failures, and lessons learned. This openness fosters more realistic expectations and helps the community address problems collectively.
- **Critical Review and Meta-Analysis:** Systematic reviews and meta-analyses that objectively evaluate the current state of IoT applications in composites can provide more nuanced insights, highlighting where IoT truly adds value and where its impact remains limited.
- **Engagement of Diverse Stakeholders:** Including perspectives from end-users, policymakers, cybersecurity experts, and ethicists can enrich discussions and highlight practical concerns that might otherwise be overlooked in technology-centric narratives.
- **Phased and Evidence-Based Deployment:** Encouraging incremental adoption and rigorous testing in real-world settings ensures that IoT implementations are proven effective before wide-scale rollouts, reducing the risk of disillusionment.
- **Awareness of Sociotechnical Dynamics:** Acknowledging that technological adoption is influenced by social, economic, and cultural factors helps temper the drive to “jump on the bandwagon” and fosters more thoughtful innovation strategies.

CONCLUSIONS AND PERSPECTIVES

Integrating IoT sensors and wireless communication technology into polymer composites enables real-time monitoring and predictive maintenance, representing a major advancement in materials science and engineering. IoT-enabled polymer composites incorporate diverse sensors such as temperature, strain, and humidity sensors, alongside various communication protocols, to capture critical data that improve performance, quality control, safety, and sustainability. These technologies find wide application in sectors including aerospace, automotive, infrastructure, and energy, where continuous monitoring of environmental and mechanical conditions is essential. Predictive maintenance supported by IoT helps optimize service schedules and reduce failure risks, but the full benefits depend on establishing standardized methods for integrating multiple sensor systems and ensuring interoperability through uniform protocols and interfaces. Additionally, the massive data generated requires sophisticated data management and analytics techniques. Cloud-based storage, combined with machine learning and digital twin technologies, enables efficient data processing, performance prediction, and rapid troubleshooting, empowering manufacturers and engineers to make data-driven decisions. This leads to optimized composite formulations and manufacturing processes that reduce waste and improve recyclability. Real-time monitoring of key parameters supports a better understanding of material behavior, proactive prevention of deterioration, accelerated product development, and tailored design improvements. Overall, the integration of IoT technologies, polymer composites, and advanced analytics

is transforming material development by creating smarter, more resilient, and sustainable products that meet the evolving demands of modern industries and pave the way for future innovations.

Data Availability Statement

Data are available on request from the authors.

Ethical Approval

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Declaration of Conflicting Interests

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