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Can bacteria and carbon-based nanomaterials revolutionize nanoremediation strategies for industrial effluents?

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In this study, we delved into cutting-edge strategies for the effective management of wastewater, a critical issue exacerbated by industrial pollution and urban expansion. We introduce the use of carbon-based nanomaterials (CBNs), either alone or functionalized with bacteria, as a novel nanobiotechnological solution for urgent nanobioremediation needs. This technique is notable for its exceptional ability to remove various industrial pollutants, including heavy metals, pesticides, textiles, and dyes, emphasizing the pivotal role of CBNs. The development of bionanocomposites through the integration of CBNs with bacteria represents a significant advancement in enhancing bioremediation efforts. In this study, we assessed the potential health and environmental risks associated with CBN usage while offering an in-depth evaluation of the adsorption mechanisms and factors influencing bioremediation effectiveness. Furthermore, the improved efficiency in treating industrial effluents facilitated by bionanocomposites was investigated, and their alignment with circular economy principles through recyclability is discussed. We aimed to provide, a detailed overview of recent advancements, challenges, and prospects for CBNs and bacterial application in sophisticated wastewater treatment, underscoring their vital importance in promoting the environment.

KEYWORDS

nanobioremediation, carbon-based nanomaterials, bacteria, genetic engineering, industrial effluents, bionanocomposite, circular economy

1 Introduction

1.1 Nanobioremediation and the challenges of industrial effluent in the era of sustainability

Efficiently managing industrial effluents is essential for preserving the environment and safeguarding public health. The UN World Water Development Report has emphasized the pressing need for clean water and sanitation, underscoring the importance of nanobioremediation in addressing these challenges (Ningombam et al., 2024b; Gwenzi et al., 2024). Enhancing bioremediation through bioaugmentation and biostimulation poses challenges such as competition from native microorganisms and the potential risks of eutrophication. The effectiveness of bioremediation can vary depending on environmental conditions and the types of pollutants present. It may also face challenges when dealing with resistant pollutants, which can impact its speed and responsiveness (Ashkanani et al., 2024; Tripathi et al., 2024).

Nanobioremediation combines the power of nanotechnology with bioremediation to tackle the obstacles faced by conventional wastewater treatment methods. This innovative approach improves the breakdown of pollutants and minimizes the impact of environmental factors. This method utilizes nanoparticles and carbon-based nanomaterials (CBNs) to effectively target both organic and inorganic pollutants. As a result, it greatly enhances the efficiency and cost-effectiveness of bioremediation practices, while also aligning with goals of environmental sustainability (Chauhan et al., 2023; Chauhan et al., 2023; Xiang et al., 2023; Dey et al., 2024a; Ningombam et al., 2024a; Singh et al., 2024a; Singh et al., 2024b; Ezeorba et al., 2024).

Significant improvements have been made in pollutant removal efficiency with carbon-based nanomaterials such as graphene and carbon nanotubes in nanobioremediation. The adaptability and interaction of these materials with microorganisms provide a sustainable solution to industrial pollution. They have proven to be effective in treating heavy metals, dye, pesticide, and complex pollutants, thereby promoting environmental sustainability (Chauhan et al., 2023; Xiang et al., 2023; Ningombam et al., 2024a; Ningombam et al. 2024a; Ningombam et al. 2024a; Chen, Liu, and Liu, 2024; Kaur et al., 2024; Ogunsola et al., 2024; Sornaly et al., 2024; Sornaly et al., 2024).

Our work highlights the importance of interdisciplinary collaboration in advancing global environmental sustainability. By introducing an innovative approach to wastewater treatment using carbon-based nanomaterials (CBNs) in conjunction with bacteria, we demonstrate remarkable efficacy in removing industrial pollutants, emphasizing the pivotal role of CBNs in nanobioremediation. The integration of CBNs with bacteria to form bionanocomposites represents a significant advancement, with research focusing on molecular mechanisms to enhance pollution remediation strategies. Additionally, our study addresses critical challenges such as sustainability, nanomaterial recovery, and circular economy, while advocating for collaborative efforts to propel future nanobioremediation research towards environmental sustainability and environmental preservation.

2 Materials and methods

2.1 Parameters considered in this review—identification of relevant studies

We systematically searched the following electronic databases to develop this review and meta-analysis: PubMed-NCBI, Google Scholar, and ScienceDirect. Only articles published in the last 2 years or articles that were fundamental to this research were included. The major scientific articles were selected using the following relevant keywords: “nanobioremediation” OR “carbon-based nanomaterials” OR “genetic engineer” OR “industrial effluents” OR “wastewater treatment” OR “bacteria” OR “bionanocomposite” OR “nanomaterials/functionalization OR “genetic engineer” OR “circular economy”. The following inclusion criteria were used to select the literature for this study: 1) An initial literature search of articles containing the exact keywords; 2) a subsequent search of selected articles containing related words; and 3) reviews published in English. We did not include articles that 1) were not written in English or 2) did not contain the exact and/or associated words cited in the title or abstract of the reference article. Two reviewers independently screened the articles. A total of 126 articles were included in this review based on the relevance of the results and the use of nanotechnologies, particularly CBNs and bacteria, for the bioremediation of industrial residues. Therefore, we considered research articles, review articles, and prospective studies focusing on the bioremediation of microorganisms associated with the use of CBNs as carrier effects and industrial residue degradability agents.

2.2 Outline the experimental setup

The manuscript critically examines the methodologies of selected studies on the use of bacteria and carbon nanomaterials for industrial waste cleanup, emphasizing replicable experimental and analytical methods, as delineated in Figure 1.

a) Identification required the collection of articles using specific keywords from databases.
b) The screening process involved carefully reviewing abstracts to determine their relevance to the topic, followed by thorough assessments of the full-text articles. Non-English works were not included in the evaluation.
c) The final selection comprised studies that met the criteria and had a specific focus on nanomaterials and bacterial bioremediation.

3 Industrial effluent treatment: the new frontier has arrived

3.1 Innovations in bacterial genetics and molecular techniques that improve the bioremediation of industrial effluent

We present a notable breakthrough in bioremediation, specifically highlighting the use of genetically modified bacteria to address challenging contaminants found in industrial wastewater. Genetic modifications seek to enhance the capacity of bacteria to break down substances that are typically resistant in the environment. Notable advancements include the following:

1) Special Metabolic Pathway Modifications: Techniques enable the introduction of genes that encode enzymes with the remarkable ability to break down specific pollutants. For instance, the xylE gene from *P. putida* is utilized for xylene degradation. An intriguing case involves the genetic modification of *P. putida*, which incorporates the

TABLE 1 Bacterial mechanisms and genes in industrial effluent bioremediation.

Bacteria	Physiological mechanisms	Responsible genes	Target contaminant	Polluting industry	Degradation efficiency (%)	References
Pseudomonas putida	Enzymatic degradation, catabolic pathway	tod, xyl	Aromatic hydrocarbons, phenol	Oil and refineries, chemical industry	70%–90%	Wu et al. (2023b)
Bacillus subtilis	Biosorption, enzymatic reduction	arsC, yqjI	Heavy metals, dyes	Mining, textile industry	60%–80%	Rather et al. (2023a)
Escherichia coli	Chemical transformation, biosorption	cueO, cusA	Volatile organic compounds, heavy metals	Chemical industry, metallurgy	50%–70%	Lee et al. (2023a)
Sphingomonas sp	Enzymatic degradation, specialized metabolism	bph, dxn	PCBs, dioxins	Paper and pulp industry, plastic manufacturing	80%–95%	Aguilar-Romero et al. (2024)
Deinococcus radiodurans	Radiation resistance, heavy metal precipitation	drA, pprA	Heavy metals, radioactive waste	Nuclear energy, waste treatment	65%–85%	Zhang et al. (2022)
Burkholderia cepacia	Enzymatic breakdown, biotransformation	mpd, opd	Organophosphates, herbicides	Agriculture, landscaping	70%–85%	Yang et al. (2024)
Rhodococcus rhodochrous	Lipid accumulation, biodegradation	alkJ, alkB	Alkanes, petroleum hydrocarbons	Oil spill, petroleum industry	60%–80%	Skinner et al. (2024)
Alcaligenes faecalis	Metal reduction, biosorption	czcA, cnr	Cadmium, nickel	Metal processing, electroplating	55%–75%	Sajjad et al. (2024)
Mycobacterium vanbaalenii	Polycyclic aromatic hydrocarbon degradation	nidA, nidB	PAHs	Coal processing, automotive exhaust	80%–90%	Lee, Lee, and Kim, (2023b)
Lysinibacillus sphaericus	Enzymatic detoxification, metal biosorption	merA, merB	Mercury	Chlor-alkali plants, battery manufacturing	75%–90%	Pardhe et al. (2023)
Clostridium sp.	Anaerobic digestion, fermentative breakdown	cooS, acs	Organic solvents, fatty acids	Biofuel production, food processing	60%–80%	Ezeorba et al. (2024)
Enterobacter cloacae	Nitrate reduction, biosorption	napA, nirS	Nitrates, nitroaromatic compounds	Agricultural runoff, explosives manufacturing	70%–85%	Huang et al. (2024)
Shewanella oneidensis	Metal reduction, electron transfer	mtrC, omcA	Chromium, uranium	Metal plating, nuclear waste	65%–90%	Ray and Pattnaik, (2024)

todC1 gene (Xue et al., 2022). This modification significantly enhances the capacity of bactéria to degrade toluene, resulting in a remarkable improvement in decontamination efficiency compared to that of nonmodified strains (Chunyan et al., 2023; Maurya et al., 2023).

2) Physiological Adaptations for Pollutant Resistance: Various techniques have been employed to enhance the resistance of bacteria to toxic conditions, such as high concentrations of heavy metals. For instance, the introduction of the acrB gene into *Escherichia coli* has proven effective in developing bacteria with enhanced resistance. This remarkable adaptation enables bacteria to not only survive but also thrive in extremely challenging environments. Genetic modifications enhance bacteria's ability to withstand toxic compounds, enabling them to thrive in polluted environments. The task at hand is to modify the bacterial efflux system to eliminate detrimental substances (Li et al., 2024; Wang et al., 2024a).
3) Genetic Modification Techniques Utilizing the CRISPR-Cas9 Technology: Cutting-edge methods, such as CRISPR-Cas9, are utilized to manipulate the bacterial genome, enabling the manipulation of DNA sequences through insertion, deletion, or modification. This technique enables precise modifications in bacterial gene expression, enhancing the synthesis of crucial enzymes involved in the breakdown of pollutants. One example involves improving the capacity of *P. putida* to produce catechol 2,3-dioxygenase, which is essential for breaking down complex xenobiotics such as aromatic compounds (A. K. Verma et al., 2024; Zhao et al., 2024).

One fascinating aspect of this research involves the development of bacteria that can break down polycyclic aromatic hydrocarbons (PAHs) and process bisphenol A (BPA), a harmful organic pollutant that disrupts the endocrine system. These genetic engineering advancements showcase the immense potential for improving bioremediation techniques, providing a more efficient and environmentally conscious method for treating industrial effluent (Aryal, 2024; Wang et al., 2024a; Wang et al., 2024b; Nandy and Kapley, 2024; Venkatraman et al., 2024; Venkatraman et al., 2024). One of the fascinating aspects of this research is the exploration of previously unknown metabolic pathways and the identification of key genes involved in the breakdown of challenging pollutants.

The progress in bioremediation technologies highlights a notable shift toward more sustainable and eco-friendly approaches to handling industrial pollutants, laying the foundation for a cleaner and more sustainable future. Different genetically distinct bacteria are involved in the bioremediation of industrial pollutants as in Table 1. The examples provided cover a wide range of applications, showcasing the effectiveness and precision of different bacterial species and their genetic mechanisms in tackling pollutants from different industrial sectors (Chauhan et al., 2023; Dey et al., 2024a; Wang et al., 2024b).

The following is a summary of bacteria commonly used in bioremediation:• *P. putida* is highly skilled in enzymatic degradation and catabolic processes. It excels in breaking down aromatic hydrocarbons and phenols, which are commonly found in oil refineries and the chemical industry. With the help of the toluene/benzene degradation pathway (Tod genes) and the xylulose reductase enzyme (Xyl gene), this degradation process has achieved an impressive efficiency of 70%–90% (Gao, Guo, and Niu, 2024; Gutiérrez et al., 2024).• *Bacillus subtilis* utilizes biosorption and enzymatic reduction mechanisms to effectively reduce heavy metals and dyes commonly present in the mining and textile industries. This process is facilitated by the presence of arsenate reductase genes (arsC), resulting in an impressive degradation efficiency of 60%–80% (Wu et al., 2023a).• *E. coli* is vital in the chemical transformation and biosorption of volatile organic compounds and heavy metals, causing it to be critical in the chemical and metallurgical sectors. The cueO and cusA genes are crucial in maintaining a copper balance, exhibiting 50%–70% efficiency in copper degradation (Kojima et al., 2024).• *Sphingomonas sp.* is highly proficient in the enzymatic breakdown of polychlorinated biphenyls (PCBs) and dioxins. The bph and dxn genes are crucial in facilitating the degradation of biphenyl and toluene/xylene, respectively. This leads to an efficiency of 80%–95%, which is vital for industries such as paper, pulp, and plastics (Sorouri et al., 2023).• Deinococcus radiodurans is widely recognized for its remarkable resistance to radiation and unique ability to remove heavy metals from the environment. The drA and pprA genes have been identified as crucial factors in these exceptional traits. This bacterium has proven to be highly effective in addressing heavy metals and radioactive waste, especially in the fields of nuclear energy and waste treatment. It has demonstrated an impressive degradation efficiency ranging from 65% to 85% (Wang et al., 2024a; Li et al., 2024).

Table 1 presents a thorough examination of different bacteria and their role in the purification of industrial effluents through bioremediation. We provide a comprehensive analysis of the physiological mechanisms employed by bacteria, the specific genes involved in these mechanisms, the types of contaminants they can target, the industries where these pollutants are frequently encountered, and the varying degrees of degradation efficiency exhibited by different bacterial species (Aguilar-Romero et al., 2024; Ezeorba et al., 2024; Huang et al., 2024; Ray and Pattnaik, 2024; Sajjad et al., 2024; Yang et al., 2024).

*Please be aware that the "Degradation Efficiencies (%)" provided are approximate values obtained from scientific literature and may differ depending on the specific research being conducted. Several variables can influence the effectiveness of degradation, such as the type of bacteria, the environment in which degradation occurs, and the presence of other microbes or chemicals. The relationship between pollutants and industries is intricate and influenced by a variety of factors, including processes, legislation, and environmental management methods. The table provided offers a simplified framework that can be used as a basis for conducting a more extensive study.

Further examples highlight the wide range of bacterial capabilities in environmental remediation. For instance, *Alcaligenes faecalis* can treat cadmium and nickel, *Mycobacterium vanbaalenii* can breakdown polycyclic aromatic hydrocarbons, and *Lysinibacillus sphaericus* can detoxify mercury. Thus, this manuscript highlights the significance of utilizing the genetic and physiological diversity of bacteria to create specific bioremediation approaches, which hold great potential for effectively removing industrial pollutants and detoxifying the environment (Ray and Pattnaik, 2024; Xu et al., 2024). The fusion of these biological insights with nanotechnology may revolutionize environmental protection and sustainability. Further research in this interdisciplinary field may greatly improve our capacity to address the effects of industrial pollutants, promoting a cleaner and more sustainable future (Chauhan et al., 2023; Ningombam et al., 2024a).

This summary emphasizes the pivotal role of genetically modified bacteria and their molecular pathways in bioremediating industrial effluents, illustrating the broad spectrum of contaminants they can address. This highlights the need for the integration of genetic and molecular innovations to improve bioremediation efficiency, as demonstrated by Wang et al., who showcased the effectiveness of genetically engineered bacteria in detoxifying wastewater (Zhang et al., 2022; Wang Xin et al., 2024; Sajjad et al., 2024). This breakthrough underlines the potential of genetic engineering to provide targeted, eco-friendly solutions for effluent treatment and promote sustainable environmental practices. Advancements in molecular engineering and synthetic biology are crucial for developing effective microbial systems capable of pinpointing and eliminating pollutants, thereby enhancing bioremediation methods, and supporting green decontamination techniques (Xue et al., 2022; Elmore et al., 2023; Hassanien et al., 2023; Wang et al., 2024a; Chen, Liu, and Liu, 2024).

3.2 How can industrial effluent treatment be enhanced through the functionalization and optimization of carbon-based nanomaterials?

CBNs, including CNTs, quantum dots (QDs), carbon fibers (CF), and graphene (G), are key for treating a variety of industrial wastes due to their superior adsorption capabilities. These nanomaterials excel in contaminant removal and wastewater purification by effectively adsorbing heavy metals such as lead, mercury, cadmium, and arsenic, thus mitigating water pollution and protecting human health and the environment (Ahmed et al., 2022). Furthermore, they are adept at handling effluents from the oil sector, which contain hydrocarbons and volatile organic compounds. Demonstrating versatility across sectors, CBNs are particularly effective in the chemical industry for detecting and decomposing pesticides and chemical residues, with efficiencies of up to 95% for pesticides (Singh and Saxena, 2022b). CNTs achieve 100% efficiency in

TABLE 2 Efficiency of carbon-based nanomaterials in industrial effluent treatment.

Carbon-based nanomaterial	Contaminants	Industrial segment	Applications	Estimated efficiency	References
Carbon Nanotubes, Graphene	Heavy metals, dyes, volatile organic compounds	Wastewater Treatment	Use of CNTs and graphene for adsorption and photocatalytic degradation of pollutants	80%–99% for heavy metals; 70%–90% for dyes	Ningombam et al. (2024a)
Graphene, Carbon Dots	Pesticides, solvents, chemical residues	Chemical Industry	Carbon dots for detection and degradation of pesticides in industrial effluents	70%–95% for pesticides	Jatoi et al. (2024)
Carbon Nanotubes, Nanostructured Diamond	Heavy metals, acids, sediments	Mining	CNTs for treatment of acid mine effluents and removal of heavy metals	80%–100% for heavy metals	Siddiqa et al., 2023b; Molavi et al., 2024b
Graphene, Carbon Nanofibers	Hydrocarbons, heavy metals	Oil and Gas	Application of graphene in treatments of produced water and oil removal	85%–95% for hydrocarbons	Jatoi et al., 2024; Zhang et al., 2024
Carbon Dots, Graphene	Nitrates, phosphates, pesticides	Agriculture	Use of graphene and carbon dots for removal of organic and inorganic contaminants in agricultural waters	75%–90% for nitrates and phosphates	Cruz-Cruz et al. (2024)
Activated Carbon Nanoparticles	Organic pollutants, odors	Water Treatment	Utilization of activated carbon nanoparticles for enhanced adsorption of organic pollutants and odor removal	80%–95% for organic pollutants	Jiang et al. (2024)
Multi-walled Carbon Nanotubes (MWCNT)	Pathogens, microbial contaminants	Healthcare, Water Treatment	MWCNTs for antibacterial applications and removal of pathogens in healthcare wastewater	85%–99% for pathogens	Jiang et al. (2024)
Fullerene Derivatives	Toxic metals, organic compounds	Environmental Cleanup	Application of fullerene derivatives in the sequestration and neutralization of toxic metals and organic compounds	75%–90% for toxic metals	Sam and Cao, (2024)

removing heavy metals from acidic mine effluents and sediments. In the oil and gas sector, CFs are crucial in treating hydrocarbons and heavy metals, with up to 95% efficiency. Moreover, in agriculture, G and CDs effectively remove nitrates, phosphates, and pesticides, reaching 90% removal rates for nitrates and phosphates, demonstrating their broad applicability and significant contributions to environmental sustainability (Dhanapal et al., 2024a; Sajjad et al., 2024; Tripathi et al., 2024).

Each of these materials, presented in Table 2, has distinct properties that make them well suited for the removal of various pollutants, as outlined below:

1) Carbon Nanotubes (CNTs) with diameters ranging from 1 nm (single-walled) to 100 nm (multi-walled) and lengths up to micrometers, have a unique structure that provides a large specific surface area up to 1,320 m^2/g. This attribute makes them highly effective at adsorbing heavy metals such as lead, mercury, cadmium, and arsenic from industrial effluents. Novel synthesis techniques, such as microwave radiation, have been introduced to enhance the production of CNTs, demonstrating their potential to remove toxic dyes from textile wastewater (Ceroni et al., 2024). Furthermore, the use of biomass-derived CNTs for heavy metal removal represents a significant step towards environmentally friendly remediation methods. Functionalizing CNTs with specific groups significantly improves their adsorption capacity, enabling selective interactions with metal ions and enhancing their effectiveness in water treatment (Dey et al., 2024a; Ningombam et al., 2024a). The adsorption of heavy metal ions in aqueous solutions is directly influenced by the functionalization of CNTs. The adsorption capacity of CNTs is significantly enhanced by the addition of specific functional groups, enabling more selective and strong interactions with specific metal ions. Thus, through a range of heavy metals, functionalization affects the affinity of CNTs. Some of the elements that fall into this category are arsenic (As), cadmium (Cd), and lead (Pb). This method of functionalization enhances the effectiveness of CNTs in eliminating metallic pollutants from industrial effluents. Additionally, it facilitates the creation of more efficient and tailored water treatment techniques, highlighting the significance of surface chemistry in optimizing adsorptive materials for environmental remediation (Lee, Lee, and Kim, 2023b; Dey et al., 2024a; Ogunsola et al., 2024). Furthermore, a novel microemulsion technique has been developed to functionalize carbon nanotubes (CNTs) with a hydrocarbon tail. The objective is to effectively eliminate various hydrocarbon contaminants from water polluted by oil spills. Several methods have been developed to modify surfaces, such as acid treatment, grafting functional groups, and impregnating with metals or metal oxides (Hu et al., 2024; Yahyaee and Mofidi, 2024). In general, the modifications of CNTs can be achieved through either covalent or non-covalent functionalization, which greatly improves their effectiveness in environmental remediation (Y. Singh and Saxena, 2022a).
2) Carbon Quantum Dot (CD) with sizes typically less than 10 nm, exhibit unique quantum properties, such as quantum confinement effects and a high surface area-to-mass ratio, causing them to be highly effective in photocatalytic pollutant degradation, with efficiencies up to 95%. Their remarkable ability to interact with a wide range of contaminants is enhanced through surface modifications with

functional groups such as carboxyls, amines, and thiols, improving adsorption and selective binding with both metal and organic ions (Hu et al., 2024; Hu et al., 2024; Soni et al., 2024). The functionalization of CDs, as all CBNs enhances their selectivity and adsorption efficiency, enabling precise chemical recognition and increased binding affinity for specific pollutants through mechanisms such as electrostatic attraction and hydrogen bonding. This adaptability and efficiency cause CDs to be a promising tool for water purification because they can effectively eliminate contaminants and have the potential for adsorbent regeneration in cases of physical adsorption, thereby demonstrating their versatility in environmental cleanup efforts (Soni et al., 2024). Various mechanisms govern this interaction, such as electrostatic attraction, hydrophobic interactions, hydrogen bonding, and metal complexation (Cruz-Cruz et al., 2024). The process of adsorption may effectively eliminate contaminants from water. In certain cases, this process can be reversed for physical adsorptions, which enables CD regeneration. In contrast, chemical adsorption has a longer-lasting effect, demonstrating the remarkable adaptability and efficiency of CD in the field of water purification (Kausar and Ahmad, 2024).

3) Carbon fibers (CF) with diameters ranging between 5 and 10 µm, possess remarkable mechanical and thermal resistance. Additionally, they exhibit a remarkable absorption capacity, enabling the efficient removal of hydrocarbons and heavy metals from effluents with impressive efficiencies up to 95%. This groundbreaking technique significantly increases the adsorption capacity of the fibers by introducing a selective and reactive surface. Furthermore, it bestows an adsorbent material with antimicrobial properties. The presence of silver nanoparticles improves the interaction with radioactive iodine ions by utilizing mechanisms such as electrostatic attractions and ion exchange. This increases the effectiveness of eliminating these detrimental pollutants (Jia et al., 2023; Joseph and Vijayanandan, 2023). Optimizing water purification processes, particularly in the remediation of radioactive effluents, can be achieved through the modification of adsorbent materials with metallic nanoparticles. This may drive major progress in ensuring environmental safety and safeguarding public health. In addition, sustainable waste management includes techniques that enable the recovery and reuse of CF obtained from bioremediation procedures. This is accomplished through a creative method that enables the repurposing of CF and follows the principles of a circular economy while minimizing the environmental consequences of disposing composites. We suggest a notable change in waste management by advocating for the recycling of CF, encouraging the growth of closed-loop value chains, and reducing the need for new resource extraction. This is a noteworthy advancement towards adopting more environmentally friendly approaches (P. Zhang et al., 2024; Joseph and Vijayanandan, 2023).
4) Graphene (G) is a remarkable material with a single layer of carbon atoms that are only 0.34 nm thick. It has an impressive surface area of 2,630 m^2/g, which enable it to efficiently adsorb a wide range of pollutants. This includes dyes and heavy metals, as G can interact effectively with different types of contaminant molecules. G, with its exceptional properties, holds immense promise for propelling progress in various scientific and technological domains. G has shown great potential in various fields, such as water filtration, advanced electronics, and the creation of composite materials. This is mostly because of its remarkable surface area, impressive mechanical strength, and excellent thermal and electrical conductivity (Obayomi et al., 2022; N; Verma et al., 2023). The remarkable versatility of G is showcased by its wide range of applications, which hold great potential for driving significant advancements in sustainable solutions and environmentally friendly technologies (Kausar and Ahmad, 2024). Additionally, the treatment of industrial effluents has been significantly transformed through the functionalization of G, enabling the development of highly efficient membranes that can selectively eliminate heavy metals and toxic organic substances. Through this procedure, the surface of G undergoes a chemical modification with specific functional groups, such as aminos groups, to effectively capture metallic ions while repelling organic compounds (Jatoi et al., 2024).
5) Nanodiamonds (ND) ranging in size from 2 to 8 nm, possess a highly adaptable surface that can be tailored to optimize interactions with targeted pollutants. With their impressive customization capability, exceptional chemical stability, and expansive surface area, these materials hold great potential as effective tools for eliminating a wide range of pollutants. The synthesis and functionalization of NDs enable them to effectively remove and break down a wide range of pollutants, including heavy metals and persistent organic compounds (Molavi et al., 2024b; Silah et al., 2024). These materials have superior performance compared to traditional materials due to their large surface area, excellent chemical stability, and impressive ability to specifically target pollutants. Utilizing nanocomposites composed of ND integrated into polyaniline/polyvinylidene fluoride (PANI/PVDF) microfiltration membranes to eliminate industrial pollutants results in a distinctive amalgamation that significantly amplifies the membranes' ability to adsorb, select, and remain stable in complex aqueous environments (Yotinov et al., 2022; Molavi et al., 2024a). This groundbreaking technique not only increases the effectiveness of eliminating pollutants, such as heavy metals and volatile organic compounds, but also provides the membranes with exceptional mechanical properties and chemical resistance. This causes them to be perfect for use in industrial effluent treatment applications (Siddiqa et al., 2023a).

Table 2 presents a summary of using different CBNs for treating industrial wastes. This shows their impressive ability to effectively remove various contaminants in different industrial sectors.

For successful remediation, it is crucial to carry out thorough preparation and functionalization procedures for CBNs. This includes synthesis, purification, functionalization, and

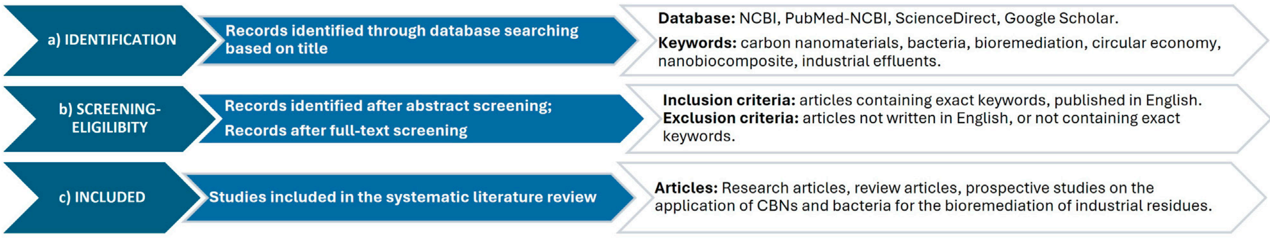

FIGURE 1
Presents a step-by-step process for conducting a thorough literature review. It involves searching various databases using specific keywords, followed by a careful evaluation of abstracts and full texts in English to determine relevance. Finally, studies that specifically address the use of carbon nanomaterials and bacteria for bioremediation of industrial waste are included.

characterization, all of which are specifically designed to optimize pollutant interaction. Various techniques, such as chemical vapor deposition and laser ablation, are used to generate a wide range of CBNs. These CBNs are then purified to enhance their effectiveness. Surface modification improves the compatibility of CBN with contaminants, while thorough characterization confirms the existence of functional groups and evaluates material properties, guaranteeing efficient removal of pollutants (Ningombam et al., 2024a; Cruz-Cruz et al., 2024; Hu et al., 2024).

3.3 How can the combined use of microbes and carbon nanomaterials enhance the removal of industrial effluents?

Recent advancements in nanotechnology have shown significant potential in environmental remediation, especially in treating industrial effluents. Integrating CBN with bacteria has emerged as an effective strategy for pollution control (Mekonnen, Aragaw, and Genet, 2024) (Y. Singh and Saxena, 2022c). Studies have highlighted that nanoparticles can enhance biohydrogen production from fermentative bacteria by improving enzyme efficiency. The use of CBNs such as G, CDs, CNTs, and CFs shows significant potential in industrial effluent remediation. The functionalization of these materials with groups such as carboxyl, amino, or hydroxyl groups enhances their interaction with bacteria, leading to more effective pollution treatment. These modifications facilitate bacterial attachment and growth and support electron transfer in bioelectrochemical systems, increasing the efficiency of the removal of complex organic pollutants. By incorporating antimicrobial agents or selecting specific microbial communities, the proliferation of harmful microorganisms can be minimized (Chen, Liu, and Liu, 2024; Cruz-Cruz et al., 2024). The development of advanced effluent treatment technologies, including microbial fuel cells and bioreactors, leverages these functionalization strategies to provide eco-friendly solutions to the challenges of industrial wastewater treatment (Hu et al., 2024; Jiang et al., 2024).

CBN and G have been developed into innovative photocatalysts in wastewater treatment. These catalysts facilitate charge and heat transfer at interfaces, effectively removing organic and inorganic pollutants from industrial wastewater. This represents a notable leap in water purification technology (Joseph and Vijayanandan, 2023). The combination of CBN with bacteria not only boosts degradation efficiency beyond traditional bioremediation methods but also accelerates the breakdown of complex organic materials otherwise resistant to conventional treatments (Figure 2). This methodology is effective against persistent pollutants such as heavy metals and polycyclic aromatic hydrocarbons, significantly reducing their toxicity and bioavailability (Abril et al., 2024; Sun et al., 2024).

Moreover, the ability to recover and reuse nanomaterials after bioremediation underscores a move toward sustainability and a circular economy, aligning with efforts to minimize environmental risks. The fusion of biology and nanotechnology in remediation with nanocomposites represents a pioneering advancement. This nanocomposite approach promises more effective, environmentally friendly solutions for industrial effluent treatment, paving the way for future research to expand and enhance its applications (Dey et al., 2024a; Singh et al., 2024a).

The interaction between bacteria and CBNs, such as CNTs and G, improves bioremediation efficiency through the extensive surface area and reactivity of materials, the unique features of CBNs, including their high porosity, adsorption capacity, and electrical properties, support this synergistic interaction, facilitating pollutant degradation and adsorption. Surface modification of CBNs broadens their application, enabling them to adapt to various pollutants and environmental conditions, thus enabling treatment diversity (Hu et al., 2024; Sun et al., 2024). Notably, nanobioremediation offers a distinct advantage over traditional bioremediation by shortening the treatment time, resulting in swift and crucial remediation for cases of acute contamination.

This approach is characterized by its specificity, selectivity, and sustainability, reducing energy consumption and chemical use while enabling resource recovery. CBNs can recover valuable metals from effluents, underscoring the process's adaptability and scalability for different contexts (Ningombam et al., 2024a; Dey et al., 2024b). Chemical functionalization of CBNs increases their hydrophilicity, thereby improving bacterial adhesion and activating essential metabolic pathways for pollutant breakdown (Ogunsola et al., 2024; Sam and Cao, 2024; Silah et al., 2024).

The integration of nanotechnology with microbial systems through nanocomposite approaches notably improves remediation outcomes by enabling more precise microbial interactions (Balakumar et al., 2024; Jagaba et al., 2024). The complementary roles of CBN adsorption capacity and bacterial biodegradation activities create a synergistic effect, while electron transfer facilitated by CBNs accelerates redox reactions critical for biodegradation. Recent advancements have highlighted how the interplay between bacteria and CBNs, including CNTs, G, and CDs, improves the removal of heavy metals, organic compounds, and other pollutants from wastewater (Dey et al., 2024a; Cruz-Cruz et al., 2024; Sam and Cao, 2024; Silah et al., 2024; Soni et al., 2024).

The use of nanocomposites in effluent treatment represents a breakthrough in environmental remediation because they can adsorb and decompose pollutants while supporting water recycling and material regeneration. This analysis highlights the potential of combining CBNs and microorganisms in nanobioremediation, offering sustainable solutions to environmental challenges (Singh et al., 2024a; Ezeorba et al., 2024). Case studies in industrial nanobioremediation have shown effective pollution removal, including hydrocarbon decomposition in oil waste, elimination of textile dyes, soil decontamination from heavy metals, and pesticide processing from agricultural waste, emphasizing the sustainability and effectiveness of these nanocomposite systems in environmental cleanup (Jatoi et al., 2024b; Yahyaee and Mofidi, 2024).

Electron conductivity facilitates electron transfer between bacteria and pollutants, which is crucial for biodegradation. Optimal CBN quantities enhance bacterial growth and metabolic activity, although excessive amounts may hinder it. Understanding these interactions is vital for developing effective and eco-conscious nanobioremediation methods. Despite its potential for effective effluent management and environmental preservation, challenges such as high development costs and technical difficulties in stabilizing CBNs in complex environments remain. This synergy between nanotechnology and microorganisms offers a sustainable approach to waste treatment, promoting renewable energy generation and resource utilization (Dey et al., 2024a; Chen, Liu, and Liu, 2024; Sun et al., 2024).

This innovative synergy between bacteria and CBNs represents a technical advancement in industrial effluent remediation, highlighting its potential for significant environmental progress (Chauhan et al., 2023; Ningombam et al., 2024a; Chen, Liu, and Liu, 2024). These challenges, along with potential environmental impacts, are the focus of ongoing research, highlighting the need for continued innovation in this promising field. Further research is needed to explore CBN-microbe-contaminant interactions for enhanced nanobioremediation, especially in challenging environments. Responsible use considers environmental, safety, and economic implications, ensuring sustainable nanobioremediation advancement (Chen, Liu, and Liu, 2024; Kaur et al., 2024).

4 Risks of nanomaterials' biopersistence in environmental remediation and contributions to the circular economy

4.1 Assessment and monitoring of nanomaterials' biopersistence risks in nanobioremediation

Progress in nanobioremediation technology relies on the development of enhanced nanomaterials that merge nanotechnology, molecular biology, and genetic engineering to offer more efficient pollution cleanup methods. While nanotechnology presents significant prospects for environmental rehabilitation, questions about its long-term ecological implications remain. A detailed understanding of nanomaterial biopersistence is crucial for accurately identifying hazards and enabling the responsible development of nanobioremediation technology. Maintaining the highest safety standards is crucial for the responsible use of nanomaterials and the advancement of sustainable practices (Rajput et al., 2022a; Hidangmayum et al., 2023a; Dey et al., 2024b; Dey et al., 2024b; Yang et al., 2024).

Therefore, it is imperative to explore its use in challenging areas and understand its long-term environmental and toxicological implications. The introduction of universal regulatory standards, sophisticated characterization techniques, and economic evaluations will aid in the sustainable expansion of nanobioremediation. The evolution of nanobioremediation hinges on creating new nanomaterials with enhanced features and biocompatibility, emphasizing the need for safety standards and responsible use. Understanding the biopersistence of nanomaterials is key to addressing environmental concerns and supporting the safe use of nanotechnology (Devasena et al., 2022; Vineeth Kumar et al., 2022; Rahman et al., 2023; Chávez-Hernández et al., 2024a). Despite its potential, addressing ecological issues remains a priority to ensure the responsible progression of technology. This thorough analysis highlights the need for ongoing research, multidisciplinary collaboration, and global cooperation to address the challenges and opportunities of nanobioremediation, ensuring that its development favorably contributes to environmental sustainability and pollution remediation (Kim et al., 2023; Chávez-Hernández et al., 2024a).

Advanced biodegradation studies employing sophisticated methodologies, such as metagenomic techniques, are crucial for understanding how microorganisms and enzymes degrade nanomaterials and the microbiota involved in these processes. High-resolution mass spectrometry is essential for accurately identifying and quantifying nanoparticles in environmental samples, providing precise traceability at very low levels. Investigations into biodegradation, including advanced approaches, such as metagenomics, enhance our knowledge of nanomaterial degradation processes and related microbial populations (Wang et al., 2024a; Cai et al., 2024). Modeling and observation methodologies can predict the accumulation of nanomaterials in the environment, which is vital for assessing long-term sustainability.

In situ transmission electron microscopy (TEM) and atomic force microscopy (AFM) are instrumental in examining the interactions between nanomaterials and organisms, as well as nanoscale changes, providing insights into the biopersistence and impact of these materials. Real-time monitoring systems, leveraging advancements in nanotechnology and molecular biology, offer swift insights into bioremediation progress, enabling adaptive management in response to environmental changes (Rather et al., 2023b; Chaudhary et al., 2023; Salazar et al., 2023). Evaluating the long-term environmental consequences and toxicity of nanomaterials and bacteria used in bioremediation is essential. Also, strategies for implementing nanobioremediation on a large scale in industry and assessing its economic and environmental viability compared to traditional remediation methods require thorough investigation (Sornaly et al., 2024; Sun et al., 2024; Tripathi et al., 2024).

This underscores the need for multidisciplinary research, ongoing progress, and global collaboration in this expanding field. The integration of degrading bacteria with CBNs in nanobioremediation systems offers a viable technique for removing environmental pollution. However, the potential toxicity of these nanocomposite systems to the food chain has raised considerable concerns. CBNs, such as non-functionalized CNTs and G, are toxic to aquatic and terrestrial animals and impact biodiversity and ecosystem functionality (Audira et al., 2024; Sandra de et al., 2024). Furthermore, the interaction between degrading bacteria and CBNs may lead to the formation of secondary metabolites or degradation intermediates, whose implications for organism health and food safety are not well characterized. The bioaccumulation of these compounds in base trophic organisms, such as phytoplankton and zooplankton, can adversely affect not only these organisms but also secondary and tertiary consumers, highlighting the need for detailed environmental risk assessments for nanobioremediation systems (Mousa, Tulbure, and Fawaeer, 2023; Petersen et al., 2023; Audira et al., 2024; Sandra de et al., 2024).

Thus, it is crucial to develop risk mitigation techniques and special restrictions for the use of nanocomposite systems combining degrading bacteria and CBNs in nanobioremediation. Establishing stringent criteria for the synthesis, release, and disposal of these systems can help minimize potential impacts on the food chain and ensure ecological safety. Additionally, promoting research on environmental detection and monitoring methods for these nanomaterials, as well as on exposure pathways and toxicity mechanisms, is key to protecting ecosystems and human health. These approaches will ensure that the benefits of nanobioremediation can be responsibly harnessed without compromising ecosystem integrity or food chain safety (Kim et al., 2023; Sandra de et al., 2024).

4.2 Enhancing the circular economy: the role of nanocomposite nanoremediation systems with carbon nanomaterials and bacteria in the reuse of industrial effluent waste

The use of nanocomposites in wastewater treatment exemplifies the concepts of circular economy by highlighting material recovery and reuse. This is crucial for the circular bioeconomy, which is built upon the principles of recycling, reusing, disposing, and reducing (Figure 3). Nanocomposites in effluent treatment exemplify CE concepts by emphasizing material recovery and regeneration (Chen, Liu, and Liu, 2024; Kaur et al., 2024). The water treated using nanobioremediation has the potential to be reused in different sectors, especially in agriculture where the environment is often polluted by pesticides and other harmful substances. This method of treatment contributes to the preservation of water resources. Postremediation recovery of biomass and nanomaterials facilitates the creation of sustainable materials and energy sources, reducing operational costs and reliance on new resources. Moreover, the conversion of biological waste into biogas offers a sustainable energy source. Nanocomposite systems capitalize on CBN features to enhance bacterial activity, pollutant adsorption, and enzymatic catalysis. This integrated approach supports efficient waste reuse within the circular economy, promoting sustainability across sectors (Awogbemi and Von Kallon, 2024; Liaquat and Muddasar, 2024; Sravan, Matsakas, and Sarkar, 2024).

The use of nanocomposites in effluent treatment promotes sustainability by minimizing pollution at their source, improving water quality, and aiding in decentralized water treatment emphasizing sustainable design and material recovery, which agree with the circular economy (CE). Their adsorption and degradation capabilities, coupled with easy regeneration, offer a sustainable solution prioritizing sustainable production methods and materials to ensure efficient recovery and reduce costs and waste. The synergistic interactions observed in nanobioremediation processes, as demonstrated by Chen et al. (2024), lead to efficient pollutant elimination. Reusing waste from these technologies is crucial for CE sustainability, (Salehi and Wang, 2022; Chen, Liu, and Liu, 2024).

Recycling nutrient-rich effluents enhances agricultural sustainability by reducing reliance on artificial fertilizers. These innovative approaches underscore the potential of nanobioremediation waste in fostering a CE, minimizing environmental impacts, and improving waste management economics. Nanobioremediation waste has significant potential for integrating into the CE, offering solutions to environmental challenges while promoting sustainability. Advanced techniques enable efficient retrieval of nanomaterials from bioremediation residues, facilitating their reuse in subsequent cycles or other industrial applications (Pereira et al., 2024; Poonia et al., 2024; Trivedi et al., 2024). Additionally, technologies such as anaerobic digestion can convert microbial biomass into renewable energy and chemicals, further minimizing landfill waste. Case studies demonstrate the successful recovery of G from water contaminated with heavy metals, demonstrating its reusability within the CE. Moreover, repurposing microbial biomass into biofertilizers enriches the soil and enhances plant growth, contributing to sustainable agriculture. These practices align with global sustainability goals, emphasizing the transformative potential of nanobioremediation waste in converting environmental liabilities into sustainable assets.

Efficient nanobioremediation of industrial pollutants requires balancing competitiveness with environmental sustainability (Bhatt et al., 2022a; Rajput and Tatiana, 2023a; Chávez-Hernández et al., 2024b). This entails evaluating nanomaterial manufacturing costs, prioritizing life cycle assessments to minimize environmental impact, and fostering collaboration among stakeholders. Continued research and development are crucial for enhancing efficiency and reducing environmental footprint. Ultimately, nanobioremediation serves as an advanced, economically viable, and sustainable industrial practice, exemplifying its potential as a transformative remediation technology.

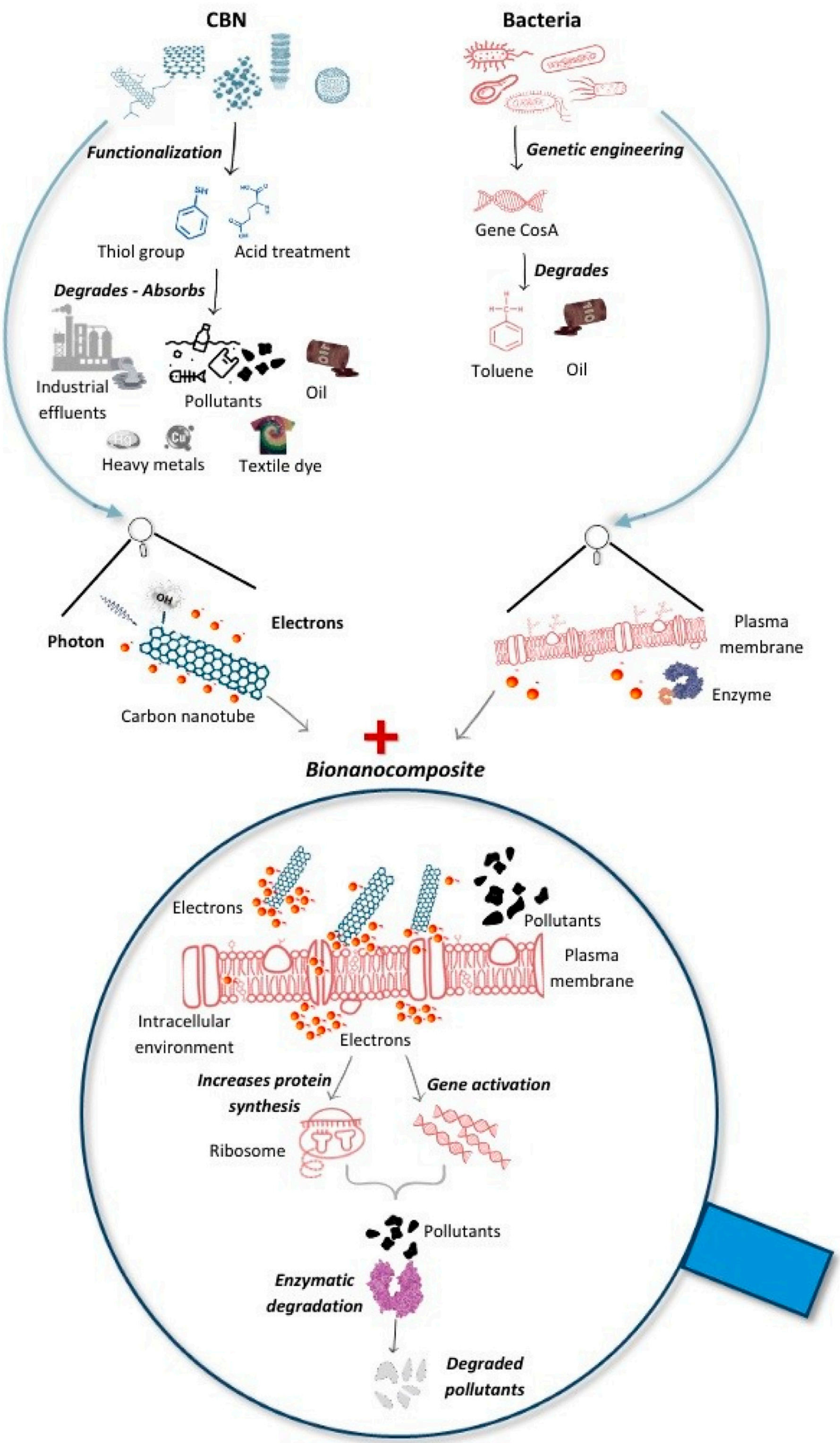

FIGURE 2
Comprehensively depicts the various bacterial species that play a crucial role in bioremediation endeavors. These bacteria play a vital role in bioaccumulation, biodegradation, and biosorption processes, which are essential for environmental purification. The figure illustrates the interplay between bacteria and carbon-based nanomaterials (CBNs) in the treatment of industrial effluents. These CBNs include carbon nanotubes (CNTs), carbon dots (CDs), graphene (G), carbon fibers (CFs), and nanodiamonds (NDs). The focus is on how these nanomaterials enhance the effectiveness of contaminant degradation and detection, highlighting their potential in advanced environmental remediation technologies (Singh and Saxena, 2022a; Mousa, Tulbure, and Fawaeer, 2023; Singh et al., 2023; Abril et al., 2024; Jatoi et al., 2024a; Balakumar et al., 2024; Ningombam et al., 2024b; Singh Simranjeet et al., 2024; Sajjad et al., 2024; Silah et al., 2024; Sun et al., 2024).

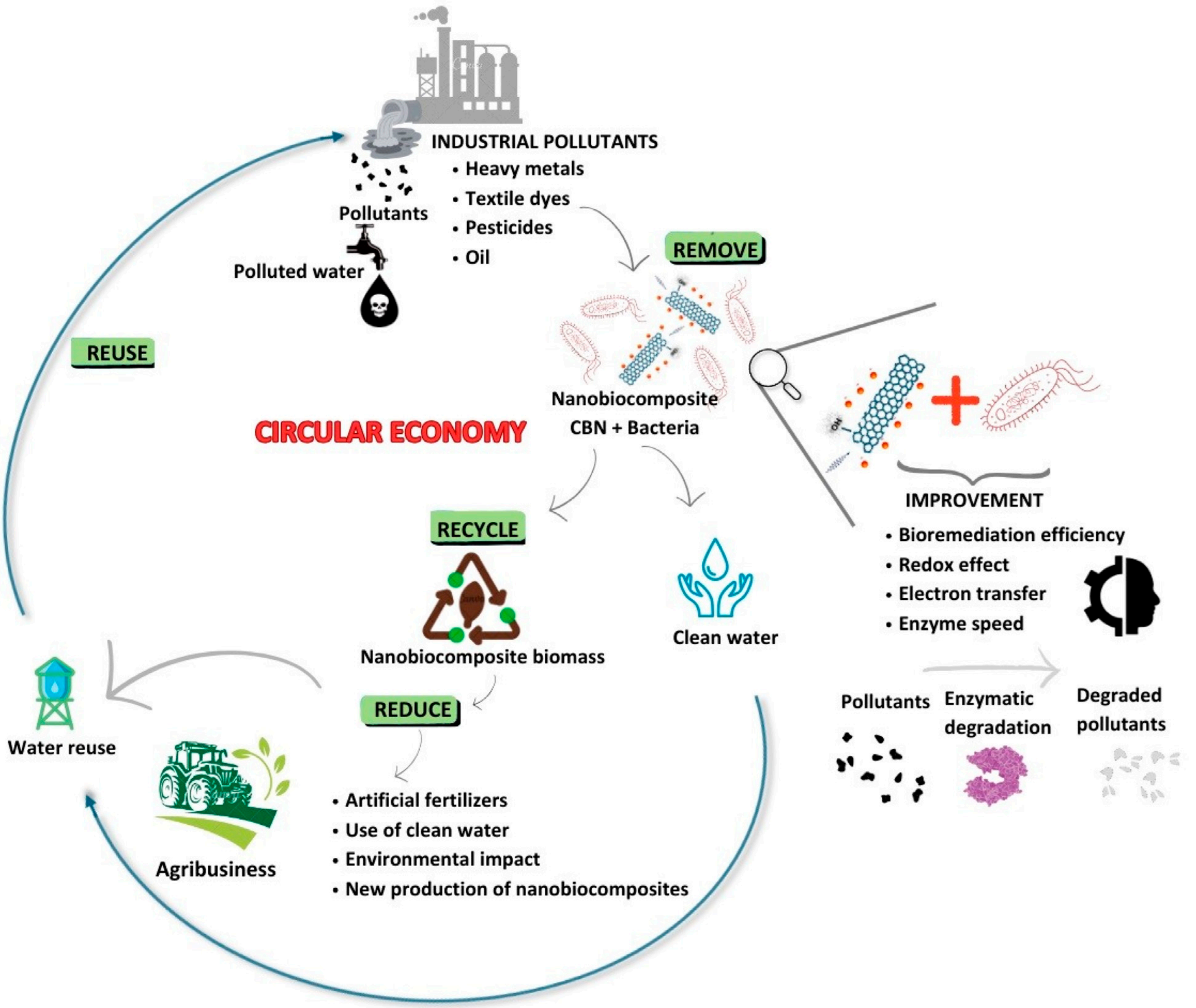

FIGURE 3
Shows a cyclical method for treating industrial wastewater using bacteria and carbon nanomaterials. This approach promotes the circular economy by eliminating pollutants, converting waste into biomass, and minimizing environmental damage (Blažina et al. 2022; Salehi and Wang 2022; Kumar et al. 2023; Zhang et al. 2023; Chen et al., 2024; Ezeorba et al. 2024; Kaur et al. 2024)

4.3 Bottlenecks in nanoremediation for the treatment of industrial wastewater: what are they?

Through the combination of CBNs and bacteria, nanobioremediation has emerged as a highly advanced method for purifying industrial effluents. This innovative approach holds great potential for tackling intricate environmental issues. Nevertheless, the wider implementation of this technology encounters challenges such as scalability, affordability, and integration with infrastructures. These obstacles go beyond technical considerations and involve economic and regulatory aspects. To address these challenges, innovative strategies and significant support from public policy are necessary (Sati et al., 2022; Pratap and Krishnan, 2024a; Roy et al., 2024). Addressing the challenges of scaling up nanobioremediation systems, ensuring consistent performance, optimizing production costs, and minimizing environmental risks linked to nanomaterials present considerable hurdles. A deep understanding of how nanomaterials and microbes interact in the environment is crucial for improving remediation efforts and safeguarding beneficial species from any negative effects (Ningombam et al., 2024b; Chen, Liu, and Liu, 2024; Kaur et al., 2024).

Adhering to regulations set by esteemed authorities such as the U.S. Environmental Protection Agency (EPA) and the European Chemicals Agency (ECHA) is essential. The registration process requires thorough presentations on safety and efficacy (Kumari et al., 2023; Chávez-Hernández et al., 2024a). In addition, it is crucial to ensure that nanoparticles are properly labeled, accounting for all possible risks, following safety regulations, and undergoing thorough assessments of their environmental impact. Efficient management of nanomaterial waste requires careful planning and a strong commitment to ethical and social responsibility (Ayilara and Babalola, 2023; Gulati et al., 2023; Olawore, Ogunmola, and Desai, 2024).

Beside this, successfully implementing and gaining recognition for nanobioremediation requires navigating bureaucratic challenges, adhering to international regulations, and actively involving stakeholders. Incorporating these technologies into a CE presents a chance for creative thinking and collaboration across different fields, promoting environmental Sustainability (Bhatt et al., 2022b; Gong et al., 2023; Dhanapal et al., 2024b). This integration promotes the adoption of sustainable practices, which agree with the principles of resource efficiency and waste reduction. Notable progress and promising potential in nanobioremediation highlight its effectiveness in addressing sustainability and CE issues (Rajput et al., 2022b; Rajput and Tatiana, 2023b; Rather et al., 2023d).

There are various obstacles to the implementation of this technology, including the technical complexities of dealing with contaminants, the economic challenges associated with system costs and benefits, and the varying regulatory restrictions across different countries. However, it is crucial to highlight the significance of collaboration across sectors, the support from policies, financial incentives, and engagement with stakeholders. These factors are essential for addressing the challenges and fully harnessing the potential of CE in sustainable resource management (Pandey et al., 2022; Hidangmayum et al., 2023b; Rather et al., 2023c; Pratap and Krishnan, 2024b). The goal is to achieve both environmental and economic advantages while maintaining strict adherence to environmental regulations. In this context, it is crucial to emphasize the importance of ongoing research and development, as well as the implementation of effective public policies, to harness these technologies for a more sustainable future.

5 Conclusion

This study represents a notable advancement in the field of nanobioremediation, providing valuable insights into the collaborative efforts of bacteria and CBNs, including CNTs and G, for the treatment of industrial effluents. We investigated the molecular mechanisms underlying this collaboration, revealing remarkably effective approaches to combating pollution. We emphasize the importance of the advanced functionalization of nanomaterials, which improves their ability to absorb and break down contaminants. Additionally, we focus on the selection of specialized bacterial strains that are more efficient at eliminating pollutants. This approach not only enhances decontamination efforts but also enhances our understanding of the underlying processes. The combination of bacteria and CBN leads to a fascinating interplay that enhances remediation, as demonstrated by compelling case studies. Although highly effective, several challenges need to be addressed in terms of sustainability, nanomaterial recovery, public acceptance, and regulatory issues concerning the biosafety of these nanocomposite systems. In this study, we highlight the latest progress in this promising area of research addressing industrial pollution and sets the stage for future investigations in nanobioremediation. We also highlight the significance of fostering innovation and continuous advancement to thoroughly unlock the possibilities of this growing field, with a focus on promoting environmental sustainability and safeguarding ecosystems. Collaboration across disciplines is essential for addressing environmental challenges, as it enables the integration of nanotechnology and biotechnology to offer promising solutions for sustainable industry and a cleaner future for generations.

Author contributions

EC: Writing–review and editing, Writing–original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal Analysis, Conceptualization. LS: Writing–original draft, Investigation. EA: Writing–original draft, Investigation. AO: Writing–original draft, Investigation. JJ: Writing–review and editing, Visualization, Validation, Supervision, Conceptualization. JP: Writing–original draft, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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