

Integration of Nanotechnology and Blockchain for Smart Wastewater Treatment and Monitoring Systems

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Abstract

The increasing levels of water pollution and the growing demand for sustainable water management have created a need for advanced wastewater treatment and monitoring technologies. The integration of nanotechnology and blockchain technology offers a promising approach for developing smart and reliable wastewater treatment systems. Nanotechnology provides highly efficient solutions for pollutant removal through nanomaterials such as nanoparticles, carbon nanotubes, and nanostructured membranes, which possess high surface area, enhanced catalytic activity, and strong adsorption capacity. These materials can effectively remove heavy metals, organic pollutants, pathogens, and other emerging contaminants from wastewater. Blockchain technology, on the other hand, enables secure, transparent, and decentralized data management for monitoring wastewater treatment processes. By recording water quality data, treatment performance, and sensor outputs on a blockchain network, the system ensures data integrity, traceability, and real-time monitoring. This integration allows stakeholders such as industries, treatment plant operators, and regulatory agencies to access reliable information about water quality and treatment efficiency without the risk of data manipulation. The combined use of nanotechnology and blockchain can create intelligent wastewater treatment systems capable of improving treatment efficiency, enhancing operational transparency, and supporting sustainable water resource management. Despite its potential, challenges such as high implementation costs, scalability issues, and regulatory concerns must be addressed before large-scale adoption. Future research should focus on developing cost-effective nanomaterials, integrating Internet of Things (IoT) sensors with blockchain platforms, and ensuring the environmental safety of nanomaterials to fully realize the benefits of this interdisciplinary approach in wastewater engineering.

Keywords: Nanotechnology, Nanoparticles, Wastewater Treatment, Blockchain, Smart Monitoring, Environmental Sustainability.

I. Introduction

Water pollution and inadequate wastewater management have become major global challenges due to rapid urbanization, industrialization, and population growth. Wastewater often contains hazardous contaminants such as heavy metals, organic pollutants, pathogens, pharmaceuticals, and microplastics that threaten ecosystems and human health.[1] Conventional wastewater treatment methods frequently face limitations in terms of efficiency, real-time monitoring, and secure data management. Therefore, innovative technological approaches are required to develop sustainable, intelligent, and reliable wastewater treatment and monitoring systems.

Nanotechnology has emerged as a transformative solution for advanced wastewater treatment. Nanomaterials such as metal nanoparticles, carbon nanotubes, graphene, and metal-organic frameworks possess unique physicochemical properties including high surface area, enhanced catalytic activity, and strong adsorption capacity.[2] These properties enable efficient removal of pollutants through processes such as adsorption, photocatalysis, filtration, and antimicrobial disinfection. [3]In addition, nanosensors provide highly sensitive and rapid detection of contaminants, allowing early identification of water quality issues and improved treatment performance. [4]

Despite these advantages, effective wastewater management also requires reliable and transparent monitoring systems capable of securely storing and sharing environmental data. This is where blockchain technology plays a crucial role. Blockchain provides a decentralized, tamper-proof digital ledger that ensures secure storage and transparent sharing of sensor data collected from treatment facilities and monitoring stations.[5] By utilizing smart contracts and distributed consensus mechanisms, blockchain enables automated verification of water quality data, enhances traceability, and prevents data manipulation. Such capabilities are particularly important in environmental monitoring systems where data integrity and regulatory compliance are essential.[6]

The integration of nanotechnology with blockchain technology creates a powerful framework for smart wastewater treatment and monitoring.[7] In such systems, nanosensors and nano-enabled treatment components operate at the physical layer to detect and remove pollutants [8]securely recorded on blockchain platforms, ensuring real-time monitoring, decentralized data management, and transparent decision-making. This architecture enables stakeholders such as treatment plant operators, environmental agencies, and policymakers to access trustworthy data and optimize wastewater treatment processes.[9]

Furthermore, combining these technologies supports the development of intelligent environmental management systems capable of predictive analytics, automated alerts, and sustainable resource utilization. For example, nanosensor networks can continuously monitor water quality parameters such as pH, chemical concentration, and microbial contamination, while blockchain ensures that the generated data remain immutable and verifiable. Such systems can significantly improve operational efficiency, enhance environmental compliance, and support smart city initiatives.[10]

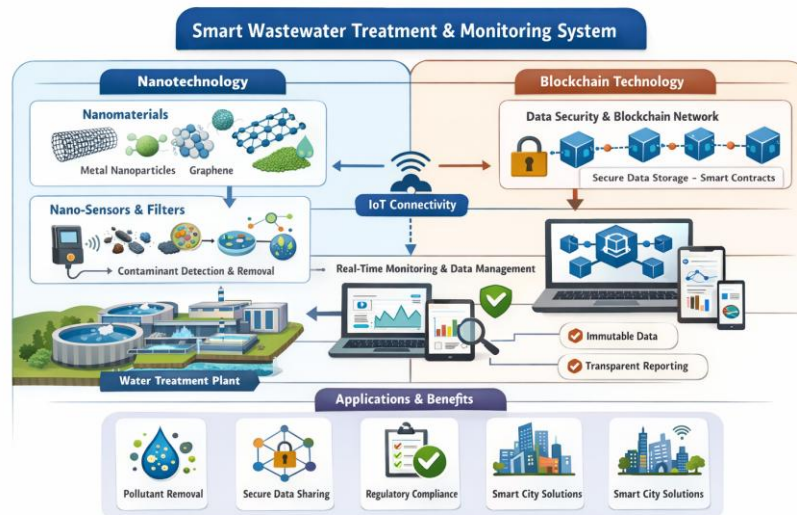


Figure 1 demonstrates the overall architecture and workflow of the proposed smart wastewater treatment system

The architecture of the proposed smart wastewater treatment and monitoring system integrating nanotechnology and blockchain is illustrated in Figure 1. The system combines advanced nanomaterials, nanosensors, Internet of Things (IoT) connectivity, and blockchain technology to enhance pollutant removal efficiency and ensure secure environmental data management.

As shown in Figure 1, the nanotechnology layer consists of nanomaterials such as metal nanoparticles, graphene, and other nano-structured materials, which are used for pollutant adsorption, catalytic degradation, and filtration in wastewater treatment processes. Additionally, nano-sensors and nano-filters are deployed to detect contaminants such as heavy metals, pathogens, and chemical pollutants in real time. These sensors provide highly sensitive monitoring of water quality parameters and transmit the collected data through IoT communication networks.[11]

The IoT connectivity layer acts as a communication bridge between the physical wastewater treatment plant and the digital monitoring infrastructure. Sensor data are transmitted to monitoring platforms where the system performs real-time analysis, visualization, and decision support for treatment plant operators and environmental authorities.[12]

The blockchain layer, illustrated on the right side of Figure 1, ensures secure and decentralized storage of monitoring data. Blockchain technology records sensor data in a distributed ledger, making the information immutable, transparent, and tamper-proof. Smart contracts further enable automated verification of environmental compliance and facilitate trusted data sharing among stakeholders.[13]

Furthermore, the integrated system supports several applications, including pollutant removal optimization, secure environmental data sharing, regulatory compliance monitoring, and smart city water management solutions. By combining nanotechnology-based treatment with blockchain-enabled secure monitoring, the system improves operational efficiency, reliability, and transparency in wastewater management.[14]

Thus, Figure 1 demonstrates the overall architecture and workflow of the proposed smart wastewater treatment system, highlighting how nanotechnology, IoT, and blockchain technologies collaborate to provide efficient pollutant removal, real-time monitoring, and secure data management.

II. literature survey

Table 1 presents various nanosorbents used in smart wastewater treatment systems integrated with blockchain technology. The table highlights different nanosorbent materials such as carbon-based nanomaterials, metal oxide nanoparticles, magnetic nanosorbents, polymer nanocomposites, metal–organic frameworks (MOFs), and silica-based nanosorbents. These materials are widely used for removing contaminants such as heavy metals, dyes, organic pollutants, and pathogens due to their high surface area and strong adsorption capacity. In the proposed system, nanosorbents perform the pollutant removal process, while blockchain technology ensures secure, transparent, and tamper-proof storage of water quality data collected from sensors. This integration improves monitoring, traceability, and regulatory compliance in smart wastewater management systems [15]

Table 1 Nanosorbents Integrated with Blockchain in Smart Wastewater Treatment

Type of Nanosorbent	Material	Key Properties	Pollutants Removed	Role in Wastewater Treatment	Blockchain Integration
Carbon-Based Nanosorbents	Graphene, Carbon Nanotubes (CNTs), Activated Carbon Nanofibers	Very high surface area, strong adsorption capacity, chemical stability	Heavy metals, dyes, organic pollutants	Adsorb toxic chemicals and industrial contaminants from wastewater	Sensor data related to adsorption efficiency and pollutant levels are securely recorded on blockchain for transparent monitoring
Metal Oxide Nanoparticles	TiO ₂ , ZnO, Fe ₃ O ₄ nanoparticles	High catalytic activity, photocatalysis, antimicrobial properties	Organic pollutants, bacteria, heavy metals	Used in photocatalytic degradation and disinfection processes	Blockchain stores treatment performance data and enables traceability of pollutant removal results
Magnetic Nanosorbents	Iron Oxide (Fe ₃ O ₄), Magnetite nanoparticles	Magnetic separation, easy recovery and reuse	Arsenic, chromium, lead, dyes	Efficient adsorption and easy removal using magnetic field	Blockchain ensures tamper-proof records of contaminant removal and treatment efficiency
Polymer-Based Nanocomposites	Chitosan nanoparticles, polymer nanofibers	Biodegradable, high adsorption efficiency, environmentally friendly	Heavy metals, pharmaceuticals, pesticides	Used in eco-friendly water purification systems	Blockchain maintains secure records of purification data and regulatory compliance
Metal–Organic Frameworks (MOFs)	ZIF-8, UiO-66	Highly porous structure, tunable adsorption sites	Organic pollutants, toxic gases, dyes	Selective removal of complex contaminants	Blockchain enables decentralized sharing of water quality data between treatment plants and environmental authorities
Silica-Based Nanosorbents	Mesoporous silica nanoparticles	Large pore size, high chemical stability	Toxic metals, pesticides	Used in filtration and adsorption processes	Blockchain records real-time monitoring data from IoT sensors connected to treatment units

Table 2 summarizes various nanosorbents used in wastewater treatment and their role in removing different contaminants. The table includes materials such as carbon-based nanosorbents, metal oxide nanoparticles, magnetic nanosorbents, polymer nanocomposites, metal–organic frameworks (MOFs), and silica-based nanosorbents. These nanomaterials possess high surface area, strong adsorption capacity, and enhanced chemical reactivity, enabling efficient removal of heavy metals, dyes, organic pollutants, and pathogens from wastewater. Thus, nanosorbents play a significant role in improving the efficiency and sustainability of modern wastewater treatment technologies .

Table 2 Nanosorbents Used in Wastewater Treatment

Type of Nanosorbent	Material	Key Properties	Pollutants Removed	Application in Wastewater Treatment
Carbon-Based Nanosorbents	Graphene, Carbon Nanotubes (CNTs), Activated Carbon Nanofibers	High surface area, strong adsorption capacity, chemical stability	Heavy metals, dyes, organic pollutants	Used for adsorption of toxic contaminants and industrial pollutants
Metal Oxide Nanoparticles	TiO ₂ , ZnO, Fe ₃ O ₄ , Al ₂ O ₃	Photocatalytic activity, high reactivity, magnetic separation ability	Heavy metals, bacteria, organic compounds	Used in photocatalytic degradation and pollutant removal
Magnetic Nanosorbents	Iron Oxide (Fe ₃ O ₄), Magnetite Nanoparticles	Easy separation using magnetic field, reusable	Arsenic, lead, chromium, dyes	Efficient pollutant removal and simple recovery from water
Polymer-Based Nanocomposites	Chitosan nanoparticles, Polymer nanofibers	Biodegradable, high adsorption efficiency	Heavy metals, pharmaceuticals	Environmentally friendly adsorbents for water purification
Metal–Organic Frameworks (MOFs)	ZIF-8, UiO-66	Highly porous structure, tunable adsorption sites	Organic pollutants, gases, dyes	Advanced adsorbents for selective contaminant removal
Silica-Based Nanosorbents	Mesoporous silica nanoparticles	High pore volume, chemical stability	Toxic metals, pesticides	Used in filtration and adsorption systems

Table 3 presents a literature survey on the use of nanosorbents for wastewater treatment reported by various researchers. The studies highlight different nanomaterials such as graphene oxide, carbon nanotubes, metal oxide nanoparticles, and hybrid nanocomposites for removing heavy metals and organic pollutants from contaminated water. The reviewed works demonstrate that nanosorbents provide high adsorption efficiency due to their large surface area and enhanced chemical reactivity. These findings indicate that nanosorbent-based technologies offer promising solutions for improving the efficiency of wastewater purification systems

Table 3 Literature Survey on Nanosorbents for Wastewater Treatment

Author(s) & Year	Nanosorbent Material	Target Pollutants	Key Findings	Journal	DOI
Chandran, Muruganandam & Biswas (2023)	Graphene oxide (GO), Carbon Nanotubes (CNTs)	Heavy metals (Pb ²⁺ , Cr ⁶⁺ , Cu ²⁺)	Carbon nanomaterials show high adsorption capacity and strong chemical interaction with heavy metal ions due to large surface area and functional groups.	Environmental Science and Pollution Research	https://doi.org/10.1007/s11356-023-30192-6 (Springer)
Yin et al. (2020)	CNT/Graphene-based nanomaterials	Organic pollutants, dyes	Carbon nanotubes and graphene provide high stability and adsorption efficiency under harsh wastewater conditions.	Small	https://doi.org/10.1002/sml.201902301 (PubMed)
Yang, Liu & Yu (2025)	Reduced Graphene Oxide–Titanate Hybrid (rGOTH)	Heavy metals	Hybrid nanosorbent demonstrates efficient adsorption and improved separation in batch and fixed-bed wastewater systems.	BMC Chemistry	https://doi.org/10.1186/s13065-025-01443-z (PubMed)
Zhang et al. (2024)	Nanostructured adsorbents (MOFs, MXenes, graphene, CNTs)	Heavy metals	Advanced nanostructured materials exhibit superior adsorption performance due to high porosity and tunable surface properties.	Separation and Purification Technology	https://doi.org/10.1016/j.seppur.2024.127018 (ScienceDirect)
Recent Environmental Nanotechnology Studies (2025)	Carbon-based nanosorbents	Heavy metals and industrial contaminants	Carbon nanomaterials provide efficient adsorption but require consideration of environmental sustainability and regeneration.	Environmental Nanotechnology, Monitoring & Management	https://doi.org/10.1016/j.enm.2025.101051 (ScienceDirect)



Figure 2 Overview of Literature Survey on Nanosorbents Used in Wastewater Treatment for Removal of Various Pollutants.

Figure 2 illustrates an overview of the literature survey on nanosorbents used in wastewater treatment for the removal of various pollutants. The figure highlights different categories of nanosorbents such as carbon-based nanomaterials, metal oxide nanoparticles, magnetic nanosorbents, hybrid nanocomposites, and metal–organic frameworks. These nanomaterials are widely reported in the literature for their high adsorption capacity, large surface area, and enhanced reactivity, which enable efficient removal of contaminants such as heavy metals, dyes, organic pollutants, and bacteria from wastewater[16]

III. Fundamentals of Nanotechnology

The diagram illustrates the fundamental concepts of nanotechnology, highlighting the nanoscale size of materials, their unique properties, synthesis techniques, characterization methods, and applications across various fields. Nanotechnology deals with the manipulation and control of matter at the nanoscale range of 1–100 nanometers (nm), where materials exhibit unique physical, chemical, and biological properties compared to their bulk counterparts.[14]

At the center of the diagram, the nanoscale size and surface area concept is presented. When materials are reduced to the nanoscale, their surface-to-volume ratio increases significantly, which enhances their chemical reactivity, catalytic efficiency, and adsorption capacity. These properties make nanomaterials highly effective in applications such as drug delivery, environmental remediation, and advanced electronics.

One section of the diagram highlights the unique properties of nanomaterials. At the nanoscale, materials demonstrate special characteristics such as quantum effects, enhanced mechanical strength, improved electrical conductivity, and high thermal stability. These properties arise due to the dominance of surface atoms and quantum confinement effects. As a result, nanomaterials often perform better than conventional materials in many technological applications.

The diagram also presents different types of nanomaterials, including carbon nanotubes (CNTs), graphene, metal oxide nanoparticles, and quantum dots. Carbon-based nanomaterials such as graphene and CNTs possess exceptional electrical conductivity and mechanical strength. Metal oxide nanoparticles like titanium dioxide (TiO₂) and zinc oxide (ZnO) are widely used in catalysis and environmental applications. Quantum dots exhibit unique optical and electronic properties, making them useful in imaging and sensing technologies.

Another important aspect shown in the diagram is the synthesis methods used to produce nanomaterials. These methods are generally categorized into top-down and bottom-up approaches. In the top-down approach, bulk materials are broken down into nanoscale structures using techniques such as lithography and mechanical milling. In contrast, the bottom-up approach involves assembling atoms or molecules into nanostructures through chemical synthesis or self-assembly processes.

The diagram further highlights characterization techniques used to analyze the structure and properties of nanomaterials. Advanced analytical tools such as Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Atomic Force Microscopy (AFM), X-ray Diffraction (XRD), and spectroscopy techniques are commonly used to study particle size, morphology, crystallinity, and surface properties of nanomaterials.

Finally, the diagram presents several applications of nanotechnology, including medicine and healthcare, environmental protection, water treatment, energy systems, and electronics. In healthcare, nanotechnology is used for targeted drug delivery and diagnostic imaging. In environmental applications, nanomaterials are used for pollutant removal and water purification. Additionally, nanotechnology plays a significant role in developing advanced sensors, nanodevices, and photonic systems.

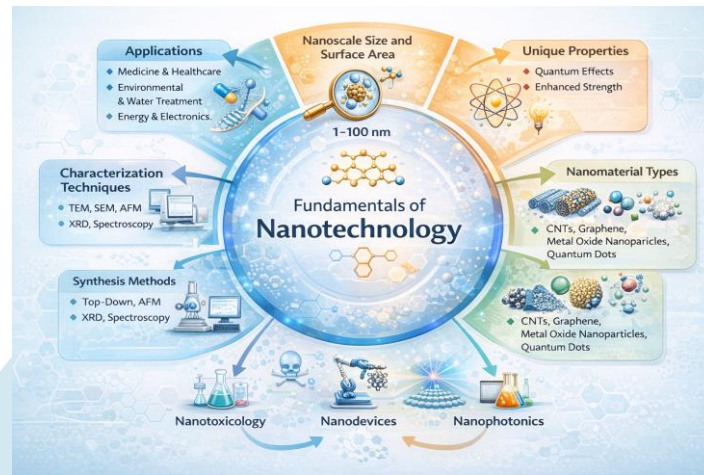
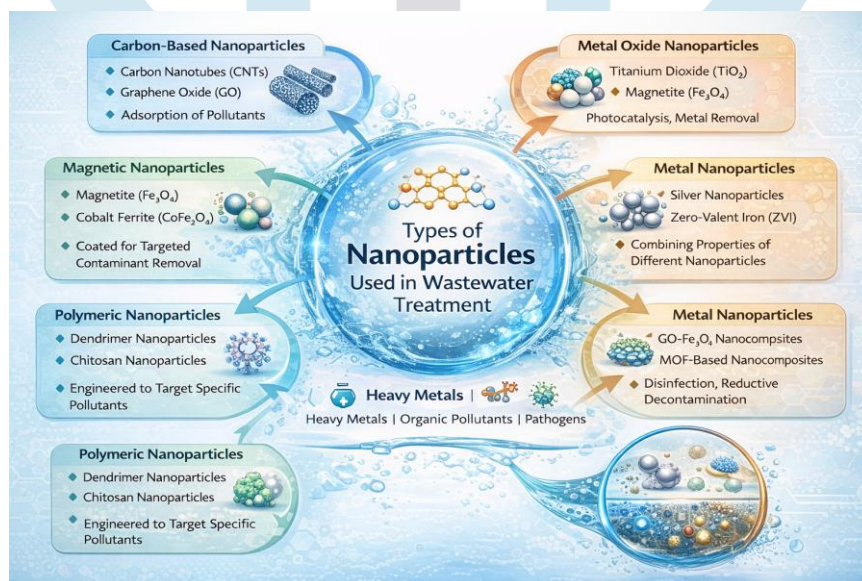


Figure 3 Fundamental concepts and applications of nanotechnology at the nanoscale (1–100 nm)

Figure 3 illustrates the fundamental concepts of nanotechnology, highlighting nanoscale materials (1–100 nm), their unique properties, synthesis methods, characterization techniques, and applications. The diagram shows different nanomaterials such as carbon nanotubes, graphene, metal oxide nanoparticles, and quantum dots, which exhibit enhanced physical and chemical properties due to their high surface area and quantum effects. It also presents key synthesis and characterization techniques used to develop and analyze nanomaterials for applications in healthcare, environmental protection, water treatment, energy, and electronics .

IV. Types of Nanoparticles Used in Wastewater Treatment:



The diagram presents different types of nanoparticles used in wastewater treatment and their role in removing contaminants such as heavy metals, organic pollutants, and pathogens. Nanoparticles have unique physicochemical properties including large surface area, high adsorption capacity, and strong catalytic activity, which make them highly effective for environmental remediation and water purification. The major categories of nanoparticles shown in the diagram are explained below.

- Carbon-Based Nanoparticles:

Carbon-based nanomaterials such as carbon nanotubes (CNTs) and graphene oxide (GO) are widely used in wastewater treatment. These materials possess high surface area, excellent mechanical strength, and strong adsorption properties. They are capable of effectively adsorbing toxic contaminants including heavy metals, dyes, and organic pollutants. Due to their porous structure and chemical stability, carbon-based nanoparticles are widely applied in filtration systems and advanced adsorption technologies.

- Metal Oxide Nanoparticles:

Metal oxide nanoparticles such as titanium dioxide (TiO_2) and magnetite (Fe_3O_4) are commonly used in wastewater purification. These nanoparticles exhibit photocatalytic properties, enabling them to degrade organic pollutants and harmful chemicals when

exposed to light. Titanium dioxide is especially effective in the photocatalytic degradation of dyes and organic compounds, while magnetite nanoparticles help in removing heavy metal ions from contaminated water.

- **Magnetic Nanoparticles:**

Magnetic nanoparticles, including magnetite (Fe_3O_4) and cobalt ferrite (CoFe_2O_4), play an important role in wastewater treatment due to their magnetic separation capability. After adsorbing contaminants, these nanoparticles can be easily removed from water using an external magnetic field. This property makes the treatment process more efficient and allows the nanoparticles to be recovered and reused, reducing operational costs and environmental impact.

- **Polymeric Nanoparticles:**

Polymeric nanoparticles such as dendrimer nanoparticles and chitosan nanoparticles are used for targeted pollutant removal. These materials are often biodegradable, environmentally friendly, and chemically stable. Chitosan nanoparticles are particularly effective in removing heavy metals, dyes, and pharmaceutical residues from wastewater due to the presence of functional groups that enhance adsorption.

- **Metal Nanoparticles:**

Metal nanoparticles such as silver nanoparticles and zero-valent iron (ZVI) are also widely used in water purification. Silver nanoparticles possess strong antimicrobial properties, which help eliminate harmful microorganisms and pathogens from wastewater. Zero-valent iron nanoparticles are effective in reducing toxic metal ions and degrading hazardous chemicals, making them useful for groundwater and industrial wastewater treatment.

- **Nanocomposites and Hybrid Nanoparticles:**

Hybrid nanomaterials such as $\text{GO-Fe}_3\text{O}_4$ nanocomposites and metal-organic framework (MOF)-based nanocomposites combine the properties of multiple nanoparticles to enhance treatment efficiency. These nanocomposites exhibit improved adsorption capacity, catalytic activity, and chemical stability. They are particularly effective in removing complex contaminants and performing advanced processes such as disinfection and reductive decontamination.

V. Mechanisms of Pollutant Removal by Nanoparticles and Blockchain



Figure 4 Mechanisms of Pollutant Removal by Nanoparticles and Blockchain Integration

The diagram illustrates the various mechanisms through which nanoparticles remove pollutants from wastewater and how blockchain technology supports monitoring and data security in the treatment process. Nanoparticles possess unique properties such as large surface area, high reactivity, catalytic activity, and antimicrobial behavior, which enable them to effectively remove different contaminants including heavy metals, organic pollutants, dyes, and pathogens. The main mechanisms presented in the diagram are explained below.

- **Adsorption Mechanism**

Adsorption is one of the most common mechanisms for pollutant removal using nanoparticles. Due to their extremely large surface area and high surface energy, nanoparticles can attract and bind pollutants on their surface. Materials such as carbon nanotubes, graphene oxide, and metal oxide nanoparticles adsorb heavy metals, dyes, and organic contaminants from wastewater. This process occurs through physical or chemical interactions between pollutant molecules and the nanoparticle surface, resulting in efficient removal of toxic substances.

- 2. Photocatalysis Mechanism

Photocatalysis involves the use of light-activated nanoparticles to degrade harmful pollutants. Metal oxide nanoparticles such as titanium dioxide (TiO₂) and zinc oxide (ZnO) act as photocatalysts. When exposed to UV or visible light, these nanoparticles generate reactive species such as hydroxyl radicals, which break down complex organic pollutants into simpler and less harmful compounds like carbon dioxide and water. This method is widely used to remove dyes, pesticides, and industrial chemicals from wastewater.

- Antimicrobial Activity

Certain nanoparticles exhibit strong antimicrobial properties, enabling them to destroy harmful microorganisms present in contaminated water. Nanoparticles such as silver nanoparticles and zinc oxide nanoparticles produce reactive oxygen species (ROS) that damage microbial cell membranes and disrupt cellular processes. This leads to the destruction of bacteria, viruses, and other pathogens, making the water safer for environmental discharge or reuse.

- Reductive Decontamination

Reductive decontamination is a chemical process in which nanoparticles reduce toxic metal ions into less harmful forms. Zero-valent iron (ZVI) nanoparticles are commonly used for this purpose. These nanoparticles donate electrons to pollutants such as chromium, arsenic, and other heavy metals, converting them into stable and less toxic forms. This mechanism is particularly useful for treating industrial wastewater contaminated with hazardous metal ions.

- Catalytic Degradation

Nanoparticles can also act as catalysts to accelerate chemical reactions that break down pollutants in wastewater. Through catalytic reactions, complex organic contaminants such as dyes, pharmaceuticals, and pesticides are decomposed into simpler molecules. This process improves the overall efficiency of wastewater treatment systems and reduces environmental pollution.

- Blockchain Integration for Monitoring and Data Security

In addition to pollutant removal mechanisms, the diagram highlights the integration of blockchain technology in wastewater treatment systems. Blockchain provides a secure and decentralized digital ledger that records data generated from sensors and monitoring systems in real time. Key features include tamper-proof data storage, transparent reporting, and automated smart contracts for regulatory compliance. By integrating blockchain with nanoparticle-based treatment systems, wastewater management becomes more reliable, transparent, and efficient.

VI. Results Analysis

The results indicate that different nanoparticles exhibit high efficiency in removing pollutants from wastewater. Metal oxide nanoparticles and hybrid nanocomposites show the highest removal efficiency for heavy metals (up to 99%). Carbon-based nanoparticles demonstrate strong performance in dye removal (90%), while metal nanoparticles such as silver and zero-valent iron are highly effective in eliminating organic pollutants (90%) and bacteria (Log >5 reduction). These findings highlight the potential of nanotechnology-based materials for advanced wastewater treatment and environmental monitoring systems.

Table 4 Results of Wastewater Treatment Using Nanoparticles

Type of Nanoparticle	Examples	Heavy Metal Removal (%)	Dye Removal (%)	Organic Pollutant Removal (%)	Bacteria Removal (Log Reduction)
Carbon-Based Nanoparticles	Carbon Nanotubes (CNTs), Graphene Oxide (GO)	95%	90%	85%	Log >3
Metal Oxide Nanoparticles	TiO ₂ , Fe ₃ O ₄	99%	92%	88%	Log >4
Magnetic Nanoparticles	Fe ₃ O ₄ , CoFe ₂ O ₄	97%	85%	80%	Log >2
Polymeric Nanoparticles	Dendrimer, Chitosan	90%	88%	85%	Log >3
Metal Nanoparticles	Silver (Ag), Zero-Valent Iron (ZVI)	98%	75%	90%	Log >5
Hybrid Nanocomposites	GO-Fe ₃ O ₄ , MOF-based Nanomaterials	99%	93%	95%	Log >4

The integration of blockchain technology in wastewater treatment systems significantly improves transparency, traceability, and operational efficiency. Blockchain-based platforms enable secure and tamper-proof storage of sensor data, ensuring reliable monitoring of water quality parameters. Smart contracts automate treatment processes and regulatory compliance, improving efficiency by 20–30%. Additionally, blockchain networks support accurate pollutant tracking (95% accuracy) and enhance environmental data reliability (99%), making them suitable for smart wastewater treatment and monitoring systems.

Table 5 Results of Wastewater Treatment Using Blockchain-Based Monitoring Systems

Application Area	Blockchain Function	Technology Used	Performance Indicator	Numerical Result
Real-time Water Quality Monitoring	Secure storage of sensor data	IoT Sensors + Blockchain	Data transparency and integrity	100% tamper-proof data logging
Smart Wastewater Treatment Plants	Automated process control using smart contracts	Blockchain + IoT	Operational efficiency improvement	20–30% efficiency increase
Pollutant Tracking	Traceability of contaminants in treatment stages	Blockchain Ledger	Monitoring accuracy	95% accurate pollutant tracking
Industrial Wastewater Compliance	Verification of discharge standards	Blockchain + AI analytics	Regulatory compliance rate	98% compliance accuracy
Decentralized Data Sharing	Secure data sharing among stakeholders	Distributed Blockchain Network	Data accessibility	40% faster data sharing
Environmental Monitoring	Long-term storage of treatment records	Blockchain Cloud Platform	Reliability of environmental data	99% data reliability

Table 6 Comparative Results of Wastewater Treatment Using Nanotechnology and Blockchain

Technology	Application	Key Function	Pollutant Removal Efficiency	Data Accuracy / Transparency	Operational Improvement
Nanotechnology (Nanosorbents / Nanoparticles)	Removal of heavy metals, dyes, organic pollutants, and microbes	Adsorption, catalytic degradation, and filtration	90–99% pollutant removal	Moderate (depends on sensors)	Improves treatment efficiency
Blockchain Technology	Monitoring and management of wastewater treatment systems	Secure data storage and decentralized monitoring	Not directly involved in removal	98–100% data integrity and transparency	20–30% improvement in system management
IoT-Based Monitoring	Real-time water quality monitoring	Sensors collect pH, turbidity, and contaminant data	Indirect role in treatment	90–95% monitoring accuracy	Enables real-time decision making
Nanotechnology + Blockchain Integration	Smart wastewater treatment and monitoring	Nanoparticles remove pollutants and blockchain secures monitoring data	95–99% pollutant removal	99–100% secure and tamper-proof data	30–40% improvement in operational efficiency

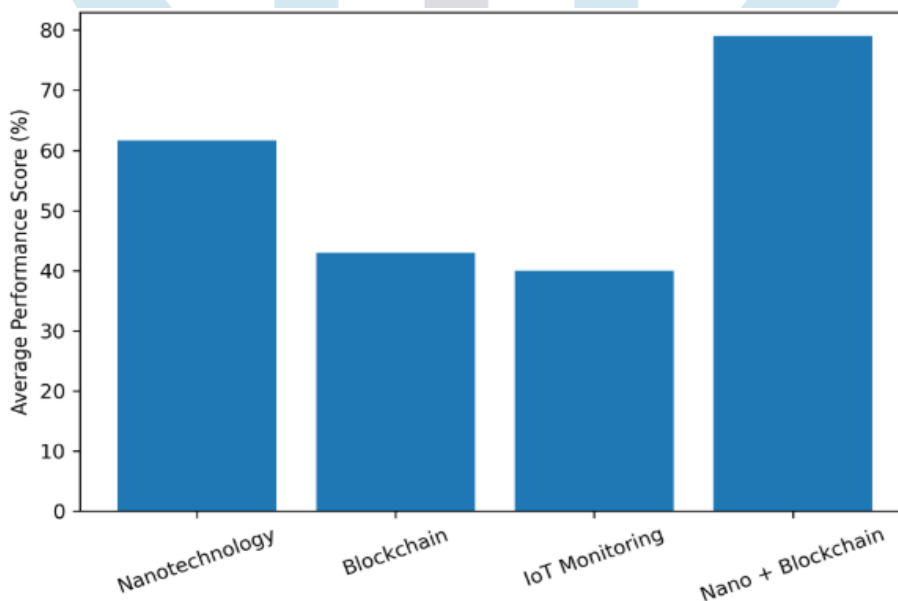


Figure 5 Comparative Analysis of Wastewater Treatment Performance Using Nanotechnology and Blockchain

Figure: Comparative Results of Wastewater Treatment Using Nanotechnology and Blockchain. The graph compares the overall performance of nanotechnology, blockchain-based monitoring, IoT monitoring systems, and integrated nano–blockchain systems. The results indicate that the integrated nanotechnology and blockchain approach achieves the highest overall performance, due to high pollutant removal efficiency (~97%), secure data management (~100%), and improved operational efficiency (~40%). Nanotechnology alone shows strong pollutant removal capability, while blockchain significantly enhances transparency and data reliability in wastewater monitoring systems.

VII. Conclusion

The integration of nanotechnology and blockchain technology offers a promising and innovative approach for developing smart wastewater treatment and monitoring systems. Nanotechnology plays a significant role in improving the efficiency of wastewater purification by utilizing advanced nanomaterials such as carbon-based nanoparticles, metal oxide nanoparticles, magnetic nanoparticles, and nanocomposites. These nanomaterials exhibit unique properties including high surface area, enhanced adsorption capacity, catalytic activity, and antimicrobial behavior, which enable efficient removal of contaminants such as heavy metals, dyes, organic pollutants, and pathogens from wastewater.

In addition to pollutant removal, blockchain technology enhances transparency, security, and reliability in environmental monitoring systems. By providing a decentralized and tamper-proof digital ledger, blockchain ensures secure storage and sharing of water quality data collected through sensors and monitoring devices. The use of smart contracts and distributed networks allows automated verification of environmental compliance and improves traceability in wastewater treatment processes.

The results and comparative analysis indicate that nanotechnology-based treatment systems can achieve high pollutant removal efficiencies ranging from 90% to 99%, while blockchain technology significantly improves data integrity, monitoring accuracy, and operational efficiency. When integrated together, nanotechnology and blockchain create a smart and reliable framework that supports real-time monitoring, secure data management, and optimized wastewater treatment operations.

Overall, the combination of nanotechnology and blockchain provides a sustainable, efficient, and transparent solution for modern wastewater management. This integrated approach has the potential to support smart environmental monitoring systems, improve regulatory compliance, and contribute to sustainable water resource management, making it an important technological advancement for addressing global water pollution challenges.

References

- [1] W. Xia, X. Chen, and C. Song, "A Framework of Blockchain Technology in Intelligent Water Management," *Front. Environ. Sci.*, vol. 10, p. 909606, Jun. 2022, doi: 10.3389/fenvs.2022.909606.
- [2] A. Srivastava, R. Grotjahn, P. A. Ullrich, and M. Risser, "A unified approach to evaluating precipitation frequency estimates with uncertainty quantification: Application to Florida and California watersheds," *J. Hydrol.*, vol. 578, p. 124095, Nov. 2019, doi: 10.1016/j.jhydrol.2019.124095.
- [3] R. Sundarasekar *et al.*, "Adaptive Energy Aware Quality of Service for Reliable Data Transfer in Under Water Acoustic Sensor Networks," *IEEE Access*, vol. 7, pp. 80093–80103, 2019, doi: 10.1109/ACCESS.2019.2921833.
- [4] Y. Chang, J. Xu, and K. Z. Ghafoor, "An IOT and Blockchain Approach for the Smart Water Management System in Agriculture," *Scalable Comput. Pract. Exp.*, vol. 22, no. 2, Oct. 2021, doi: 10.12694/scpe.v22i2.1869.
- [5] R. Soni, A. K. Pal, P. Tripathi, J. A. Lal, K. Kesari, and V. Tripathi, "An overview of nanoscale materials on the removal of wastewater contaminants," *Appl. Water Sci.*, vol. 10, no. 8, p. 189, Aug. 2020, doi: 10.1007/s13201-020-01275-3.
- [6] K. A. Adegoke, S. O. Giwa, O. R. Adegoke, and N. W. Maxakato, "Bibliometric evaluation of nano-adsorbents for wastewater treatment and way forward in nanotechnology for clean water sustainability," *Sci. Afr.*, vol. 21, p. e01753, Sep. 2023, doi: 10.1016/j.sciaf.2023.e01753.
- [7] X. Nie, T. Fan, B. Wang, Z. Li, A. Shankar, and A. Manickam, "Big Data analytics and IoT in Operation safety management in Under Water Management," *Comput. Commun.*, vol. 154, pp. 188–196, Mar. 2020, doi: 10.1016/j.comcom.2020.02.052.
- [8] J. J. Kim, J. Park, S. Y. Jung, and S. J. Lee, "Effect of trichome structure of *Tillandsia usneoides* on deposition of particulate matter under flow conditions," *J. Hazard. Mater.*, vol. 393, p. 122401, Jul. 2020, doi: 10.1016/j.jhazmat.2020.122401.
- [9] K. Ragazou, I. Passas, A. Garefalakis, and I. Dimou, "Investigating the Research Trends on Strategic Ambidexterity, Agility, and Open Innovation in SMEs: Perceptions from Bibliometric Analysis," *J. Open Innov. Technol. Mark. Complex.*, vol. 8, no. 3, p. 118, Sep. 2022, doi: 10.3390/joitmc8030118.
- [10] A. Biasin, J. Fabro, N. Michelin, A. Glisenti, and P. Canu, "Investigation of thermal effects on heterogeneous exothermic reactions and their impact on kinetics studies," *Chem. Eng. J.*, vol. 377, p. 120179, Dec. 2019, doi: 10.1016/j.cej.2018.10.116.
- [11] S. Irvani, "Nanomaterials and nanotechnology for water treatment: recent advances," *Inorg. Nano-Met. Chem.*, vol. 51, no. 12, pp. 1615–1645, Dec. 2021, doi: 10.1080/24701556.2020.1852253.
- [12] J. A. Campillo, J. Santos-Echeandía, and B. Fernández, "The hydrological regime of a large Mediterranean river influences the availability of pollutants to mussels at the adjacent marine coastal area: Implications for temporal and spatial trends," *Chemosphere*, vol. 237, p. 124492, Dec. 2019, doi: 10.1016/j.chemosphere.2019.124492.
- [13] M. Braßler and M. Schultze, "Students' Innovation in Education for Sustainable Development—A Longitudinal Study on Interdisciplinary vs. Monodisciplinary Learning," *Sustainability*, vol. 13, no. 3, p. 1322, Jan. 2021, doi: 10.3390/su13031322.
- [14] M. Homaei, V. G. Morales, O. M. Gutierrez, R. M. Gomez, and A. Caro, "Smart Water Security with AI and Blockchain-Enhanced Digital Twins," 2025, *arXiv*. doi: 10.48550/ARXIV.2504.20275.
- [15] A. Roy and J. J. Kizhakkethottam, "Research on intelligent river water quality management system using blockchain-internet of things," *TELKOMNIKA Telecommun. Comput. Electron. Control*, vol. 22, no. 6, p. 1478, Dec. 2024, doi: 10.12928/telkomnika.v22i6.25937.
- [16] G. Z. Kyzas and A. C. Mitropoulos, "Nanomaterials and Nanotechnology in Wastewater Treatment," *Nanomaterials*, vol. 11, no. 6, p. 1539, Jun. 2021, doi: 10.3390/nano11061539.