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ORIGINAL ARTICLE

Assessment of the role of nanotechnology in water sector: an expert opinion

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Abstract

Water scarcity and pollution are significant global challenges impacting human health, the environment, and economic development. Addressing these issues is a priority under the United Nations Sustainable Development Goals. Despite progress, research for sustainable approaches in water resource management continues to evolve. This study investigates the role of nanotechnology in the water sector, focusing on its applications in water purification and addressing challenges in adoption. Expert opinions from 29 participants across diverse regions, including Asia, Europe, North America, and the Middle East, were analysed to provide a global perspective. According to the results of experts, nano catalysts (34.48%) were the most encountered technology, followed by nanofiltration membranes (31.03%), nano-adsorbents (27.59%), and carbon nanotubes (6.9%). While 68.97% of experts are concerned about the potential toxicity of nanomaterials, 20.69% about high operational costs, and 10.34% about higher energy consumption. Over 80% of experts agreed that collaboration among scientists, engineers, policymakers, and industry stakeholders is crucial for achieving sustainable and scalable solutions. The study underscores the need for innovative research to reduce the cost of nanomaterials, improve energy efficiency of processes by developing low-energy nanofiltration membranes, and mitigate toxicity risks through the development of biodegradable or safer-by-design nanoparticles. Furthermore, the findings emphasize the importance of interdisciplinary collaboration and regulatory frameworks to mitigate environmental risks and make nanotechnology more accessible and scalable for industrial and residential applications.

Keywords Nanotechnology · Water purification · Water sector · Expert opinion · Sustainability

Introduction

Nanotechnology is pivotal for water and wastewater treatment, employing nanomaterials to remove pollutants (Singh, 2022; Thamarai et al., 2024). However, inadequate wastewater treatment in developing countries underscores the urgent need for efficient solutions (Onu et al., 2023). Recent advances in nanomaterial manipulation offer novel water treatment approaches, albeit with concerns about environmental and health risks (Iravani, 2021; Saleem & Zaidi, 2020; Vaidh et al., 2022). Nanotechnology is revolutionizing water purification by offering innovative solutions to address various water quality issues. Water scarcity and pollution pose significant global challenges, impacting human health, the environment, and economic development. As populations grow and urbanization and industrialization expand, the demand for clean water increases while water resources dwindle (Filipponi & Sutherland, 2012; Wang et al., 2021; Yang & Khan, 2022). Current applications include the use of nanomaterials such as carbon nanotubes, graphene oxide, and silver nanoparticles in filtration and disinfection processes (Bhardwaj et al., 2021; Naskar et al., 2022; Omran & Baek, 2022; Zahoor et al., 2021). These materials exhibit unique properties like high surface area, antimicrobial

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activity, and selective adsorption, enabling the removal of a wide range of pollutants including heavy metals, pathogens, and organic compounds (Baruah et al., 2016).

Membrane technologies incorporating nanomaterials improve permeability and fouling resistance, while nano catalysts facilitate advanced oxidation processes for degrading persistent organic pollutants. These innovations not only enhance water quality but also offer energy-efficient and cost-effective solutions for addressing global water scarcity and pollution challenges (Palit, 2017; Tawiah et al., 2024; Thanigaivel et al., 2022). While nanotechnology offers promising advancements in water purification, it also faces several challenges and limitations. Nanotechnology plays a crucial role in advancing water purification technologies due to its unique properties and capabilities. Significant advantages include enhanced filtration efficiency, selective removal of contaminants, cost-effectiveness, improved disinfection, reduced chemical usage, and environmental sustainability (Wilson et al., 2021). Nanomaterials, due to their extremely high surface area-to-volume ratio and unique physicochemical properties, significantly enhance the efficiency of filtration processes (Kamath et al., 2022). For instance, nanofiltration membranes can remove particles as small as 1 nm, including viruses, bacteria, and dissolved organic substances that conventional filters cannot effectively eliminate (Gong et al., 2018). The preceding academic literature on nanotechnology for water sector shows that great progress has been achieved in investigating the applications and implications of nanoparticles in various elements of water treatment and management.

Despite progress, there are notable gaps in the current body of research on nanotechnology for water treatment that require attention. While numerous studies have demonstrated the efficacy of nanomaterials in pollutant removal (Anoob et al., 2024; Palani et al., 2021; Roy et al., 2021), there is limited understanding of their long-term environmental impacts. Concerns include the release, accumulation, and transformation of nanoparticles in aquatic ecosystems, which could pose significant ecological and health risks (Makhesana et al., 2024; Rathod et al., 2024). Research is needed to evaluate the behaviour of nanoparticles post-application, including bioaccumulation and toxicity pathways (Yamini et al., 2023; Zhang et al., 2021). The scalability of nanotechnology-based solutions remains a challenge, particularly for resource-constrained regions. High production costs and limited infrastructure for large-scale deployment hinder widespread adoption (Ahmed et al., 2023; Kumar et al., 2023b). Research must focus on developing cost-effective synthesis methods and integrating nanotechnology into existing water treatment systems to improve accessibility and scalability. Current water treatment infrastructure in many regions is not optimized for the adoption of nanotechnology. Studies are required to explore how nanomaterials can be incorporated into conventional systems to enhance compatibility and performance (Mauter et al., 2018; Pérez et al., 2023). This includes assessing the retrofitting potential of existing facilities and identifying barriers to integration. While nanotechnology contributes to reducing chemical use and improving resource efficiency, its energy-intensive processes need optimization. Studies should investigate the integration of renewable energy sources, such as solar or wind power, to improve the sustainability of nanotechnology applications (Pérez et al., 2023; Tawiah et al., 2024). In addition, more research is needed on how nanotechnology might be integrated with current wastewater infrastructure and management technologies to improve their performance and compatibility. Addressing research gaps will be critical for promoting the safe and sustainable use of nanotechnology in water sector (Mauter et al., 2018). Given the inadequacies revealed in present research on nanotechnology for water sector, there is a critical need for additional exploration and inquiry. Understanding the long-term environmental effects, assuring adaptability and cost-effectiveness, and optimizing interaction with existing water management systems are all significant issues that require further investigation (Bouramdane, 2023).

Given these gaps, this study aims to provide a comprehensive evaluation of nanotechnology's role in the water sector by synthesizing expert opinions from diverse geographic and professional backgrounds. Addressing these research gaps will not only broaden our understanding of nanotechnology's function in water sector but will also open the way for the creation of more sustainable, successful, and resilient water treatment and management technologies. As a result, this study aims to contribute to closing these gaps by investigating the role of nanotechnology in water sector, providing significant insights and recommendations for improving the effectiveness and sustainability of water sector thorough the expert opinion.

What we know?

Current applications of nanotechnology in water purification

Nanotechnology is revolutionizing water purification by offering innovative solutions to address various water quality issues. Current applications include the use of nanomaterials such as carbon nanotubes, graphene oxide, and silver nanoparticles in filtration and disinfection processes (Naskar et al., 2022). These materials exhibit unique properties like high surface area, antimicrobial activity, and selective adsorption, enabling the removal of a wide range of pollutants including heavy metals, pathogens, and organic compounds (Baruah et al., 2016). Membrane technologies incorporating nanomaterials improve permeability (Zeng et al., 2022) and fouling resistance (Yadav et al., 2020), while nano catalysts facilitate advanced oxidation processes for degrading persistent organic pollutants. These innovations not only enhance water quality but also offer energy-efficient and cost-effective solutions for addressing global water scarcity and pollution challenges (Palit, 2017).

Nanofiltration membranes: Polyamides, cellulose acetates, polyvinyl alcohol, polysulfones, and metal oxides can all be used to create nanofiltration membranes. The pollutants that are adsorbed onto the membrane may exhibit strong chemical bonds that are irreversible, complete reversible physical attachment, or both (Fane et al., 2011). To eliminate any contamination from the pipes between the water treatment facility and the point of usage, filters with pores measuring 100 nm are employed. Nanofiltration membranes are used to filter out contaminants at the nanoscale, including dissolved salts, organic molecules, and heavy metals. They offer a high rejection rate for multivalent ions while allowing monovalent ions to pass through, making them ideal for water softening and desalination (Geise et al., 2010). The working of nanofiltration membrane is demonstrated in Fig. 1.

Nanocomposite membranes: Innovations in combining graphene oxide and metal–organic frameworks with polymer membranes have improved fouling resistance and enhanced water flux (Zhang et al., 2021).

Photocatalytic applications: Developments in visible-light-responsive photocatalysts, such as titanium dioxide doped with carbon or nitrogen, have significantly increased the degradation efficiency of persistent organic pollutants (Ahmed et al., 2023).

Bio-Inspired nanomaterials: Chitosan-based composites and bio-functionalized nanoparticles have emerged as sustainable, biodegradable alternatives for heavy metal and dye removal in water treatment (Makhesana et al., 2024).

Contribution to sustainable water purification practices

Nanotechnology has significantly contributed to sustainable water purification practices by revolutionizing the efficiency and effectiveness of treatment methods. Through the development of nanoparticle-based materials, such as carbon nanotubes, graphene oxide, and metal oxide nanoparticles, nanotechnology has provided innovative solutions for removing contaminants from water while minimizing energy consumption and environmental impact. Furthermore, nanomaterials can be functionalized to target specific pollutants, providing tailored solutions for diverse water sources and contamination scenarios. Overall, nanotechnology plays a pivotal role in advancing sustainable water purification practices by offering cost-effective, scalable, and environmentally friendly solutions to address global water challenges. Some of the sustainable water purification methods are as follows:

Reverse Osmosis (RO): Energy efficiency is a critical aspect of sustainable water purification practices. Reverse osmosis is a widely used membrane technology for desalination and water purification. RO, which uses a partly permeable membrane under pressure, is extensively employed for advanced drinking water filtration (Zhai et al., 2022). Recent advancements have focused on improving the energy efficiency of RO systems by developing low-energy membranes and optimizing operational parameters. Contaminants are trapped in the concentrate during RO membrane filtering, necessitating treatment prior to disposal. Extracted from plant materials, cellulose can be chemically modified to enhance its adsorption capacity. It is used in filtration membranes and adsorbents for removing organic and inorganic pollutants. The sort of concentrate disposal employed might also be determined by certain water pollutants (Greenlee et al., 2009).

Chitosan: Derived from chitin found in crustacean shells, chitosan is biodegradable and non-toxic. This

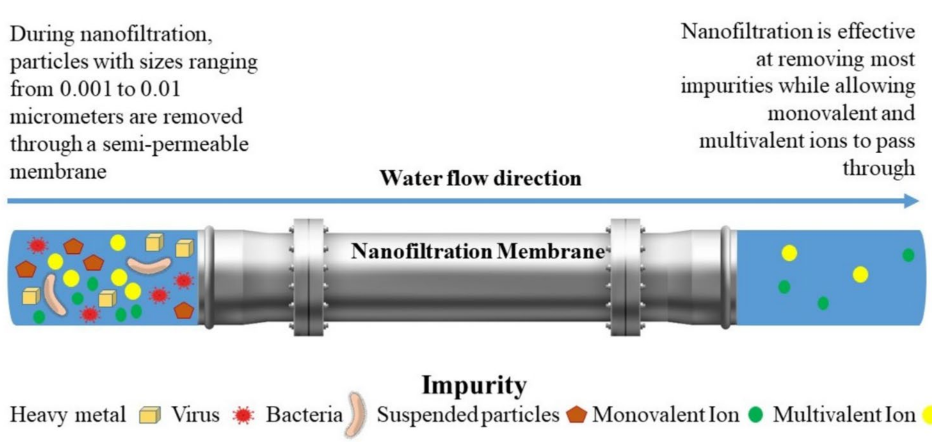


Fig. 1 How nanofiltration works. Contaminated water is forced through a semi-permeable membrane under pressure; only small molecules can go through the membrane while large particles are trapped

natural polymer is a potent biosorbent for colour removal because of several inherent qualities. Chitosan is a nano- and micro-carrier, elicitor, and plant growth regulator with applications in disease management, physiological stress, and growth development. The amino and hydroxyl groups found in chitosan were responsible for eliminating contaminants from wastewater. Furthermore, it drew interest for its unique characteristic traits such as biodegradable qualities, cheap productivity cost, simplicity of availability, and sustainability (Mohan et al., 2023). It is effective in removing heavy metals, dyes, and other contaminants from water due to its high affinity for pollutants. Because the chitosan-based polymers are easily prepared under mild circumstances with relatively inexpensive chemical reagents, their manufacture is economically feasible (Crini & Badot, 2008).

Natural clays: Clay minerals are defined as layers of mineral silicates that are naturally abundant, affordable, non-toxic to the environment, composed of an amorphous phase, and have many sorts of geometry. It is recommended due to its strong adsorption capacity, reactivity, and stability. Clays and clay minerals have previously been used as natural adsorbents to remove Orange G dye, Direct Red 23 dye, phenolic compounds, Cr(III) by Kaolin-biofilm, copper (II), and nickel (II) from water and wastewater(Ashour & Tony, 2020). It has been discovered that clays and modified clays are especially helpful for the adsorption of heavy metals. The ability of clays to scavenge ionic forms of As, Cd, Cr, Co, Cu, Fe, Pb, Mn, Ni, and Zn from aqueous media has drawn attention (Bhattacharyya & Gupta, 2008).

Biochar (BC): Biochar is a carbon-rich solid produced by pyrolyzing biomass at temperatures exceeding 250 °C without oxygen. Currently, the manufacture of BC from biomass is considered a possibility for carbon capture and storage to prevent negative environmental impacts caused by CO_2 accumulation in the atmosphere, which leads to climate change. BC's high carbon content and wide specific surface area have made it a viable contender for a range of environmental applications, including soil amendment. It has been extensively investigated for its ability to extract organic and inorganic environmental contaminants, and it is employed as an adsorbent for the immobilisation of hazardous components like as heavy metals (Kamali et al., 2021). Biochar's high organic C content makes it a promising water conditioner that can enhance the biological and physicochemical characteristics of water. Because of its many uses, biochar has the potential to be a very powerful environmental sorbent for both organic and inorganic pollutants found in soil and water. Due to its large surface area and microporous structure, biochar effectively absorbs organic pollutants from water, trapping them on its surface. It also can adsorb metal ions such as Cu^{2+}, Cd^{2+}, Ni^{2+}, and Zn^{2+} from water (Ahmad et al., 2014). The adsorption of heavy metals by biochar is depicted in Fig. 2.

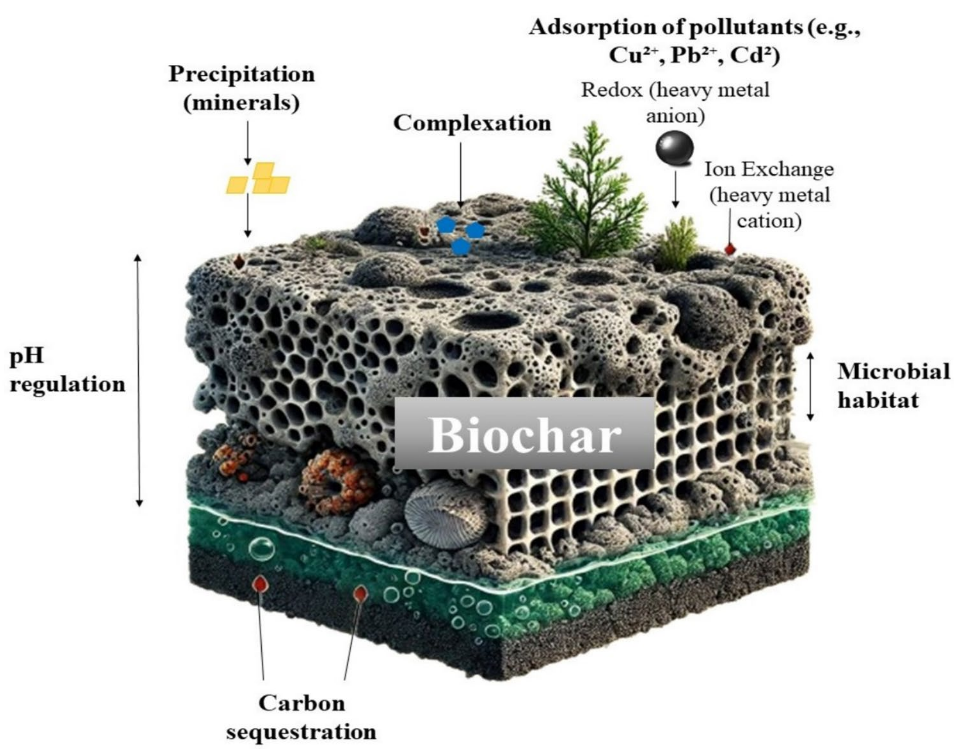


Fig. 2 Functions of biochar in adsorbing pollutants, ion exchange, pH regulation, carbon sequestration and providing microbial habitats

Challenges and limitations of nanotechnology in water purification

While nanotechnology offers promising advancements in water purification, it also faces several challenges and limitations. One of the primary concerns is the potential environmental and health risks associated with the release of nanoparticles into the environment, as their long-term effects are not fully understood. Some of the challenges include:

Environmental concerns: Nanoparticles may persist in the environment for extended periods, leading to long-term ecological impacts. Their accumulation in soil and water bodies can disrupt ecosystems and affect biodiversity. Nanoparticles may bioaccumulate in organisms, especially in the food chain, leading to biomagnification and potential health risks for consumers. Nanoparticles can accumulate in living organisms, leading to long-term exposure risks. This bioaccumulation can affect various biological processes, potentially leading to chronic health issues in humans and wildlife. There is always an inherent risk involved in using agrochemicals, therefore it's necessary to evaluate the advantages and disadvantages of new nano strategies by methodically comparing their safety to that of current ones (Kah et al., 2019; Zheng et al., 2019). Synthesis and degradation of nanomaterials can generate hazardous byproducts that may contaminate the environment if not properly managed. Some nanotechnology-based water treatment methods require high energy inputs for nanoparticle synthesis or operation, contributing to increased carbon emissions and environmental footprint (Wang & Liu, 2021).

Impact of nanomaterials on ecosystems: Nanomaterials used in water purification, such as nanoparticles of silver, titanium dioxide, and carbon nanotubes, can potentially leach into the environment during their production, use, and disposal. These nanoparticles may interact with organisms in aquatic ecosystems, leading to various ecological impacts. The presence of nanomaterials in aquatic environments can disrupt ecosystem functioning by affecting microbial communities, algae, aquatic plants, and higher organisms. Changes in species composition and ecosystem dynamics may occur, leading to cascading effects on ecosystem services. Understanding the transformation pathways and fate of nanomaterials in aquatic environments is crucial for assessing their environmental impacts. Factors such as aggregation, sedimentation, and interactions with natural organic matter can influence the behaviour of nanomaterials in water bodies (Handy et al., 2008b). Nanoparticles in aquatic systems can be formed by several ecological natural or artificial processes, human activity such as mining, and the occurrence of these activities, as well as synthetic nanoparticles that enter aquatic systems by accident or on design (Yamini et al., 2023).

Health risks: Workers handling nanomaterials during the manufacturing, application, or disposal processes are at risk of inhaling nanoparticles, which can penetrate deep into the lungs and enter the bloodstream, potentially causing respiratory and cardiovascular problems (Schulte et al., 2008). Nanoparticles can penetrate the skin, especially if there are cuts or abrasions. Some nanomaterials can penetrate the skin barrier, leading to local and systemic toxic effects. Titanium dioxide nanoparticles, for instance, can cause oxidative stress and inflammation upon dermal exposure. Prolonged skin exposure to certain nanomaterials may lead to dermatitis or other skin conditions (Monteiro-Riviere & Baroli, 2010). If nanomaterials are not completely removed during water purification, they can enter the drinking water supply. Ingesting these particles can cause gastrointestinal and systemic toxicity. For example, silver nanoparticles have been shown to induce cytotoxic effects, including DNA damage and apoptosis, in human cells (McShan et al., 2014).

Evolution of research in nanotechnology for water treatment

Research in nanotechnology for water treatment has grown exponentially over the years, as evidenced by the sharp increase in the number of articles published across different time periods. Between 1980 and 2010, research was in its early stages, with relatively few publications, as scientists focused on exploring the fundamental properties and potential applications of nanomaterials in water purification. From 2010 to 2015, interest in the field began to surge, driven by innovations in nanomaterials such as graphene oxide and carbon nanotubes, which led to a moderate increase in publications. The momentum continued between 2015 and 2020, with a more noticeable rise in research output as focus shifted toward practical applications, scalability, and addressing environmental impacts. Most strikingly, the period from 2020 to 2025 has seen an exponential growth in research activity. The drastic increase of publications is depicted in Table 1. According to data from ScienceDirect, approximately 22,791 articles were published on nanomaterials in wastewater treatment between 2021 and 2025 alone and is illustrated in Appendix 1. This dramatic increase clearly illustrates how research in this area has accelerated significantly, reflecting the rising global demand for

Table 1 Number of publications in nanotechnology in between 1980 and 2025

Year	Number of publications
1980–2010	3,247
2011–2015	6,295
2016–2020	13,203
2021–2025	22,791

sustainable and advanced water treatment technologies powered by nanotechnology. The increase in the publications has been listed in Table 1. The graphical representation of increase in number of publications has been depicted in Fig. 3.

Study's contribution to the literature

While existing studies predominantly focus on the technical capabilities of nanotechnology, this manuscript uniquely incorporates expert opinions to address real-world adoption challenges. This approach provides actionable insights into barriers such as toxicity, cost, and scalability, which are less explored in laboratory-centric research. Furthermore, the study includes diverse geographical perspectives, offering a global view of nanotechnology's applications and challenges, which contrasts with region-specific analyses (Bouramdane, 2023; Pérez et al., 2023). The study also emphasizes interdisciplinary collaboration, echoing calls from recent literature for integrative approaches involving materials scientists, environmental engineers, and policymakers (Kuhn et al., 2022). By synthesizing expert insights, this research advances the understanding of nanotechnology's role in sustainable water purification and sets the stage for future investigations into scalable and eco-friendly solutions.

Materials and methods

For this study, expert opinion has been selected as a method because it allows for the identification of trends and patterns across a broad sample of experts, offering a clear, generalizable understanding of the role of nanotechnology in water sector. Experts, defined as individuals with extensive and relevant knowledge on a topic Krueger et al. (2012) include scientists, and experienced members. By using structured data collection and statistical analysis, the study can quantify expert views and make data-driven conclusions about the benefits, challenges, and prospects of nanotechnology in this field. Targeting experts ensures that the data collected is rich in insight and relevance, as these individuals possess specialized knowledge and experience in nanotechnology and water sector.

Novelty of the methodology

While expert opinion is commonly used in qualitative research, this study adopts a quantitative framework to systematically evaluate and generalize expert insights. This approach bridges the gap between subjective knowledge and empirical analysis, offering a structured pathway for synthesizing diverse expert perspectives (Adams et al., 2023).

The study captures a diverse range of opinions from experts in nanotechnology, environmental engineering, and water management, providing a holistic view of the subject. This interdisciplinary perspective aligns with the call for integrative research approaches in sustainability studies (Kuhn et al., 2022).

The study incorporates a meticulous validation process and stringent inclusion criteria to enhance data reliability and credibility. By targeting only highly qualified experts with direct experience in nanotechnology applications, the study sets a new benchmark for leveraging expert opinion in water research (Pérez et al., 2023).

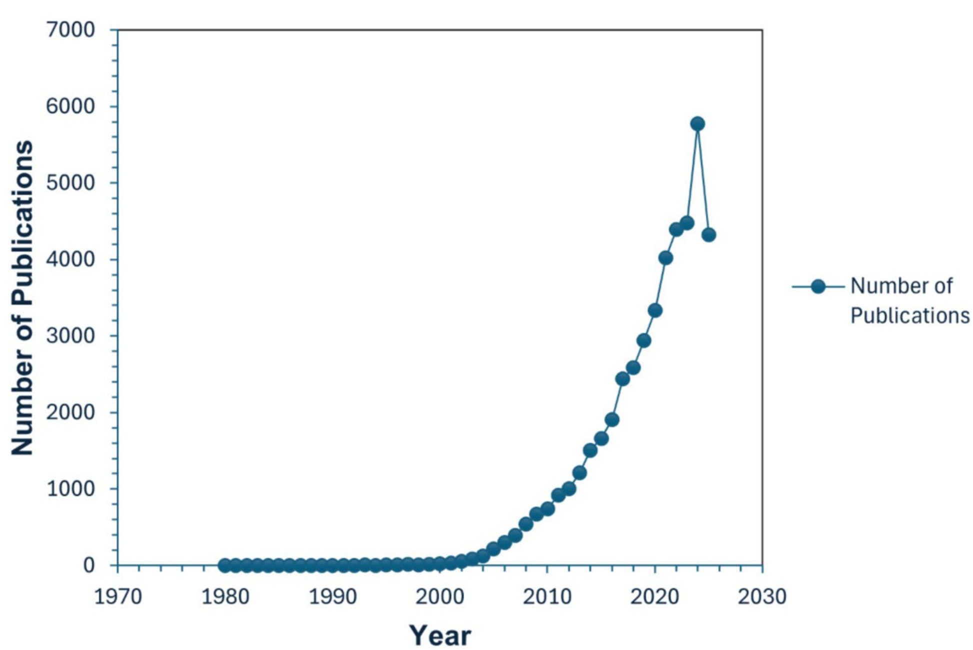


Fig. 3 Number of Publications over Years (1980–2025)

Unlike traditional expert opinion studies that rely on thematic analysis, this research employs advanced statistical tools to extract deeper insights from the data. The combination of descriptive and inferential statistics provides robust findings with greater generalizability, addressing gaps in previous methodologies (Rathod et al., 2024).

Implementation of methodology

The implementation of methodology for this study was systematically structured into several key steps, each contributing to the overall robustness and reliability of the research:

Design

This study used an expert opinion with structured questionnaire as its main research tool. Most of the questions on the questionnaire were closed-ended, designed to quantify expert opinions on various aspects of nanotechnology's role in water sector, making comparison and analysis simple. The design emphasized accuracy, impartiality, and relevance to ensure effective data collection and straightforward comparative analysis. The structured format facilitated precise interpretation of results while minimizing potential biases inherent in open-ended surveys.

Validation of questions

After drafting the questionnaire, the next crucial step in validating the questions was to seek approval from the in-house validators from University of Central Lancashire. This process was involved submitting the draft questionnaire to the team for review and feedback. The team, with their expertise and experience, assessed the questions for clarity, relevance, and alignment with the study's objectives. Feedback from these experts was used to refine questions, ensuring alignment with the study's objectives and clarity for respondents. This process was informed by best practices in questionnaire validation, as outlined by (Taherdoost, 2019), and ensured that the questions captured relevant and meaningful data. By incorporating the supervisor's insights, the final questionnaire was better positioned to yield accurate and meaningful responses from experts.

Sampling

The study targeted a population of experts with significant experience and knowledge in nanotechnology, water sector, environmental engineering, and related disciplines. A purposive sampling method is employed to select participants who are well-qualified to provide informed insights on the subject matter. Approximately 150 experts in nanotechnology and water management all over the world were targeted to ensure a diverse and comprehensive representation of opinions. However, only 29 responses were included in the final analysis due to strict inclusion criteria. These criteria ensured the credibility and relevance of the dataset by prioritizing participants. Experts were required to have advanced degrees in nanotechnology, environmental engineering, or related fields. Only individuals with significant experience (minimum of 5 years) in research, application, or policy development within the water and nanotechnology sectors were considered. Additionally, experts were prioritized if they had authored at least 10 Scopus-indexed publications, demonstrating a proven research track record in the field. The study included experts who demonstrated notable contributions through peer-reviewed publications, or professional leadership roles in the field. While the small sample size is a limitation, the focus on highly qualified participants ensures the quality and relevance of the data. This purposive sampling approach aligns with strategies recommended by Etikan et al. (2016) for collecting specialized, high-quality input in exploratory studies.

Data collection

The online platform Google Forms was the primary tool for data collection from the experts in the field of nanotechnology and water management. This approach was selected because of its accessibility, ease of use, and efficient data management features. The platform allowed seamless dissemination of the questionnaire to experts located in diverse geographic regions. A user-friendly interface ensured that participants could complete the questionnaire with minimal technical barriers, increasing response rates. Google Forms facilitated real-time data organization and export into structured formats, streamlining the analysis process. Additionally, responses were restricted to participants with verified professional email addresses, ensuring that only qualified experts participated. This strategy aligns with digital survey methodologies described by Hao et al. (2017), which emphasize accessibility and data integrity in global research contexts. The nature of the study and the profile of the respondents, who were familiar with online academic tools, ensured the appropriateness of this platform for the research objectives. The link to the Google Forms questionnaire was sent to over 150 experts across the globe. To increase response rates, an email reminder was sent out after the first two weeks. The data gathered through Google Forms was methodically exported into a spreadsheet for initial examination. This method made it possible to compile data in an exact and orderly manner, which made the analysis process easier.

Data analysis

Data analysis for this study was conducted using SPSS version 29, a sophisticated statistical software program widely recognized for its ability to manage and analyse complex data sets. The software's capabilities were leveraged to perform a comprehensive analysis of the quantitative data collected from the experts in nanotechnology and water sector. The novelty of the approach lies in integrating descriptive statistics to summarize trends and patterns, alongside inferential techniques, including correlation and regression analysis, to explore relationships between variables. This combination provided a comprehensive understanding of nanotechnology's role in water management, as supported by statistical methods outlined by Aldrich (2018). Visual representations, such as graphs and charts, were generated to effectively communicate findings. This combination of descriptive and inferential statistics provided a solid foundation for interpreting the data and drawing meaningful conclusions from the expert responses.

Data validity and reliability

In quantitative investigations, ensuring the validity and reliability of the study data is essential. To maintain these criteria, the following actions were done in this study:

Expertise: To ensure that the respondents had the necessary knowledge and experience, they were chosen based on their professional roles in water and nanotechnology initiatives. Their comments gained legitimacy and credibility from this knowledge.

Questionnaire design: To guarantee clarity and prevent bias, a meticulous design was made using Google Forms. The platform's adaptability made it possible to create questions that were clear-cut, closely tied to the study's goals, and worded to reduce the likelihood of misunderstanding.

Piloting: The questionnaire's initial phase was designed to assess the questions' comprehensibility and clarity. The questionnaire was improved by the pilot's feedback, which also improved the responses' validity and reliability.

Diverse participant selection: To minimise bias and improve the generalizability of the results, the study selected participants from a variety of categories within the water sector. This allowed for the capture of a wide range of opinions.

Data recording and analysis: For analysis, Google Forms structured and arranged data were exported into SPSS version 29. A thorough and accurate analysis of the data was made possible using SPSS, and its sophisticated facilities guaranteed the validity of the statistical analysis carried out. A flowchart describing the methodology has been displayed in Fig. 4.

Fig. 4 A flowchart illustrating the methodology for the study on the role of nanotechnology in the water sector

Ethical considerations

Ethical clearance to conduct this study was obtained from the University of Central Lancashire, United Kingdom on April 10, 2024. Ethical considerations are paramount in this study. An informed consent statement is included at the beginning of the questionnaire, explaining the purpose of the study, the voluntary nature of participation, and the confidentiality of responses. All data was anonymized and securely stored to protect participant privacy, adhering to international research guidelines (Bryman, 2016).

Participants were assured with the same. The study adheres to ethical guidelines for research involving human subjects, ensuring that the rights and well-being of the participants are safeguarded.

Results and discussion

Results

The sampling period for the study was conducted between May 2024 and August 2024. 150 subject experts were initially contacted, and invitations were sent out to them. However, several experts did not fill out the forms on time, even with extended deadlines. Two reminders were sent, and we finally received 35 completed forms. However, 6 forms were not valid due to incomplete information. As a result, we considered the opinions of 29 experts for the assessment. The data includes information on the respondents' professional role, countries, areas of expertise, years of experience in academia, and the number of publications they have authored. Understanding the demographic background of the respondents is crucial for contextualizing their opinions and assessing the diversity of perspectives in the study. Totally 10 subject questions were sent out to the experts.

Most respondents were Assistant Professors (41.38%), followed by Professors (31.03%), and Associate Professors (13.79%). The remaining 13.8% were distributed among Senior Professor, Reader in Nanomaterials, Technical Director and Assessment Director. The respondents were predominantly from India (82.76%) followed by UK (10.34%). The remaining 6.9% were distributed among US and UAE. Figure 5 shows the number of respondents from each country, with India leading. While the overrepresentation of Indian experts introduces a potential bias, their dominance aligns with the country's significant academic focus and advancements in nanotechnology and water management. The chart emphasises the geographical diversity of the participants. Importantly, efforts were made to contact professors from Chinese institutions; however, despite multiple follow-up attempts, we did not receive responses from these experts.

The respondents' expertise was varied, with the largest group specializing in Nanotechnology (44.83%). 20.69% contributed by Water Treatment and Materials Science each, and Nanotechnology with Water Treatment (13.79%). Years of experience in academia of the 29 experts took part have minimum of 4 to the maximum of 46. The number of publications varied widely, with some respondents having fewer than 10, some exceeding 200, and few having more than 500.

Experts were identified and contacted based on clear inclusion criteria designed to capture a high level of specialization and contribution to the fields of nanotechnology and water management. Specifically, individuals with a Scopus-indexed publication record of more than 15 papers were prioritized, ensuring that participants had a proven research track record. The survey was limited to academicians; however, most respondents had established collaborations with industry stakeholders. These partnerships often involved consulting, joint research projects, and technology transfer initiatives. This ensured that their opinions reflected both academic insights and industry requirements, bridging the gap between theoretical knowledge and practical applications.

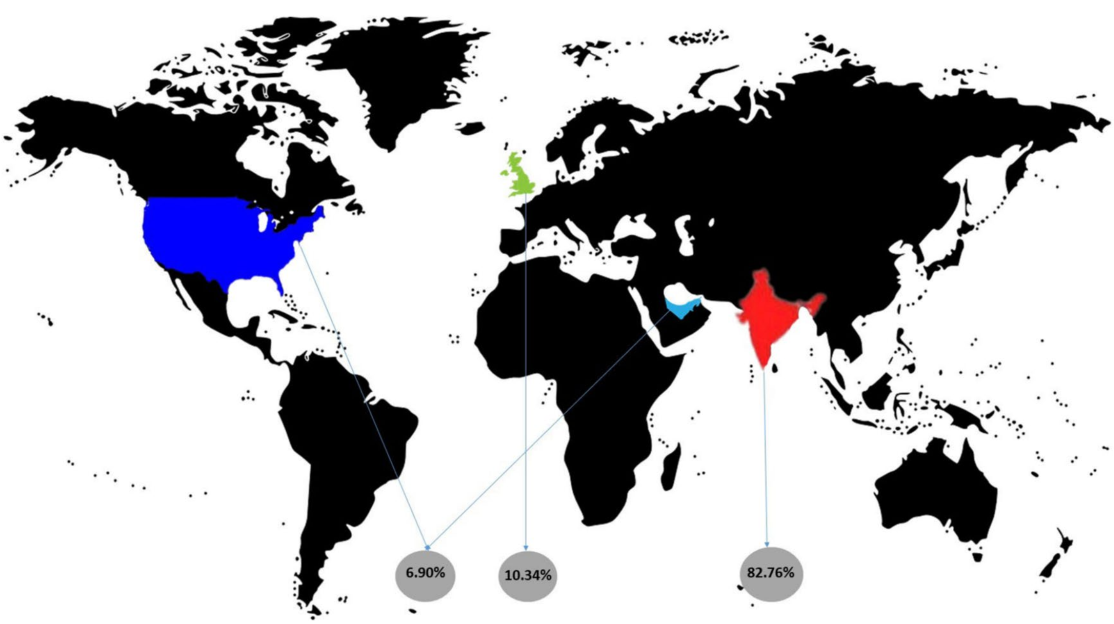


Fig. 5 Respondents per country with India leading at 82.76%, followed by UK at 10.34% and US and UAE at 6.90%

While the study provides valuable insights, it acknowledges the need for broader inclusion of scientists working directly in industrial settings and end-users, such as water treatment plant operators and municipal stakeholders. Future research should aim to incorporate these groups to present a more comprehensive understanding of the adoption and impact of nanotechnology in water management.

Responses from experts to the questions under different themes

a. Nanotechnologies encountered in water purification sectors

According to experts, nano catalysts (34.48%) were the most encountered technology, followed by nanofiltration membranes (31.03%), nano-adsorbents (27.59%), and carbon nanotubes (6.9%). Figure 6a and Fig. 7a displays the frequency of each nanotechnology encountered, with Nano catalysts clearly being the most prevalent.The prevalence of nano catalysts can be attributed to their versatility and efficiency in facilitating advanced oxidation processes, which degrade persistent organic pollutants effectively (Zhao et al., 2023). Unlike carbon nanotubes, which are often cost-prohibitive and limited by production scalability, nano catalysts are more adaptable to varied water treatment systems and exhibit higher cost-efficiency, making them a preferred choice in industrial applications (Palit, 2017).

b. Primary advantage of using nanotechnology in water purification:

Higher efficiency in contaminant removal was cited as the primary advantage by 58.62% of respondents, indicating that the ability to purify water more effectively is a significant benefit of using nanotechnology. It is followed by the ability to remove a broader range of contaminants (20.69%), cost-effectiveness (10.34%), scalability of technology (6.90%) and lower energy consumption (15%). Figure 6b and Fig. 7b highlights these findings. The ability to effectively remove complex pollutants, including pathogens and heavy metals, positions nanotechnology as superior to traditional water purification methods (Tawiah et al., 2024). However, balancing these advantages with cost and scalability remains a challenge, especially in resource-constrained settings.

c. Most significant challenge in implementing nanotechnology

Health and safety concerns (27.59%) were the most significant challenges identified, followed by high initial costs (24.14%), regulatory and policy issues (17.24%), technical complexity (17.24%), and environmental impact concerns (13.79%). Figure 6c and Fig. 7c displays these challenges. The concerns about health risks underscore the potential for nanoparticles, such as silver and titanium dioxide, to bioaccumulate in ecosystems and cause toxicity to aquatic life (Zhang et al., 2021). To mitigate these risks, safer synthesis methods, encapsulation technologies, and stricter regulatory standards should be prioritized (Pérez et al., 2023).

d. Nanomaterial known for high reactivity and efficiency in degrading pollutants

Titanium dioxide was recognized by 37.93% of respondents for its high reactivity, followed by silver nanoparticles (27.59%), carbon nanotubes (24.14%) and other including graphene and activated carbon (10.34%). This is depicted in Fig. 6d and Fig. 7d. Titanium dioxide's wide use stems from its ability to generate reactive oxygen species under UV light, making it effective in breaking down organic contaminants (Makhesana et al., 2024). However, advancements in visible-light-activated variants are essential for increasing its practical applicability (Rathod et al., 2024).

e. Major barrier to widespread adoption of nanotechnology

Cost was the most cited barrier (51.72%), followed by a lack of expertise (20.69%) and inefficiency (17.24%). Figure 6e and Fig. 7e highlight these barriers. The trade-offs between cost and efficiency pose a significant challenge. For instance, while nanotechnology often delivers superior purification, the high cost of materials like carbon nanotubes and silver nanoparticles limits widespread adoption (Ahmed et al., 2023). Research into cost-effective alternatives, such as bio-based nanomaterials, and economies of scale in production can help mitigate this barrier.

f. Primary environmental concern associated with nanomaterials

68.97% of respondents are concerned about the potential toxicity of nanomaterials, 20.69% about high operational costs, and 10.34% about higher energy consumption. Figure 6f and Fig. 7f emphasize these concerns. Toxicity concerns primarily arise from the release of nanoparticles into the environment, where they may interact with microorganisms, accumulate in the food chain, or persist as pollutants (Handy et al., 2008a). Mitigation strategies include developing biodegradable or environmentally inert nanoparticles, enhancing recovery methods post-treatment, and conducting lifecycle analyses to assess long-term impacts (Zheng et al., 2019).

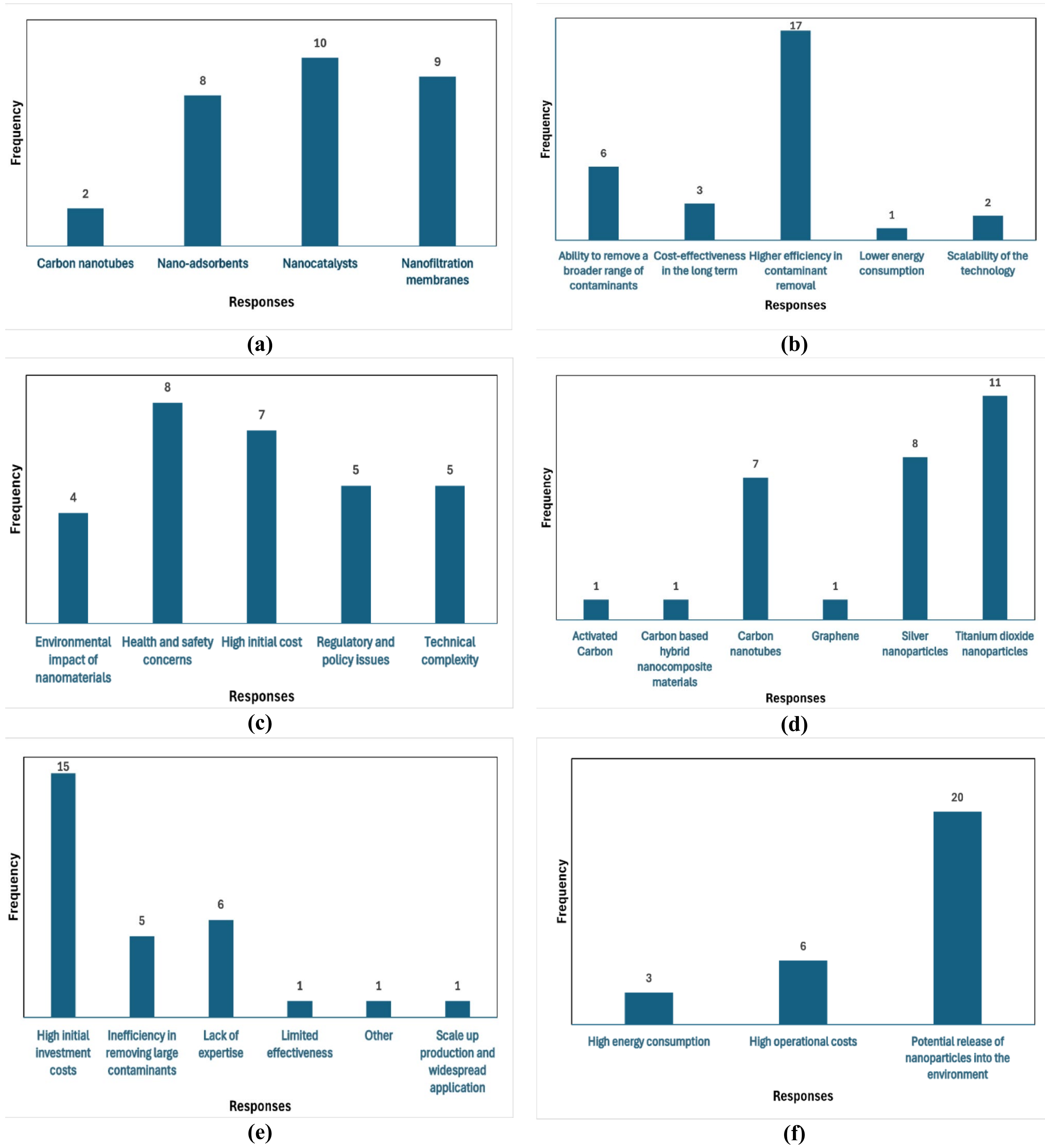


Fig. 6 Bar Diagram depicting, **a** Nanotechnologies that have been used, **b** Main Benefit, **c** Major Challenge, **d** Extremely reactive yet Efficient Nanomaterial, **e** Adoption Limitations, **f** Ecological Problems

g. Effectiveness of current nanotechnologies compared to traditional methods

55.17% of respondents found nanotechnologies to be more effective than traditional methods, while 24.14% found them much more effective, 13.79% believed they were equally effective, and 6.9% believed they were less effective. A lower frequency of responses indicate that a small number of respondents find traditional methods equally or more effective. Figure 7g depicts these perceptions. The increased effectiveness is primarily attributed to the ability of nanomaterials to target and remove contaminants that traditional

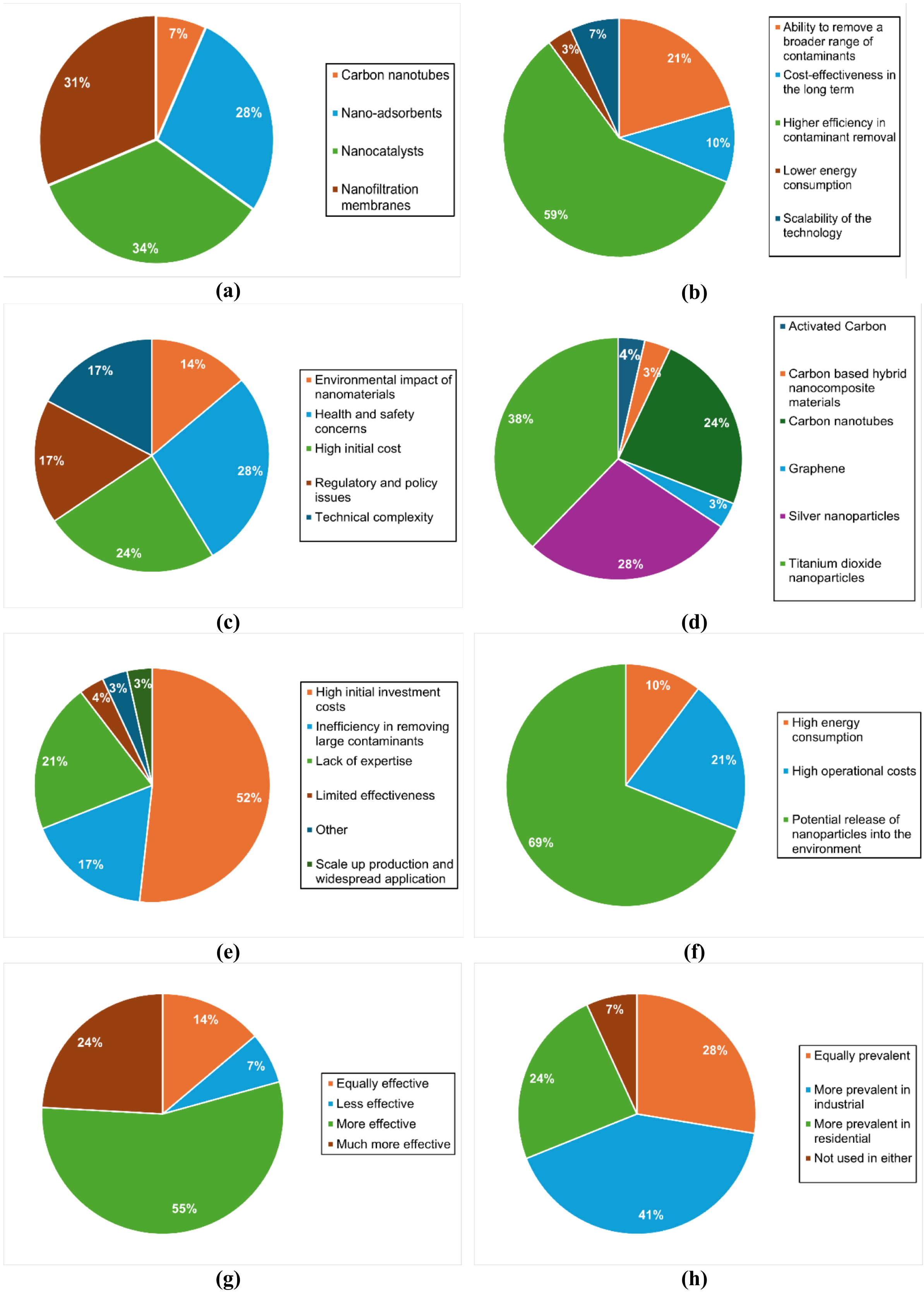
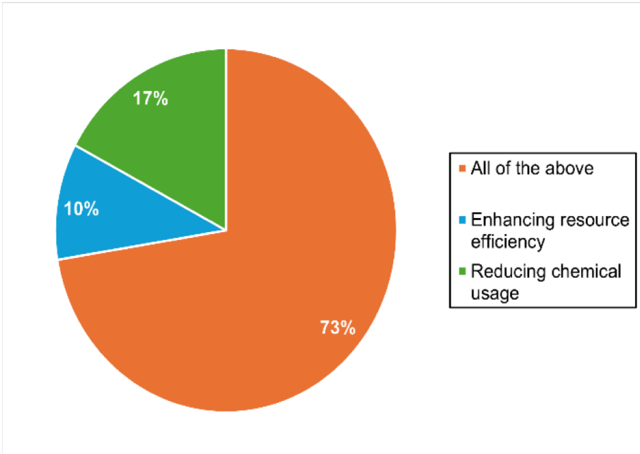
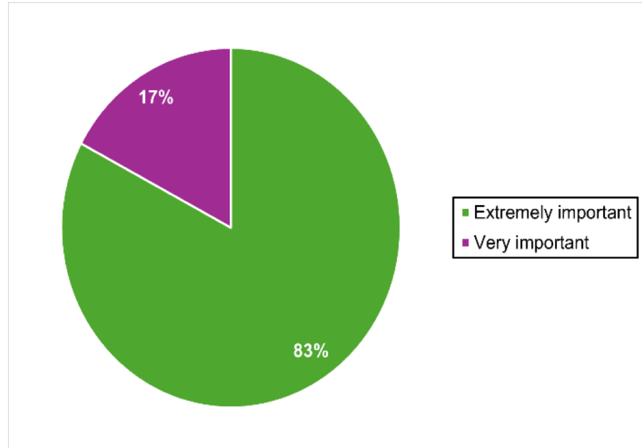


Fig. 7 Pie chart with percentage distributed representing, **a** Encountered nanotechnologies, **b** Significant Advantage, **c** Main Challenge, **d** Efficient Nanomaterial with high reactivity, **e** Adoption Barriers, **f** Environmental Problems, **g** Capability of Present Nanotechnologies, **h** Prevalent Uses, **i** Benefit in Sustainability, **j** Collaboration Significance



(i)



(j)

Fig. 7 (continued)

methods cannot address, such as pharmaceuticals and pesticides (Bouramdane, 2023).

h. Prevalence of nanotechnology in industrial vs. residential water treatment

41.38% of respondents say the use of nanotechnology is predominantly in industrial applications, while 24.14% believe in residential applications. 27.59% think it is equally prevalent. It reflects that nanotechnology is currently most utilized in industries, its use in residential applications is still emerging, likely due to cost or regulatory factors. Figure 7h illustrates these findings. The higher prevalence in industry is driven by cost and scalability factors, as well as the demand for advanced treatment systems in manufacturing and energy sectors (Pérez et al., 2023).

i. Contribution of nanotechnology to sustainability

72.41% of respondents believe that nanotechnology significantly contributes to sustainability through reducing chemical usage, enhancing resource efficiency and lowering energy consumption it reflects the potential of these technologies to address global environmental challenges. This shows a strong belief in the positive impact of nanotechnology on sustainability, indicating that respondents generally agree that nanotechnology enhances sustainability in water purification sector. Figure 7i indicates the sustainability contribution. These technologies align with global efforts to address water scarcity while minimizing environmental impacts (Tawiah et al., 2024).

j. Importance of interdisciplinary collaboration

A significant 82.76% of respondents agree that interdisciplinary collaboration is crucial for advancing nanotechnology in water purification, highlighting the need for cooperation among different fields to realize the full potential of these technologies. It emphasises the strong belief of the experts on the significance of interdisciplinary collaboration, indicating that there will be more collaborated projects between various discipline soon for water purification. Figure 7j displays the importance of collaboration. Collaborative efforts between scientists, engineers, policymakers, and industry stakeholders are essential to develop scalable and effective solutions (Kuhn et al., 2022).

Discussion

Barriers to widespread adoption

The correlation analysis revealed a significant link between the number of nanotechnologies encountered and the perceived barriers to their adoption. Singh & Gurjar (2022) found that as industries and researchers explore more diverse nanotechnologies, they face growing challenges in scaling up these solutions, particularly due to technical complexity and regulatory approval hurdles. Like current findings, Singh & Gurjar (2022) noted that more advanced nanotechnologies require stricter regulatory frameworks, which can slow down their adoption.

Rathod et al. (2024) also pointed to the complexity and high initial investment costs as ongoing barriers to integrating nanotechnology into mainstream water treatment sector. These complexities mirror the experience of the experts, especially in industrial versus residential applications, where nanotechnology adoption is seen as more prevalent in the former due to easier scalability and economic feasibility.

Sustainability and interdisciplinary collaboration

This study found that 72.4% of experts believed that nanotechnology significantly contributes to sustainability by reducing chemical usage and enhancing resource efficiency. Pérez et al. (2023) emphasized nanotechnology's potential to reduce the environmental footprint of water purification by minimizing the use of harsh chemicals and lowering energy consumption. They also noted that nanomaterials could be combined with renewable energy sources like solar power, further boosting sustainability, a recommendation that aligns with the views of the experts.

Kuhn et al. (2022) stressed the need for interdisciplinary collaboration, much like the 82.8% of experts who emphasized its importance in advancing nanotechnology in water management. Collaborative efforts between materials scientists, environmental engineers, and policymakers are critical for overcoming challenges such as technical complexity and regulatory approval, ensuring nanotechnology solutions are both scalable and safe.

Correlation between efficiency and barriers

Current findings showed a positive correlation between the perceived benefits in efficiency and barriers to adoption Kumar et al(2023b) found that while nanotechnology offers high performance in contaminant removal, these gains often come with higher operational and maintenance costs, which can be a significant barrier to adoption. This mirrors the study's conclusion as the perceived efficiency of nanotechnology increases, so do the complexities and costs associate with its implementation.

Similarly Chakrabarty & Jasuja (2022), reported that industries are more likely to adopt nanotechnology for water treatment when the long-term cost savings outweigh the initial capital investment. This reflects the finding in this study where cost was cited as a major barrier to the broader application of nanotechnology in water sector.

Implications of nanoparticle toxicity

The study highlighted significant concerns regarding the environmental and health risks associated with nanoparticles, with 68.97% of experts identifying toxicity as the primary environmental issue. The release of nanoparticles into aquatic ecosystems raises risks of bioaccumulation and biomagnification, potentially disrupting microbial communities and entering the food chain (Zhang et al., 2021). Rathod et al. (2024) emphasized the need for research into nanoparticle degradation pathways and safer disposal methods.

Mitigation strategies: Developing biodegradable or environmentally inert nanoparticles to reduce ecological risks (Makhesana et al., 2024), using coatings or polymers to stabilize nanoparticles and prevent leaching during use (Ahmed et al., 2023), and conducting comprehensive evaluations of nanoparticle behaviour across production, application, and disposal phases (Zheng et al., 2019).

Key advantages

Higher efficiency in contaminant removal: A significant 58.6% of experts in the study cited higher efficiency in removing contaminants as the primary advantage of nanotechnology in water purification. This is supported by numerous recent studies, including Kumar et al. (2023a) and Liu et al. (2022), which found that nanomaterials, such as nanofiltration membranes and nano-adsorbents, offer superior performance in removing a wide range of contaminants, including heavy metals, pathogens, and organic compounds.

Broader range of pollutant removal: Another advantage identified by 20.7% of the experts was the ability of nanotechnology to remove a wider range of pollutants compared to traditional methods. Recent studies, such as Kumar. et al. (2023b), highlighted nanomaterials' effectiveness in addressing microplastics, pharmaceuticals, and other emerging pollutants.

Contribution to sustainability: 72.4% of experts in the study agreed that nanotechnology contributes significantly to sustainability, primarily through reducing chemical usage, lowering energy consumption, and enhancing resource efficiency. Recent research, such as Pérez et al. (2023), highlights nanotechnology's potential to create eco-friendly water purification systems that reduce the environmental footprint by minimizing reliance on chemicals and promoting energy-efficient processes.

Key challenges

High initial costs: The high initial investment cost was cited by 24.1% of experts as one of the biggest challenges. This concern is echoed in several recent studies, including Ahmed et al., (2023) and Singh & Gurjar, (2022), which found that the cost of producing and implementing nanomaterials remains a barrier to their widespread adoption, particularly in residential or small-scale water treatment sector. High operational costs further exacerbate the challenge, making it difficult for many regions, especially developing countries, to implement nanotechnology solutions.

The expense of manufacturing advanced nanomaterials, such as carbon nanotubes, remains a key limitation (Ahmed et al., 2023). Scaling these materials for widespread use requires innovations in production techniques to reduce costs, particularly for residential applications.

Trade-offs between cost and efficiency: Nanotechnology delivers exceptional contaminant removal but often at a high financial cost. For instance, silver nanoparticles provide strong antimicrobial properties but are expensive to produce and dispose of due to toxicity concerns (Kumar et al., 2023b). While nanofiltration membranes are effective, their operational costs, such as maintenance and energy usage, limit their accessibility in resource-constrained settings (Chakrabarty & Jasuja, 2022). Addressing these trade-offs requires developing cost-effective alternatives, such as bio-based nanomaterials, enhancing manufacturing scalability to achieve economies of scale, and incentivizing adoption through subsidies or government-supported programs.

Health and safety concerns: 27.6% of experts indicated that health and safety risks related to nanotechnology are a major concern. This aligns with the findings of Rathod et al. (2024), who warned about the potential risks of nanoparticles entering water systems, posing health hazards to humans and ecosystems. The potential release of nanoparticles into water systems raises concerns about bioaccumulation and long-term toxicity (Zhang et al., 2021). The long-term impacts of nanoparticle release and bioaccumulation are still under-researched, adding to regulatory concerns.

Mitigation strategies include encapsulation of nanoparticles to prevent their release into the environment, developing biodegradable or environmentally inert nanomaterials (Rathod et al., 2024) and implementing robust recovery systems post-treatment to capture nanoparticles before they enter natural ecosystems. These measures can help address health and safety risks while fostering regulatory compliance.

Regulatory and policy issues: 17.2% of experts in the current study mentioned regulatory challenges as a key obstacle to the adoption of nanotechnology. Recent research by Chakrabarty & Jasuja (2022) pointed out that the lack of clear, harmonized regulatory frameworks complicates the approval process for nanotechnology-based water treatment systems, delaying their widespread application. Kanoun et al., (2021) noted that harmonized international guidelines are essential for accelerating nanotechnology adoption. Ensuring compliance with safety standards and navigating the regulatory landscape remains a major challenge for scaling these technologies.

Technical complexity and scalability: Another 17.2% of experts pointed to technical complexity as a barrier. As recent studies by Rathod et al. (2024) and Singh & Gurjar (2022) noted, advanced nanomaterials, while highly effective, are often difficult to scale due to technical hurdles. Manufacturing processes are intricate, and the integration of nanotechnology with existing water treatment systems requires specialized expertise, which can limit adoption in smaller or rural communities. To overcome these issues, investments in training and the development of modular systems that simplify integration are essential.

Overview of results

The perception of barriers is linked to the prevalence of nanotechnology, possibly due to differences in application environments (industrial vs. residential), which could affect scalability and adoption. These correlations offer informative patterns that show how attitudes and views regarding the role of nanotechnology in water sector are influenced by professional responsibilities and experience. A key outcome of the expert opinion study is the significant consensus around the effectiveness of nanotechnology in water purification. More than 55% of respondents reported that nanotechnologies were more effective than traditional methods, and 24% found them to be much more effective. This aligns with the notion that advancements in nanomaterials like nanofiltration membranes, nano-catalysts, and nano-adsorbents are driving improvements in water treatment processes. The demographic breakdown of respondents indicated a strong representation from academia, with most participants having extensive experience in nanotechnology and water treatment. This background diversity underscores the credibility of the findings, as experts with varied experience levels provided a broad perspective on nanotechnology's applications and challenges.

Correlation analysis

The quantitative analysis in this study provided critical insights into the perceptions of experts regarding the effectiveness and challenges of nanotechnology in water sector. Descriptive statistics, such as means and standard deviations, helped identify central tendencies and the spread of expert opinions. For example, most respondents believed that nanotechnology was more effective than traditional water treatment methods, with over 55% stating it was "more effective" and 24% indicating it was "much more effective." This finding is consistent with existing studies by Wang et al. (2019) and Nasrollahzadeh et al. (2021), which demonstrated the enhanced efficiency of nanofiltration membranes and nano-adsorbents in removing a broader range of contaminants compared to conventional methods.

However, the study also revealed significant challenges, particularly in relation to cost and health concerns. The most significant challenge identified was health and safety risks (27.6%), followed closely by high initial costs (24.1%). These findings align with prior research, such as Rathod et al. (2024), which highlighted the high costs and potential environmental risks as key barriers to adopting nanotechnology in water sector. In both studies, the high capital investment required for deploying nanotechnology solutions was a consistent theme, underscoring the need for more cost-effective and scalable technologies. The correlation analysis further deepened the understanding of these challenges. A notable correlation emerged between the perception of greater efficiency and the identification of cost as a major barrier. This suggests that while experts recognize the benefits of nanotechnology, they also associate higher efficiency with increased costs, reflecting the technological complexity of nanomaterial-based solutions. This is comparable to findings by Mauter et al. (2018), who argued that the advanced materials required for nanotechnology often drive-up costs, limiting their widespread adoption, particularly in resource-constrained areas. Interestingly, the study also found a significant correlation between the number of nanotechnologies encountered and the perceived barriers to their adoption. Experts who had more exposure to different nanotechnologies tended to report more barriers, particularly regarding costs and regulatory challenges. This aligns with the work of Kanoun et al. (2021), who noted that while the diversity of nanotechnological applications is growing, so too are the complexities associated with their deployment, especially in terms of regulatory approval and public acceptance. The output of the correlation is depicted in Appendix: 2, 3.

In conclusion, the quantitative analysis and correlations in this study provide a comprehensive view of the dual-edged nature of nanotechnology in water sector: while it offers significant efficiency gains, these benefits are often tempered by substantial costs and technical barriers. Future research and technological advancements must focus on overcoming these hurdles, particularly through cost-reduction strategies and enhanced regulatory frameworks.

Comparative analysis with existing literature on nanotechnology in water treatment

This section critically compares the results of the current expert opinion study with recent findings reported in peer-reviewed literature and is depicted in Table 2. By aligning expert insights with empirical research trends, the analysis aims to evaluate the consistency of observed perceptions with established scientific knowledge. Such a comparison enhances the reliability of expert-based assessments and contextualizes the study's conclusions within the broader academic discourse on nanotechnology applications in water treatment. Through this comparative lens, the section highlights both corroborative and divergent themes, offering a nuanced understanding of the progress, challenges, and future directions in the field.

This study highlights the promising role of nanotechnology in addressing global water challenges, particularly in improving purification efficiency, sustainability, and adaptability across various treatment contexts. Expert insights reveal a strong consensus on the advantages of nanotechnologies—especially nano catalysts—in enhancing contaminant removal while also acknowledging critical concerns such as toxicity, high costs, and regulatory complexities. The findings underscore the importance of interdisciplinary collaboration to bridge gaps between scientific innovation, policy development, and practical application.

Recommendations

Reducing costs and enhancing scalability: The high cost of nanotechnology remains a major barrier to its widespread adoption, particularly for residential water treatment. Future steps include developing cost-effective synthesis methods, such as green nanotechnology approaches that use plant-based precursors or biopolymers, exploring economies of scale in manufacturing processes to reduce per-unit costs of advanced nanomaterials like carbon nanotubes and graphene, implementing financial models like public–private partnerships (PPPs) to share investment risks and facilitate large-scale deployments in industrial and municipal water systems, and designing modular, scalable technologies that can be adapted for both small-scale residential and large-scale industrial applications.

Investigating environmental and health risks: As identified by experts, the environmental and health risks associated with nanomaterials are a significant concern. Actionable research priorities include conducting longitudinal studies to examine the fate and behaviour of nanoparticles in aquatic ecosystems, including their bioaccumulation potential, developing biodegradable nanomaterials to minimize risks associated with nanoparticle release, enhancing nanoparticle recovery technologies post-water treatment to reduce their release into the environment. These studies will inform regulatory bodies to develop comprehensive safety guidelines for the use of nanotechnology in water management.

Strengthening regulatory frameworks: The study identified regulatory uncertainty as a key challenge in implementing nanotechnology-based water solutions. Recommendations include collaborating with policymakers to create internationally harmonized regulations for the safe use of nanomaterials in water management, and establishing guidelines for risk assessment, informed by lifecycle analyses. These frameworks should address issues such as nanoparticle release, safe disposal, and environmental monitoring to ensure that nanotechnology is applied in a way that minimizes risks while maximizing benefits.

Encouraging interdisciplinary collaboration: Advancing nanotechnology in water management requires collaboration across various fields, including materials science, environmental engineering, and public health. Future research

Table 2 Comparative Analysis of Findings with Recent Literature

Key focus area	Recent literature	Findings from the recent literature	Findings from expert opinion study
Nanotechnologies Encountered in Water Purification Sectors	Application of nanocatalysts in advanced oxidation processes for wastewater purification: Challenges and future prospects (Masood et al., 2022)	Nanoparticles serve as highly efficient catalysts in wastewater treatment. Advanced oxidation processes utilizing nanocatalysis should be integrated with conventional treatment methods to effectively eliminate a wide range of biologically resistant contaminants from wastewater	Nano catalysts emerged as the most encountered nanotechnology among experts (34.48%), primarily due to their proven effectiveness in facilitating advanced oxidation processes, adaptability across various water treatment systems
Primary Advantage of Using Nanotechnology in Water Purification	Role of nanomaterials in the treatment of wastewater: A review (Yaqoob et al., 2020)	Because of their special qualities and quick reaction rates, nanomaterials are very effective at eliminating a variety of pollutants from contaminated water	Higher efficiency in contaminant removal stands out as the primary advantage of nanotechnology in water purification, as highlighted by 58.62% of respondents
Primary Environmental Concern Associated with Nanomaterials	Engineered nanomaterials in the environment: Are they safe? (Zhao et al., 2021)	In wastewater, nanomaterials exhibit greater toxicity compared to natural surface water, potentially impacting the performance of wastewater treatment plants	The toxicity of nanomaterials is the primary environmental concern identified by experts (68.97%), largely due to the potential release of nanoparticles
Contribution of Nanotechnology to Sustainability	Clean water through nanotechnology: needs, gaps, and fulfilment (Nagar & Pradeep, 2020)	Nanotechnology has made substantial contributions in providing contaminant-free water and can help realize sustainability in clean water	Nanotechnology is widely perceived to contribute significantly to sustainability, with 72.41% of respondents affirming its role in reducing chemical usage, improving resource efficiency, and lowering energy consumption
Importance of Interdisciplinary Collaboration	Advancement of membrane separation technology for organic pollutant removal (Kafle et al., 2024)	Membrane technologies are promising for removing diverse organic pollutants from wastewater, and interdisciplinary collaboration is vital for advancing water purification innovation	Interdisciplinary collaboration is considered essential for advancing nanotechnology in water purification, as affirmed by 82.76% of respondents, emphasizing the need for integrated efforts

initiatives should prioritize interdisciplinary projects that bring together experts from different sectors to develop holistic solutions. Such collaborations can accelerate innovation and ensure that technological advancements align with societal and environmental needs.

Further actionable steps include funding interdisciplinary research initiatives to connect materials scientists, environmental engineers, and policymakers and creating knowledge-sharing platforms to foster collaboration between academic and industry stakeholders.

Expanding research on sustainability: Sustainability remains a key advantage of nanotechnology in water purification, with its ability to reduce chemical usage and energy consumption. Future research should further investigate how nanotechnology can contribute to sustainable water management practices. Studies should explore ways to integrate renewable energy sources with nanotechnology-based water treatment systems and assess their long-term impact on resource conservation and environmental protection.

Future research

Nanotechnology offers transformative potential for addressing water scarcity and pollution challenges by providing efficient and innovative solutions for water purification. However, to fully realize this potential, the barriers of cost, scalability, health risks, and regulatory uncertainty must be addressed. Through focused research efforts, interdisciplinary collaboration, and the development of clear regulatory frameworks, nanotechnology can play a central role in ensuring sustainable and resilient water management systems for the future.

Future research directions include exploring green manufacturing methods to lower the cost of nanomaterials and improve scalability, investigating advanced nanoparticle recovery systems to mitigate environmental risks, collaborating with policymakers to develop streamlined regulatory frameworks for the safe adoption of nanotechnology, and expanding studies on the integration of nanotechnology with renewable energy systems for sustainable water management.

Additionally, future studies could incorporate bibliometric mapping of global nanotechnology research using keyword analyses to highlight emerging trends and regional contributions, particularly addressing underrepresented regions such as China. Expanding the expert survey to include a wider range of stakeholders, including industrial practitioners, municipal water managers, and policymakers, is also recommended to capture diverse, real-world perspectives and facilitate broader adoption of nanotechnology innovations in water sector applications.

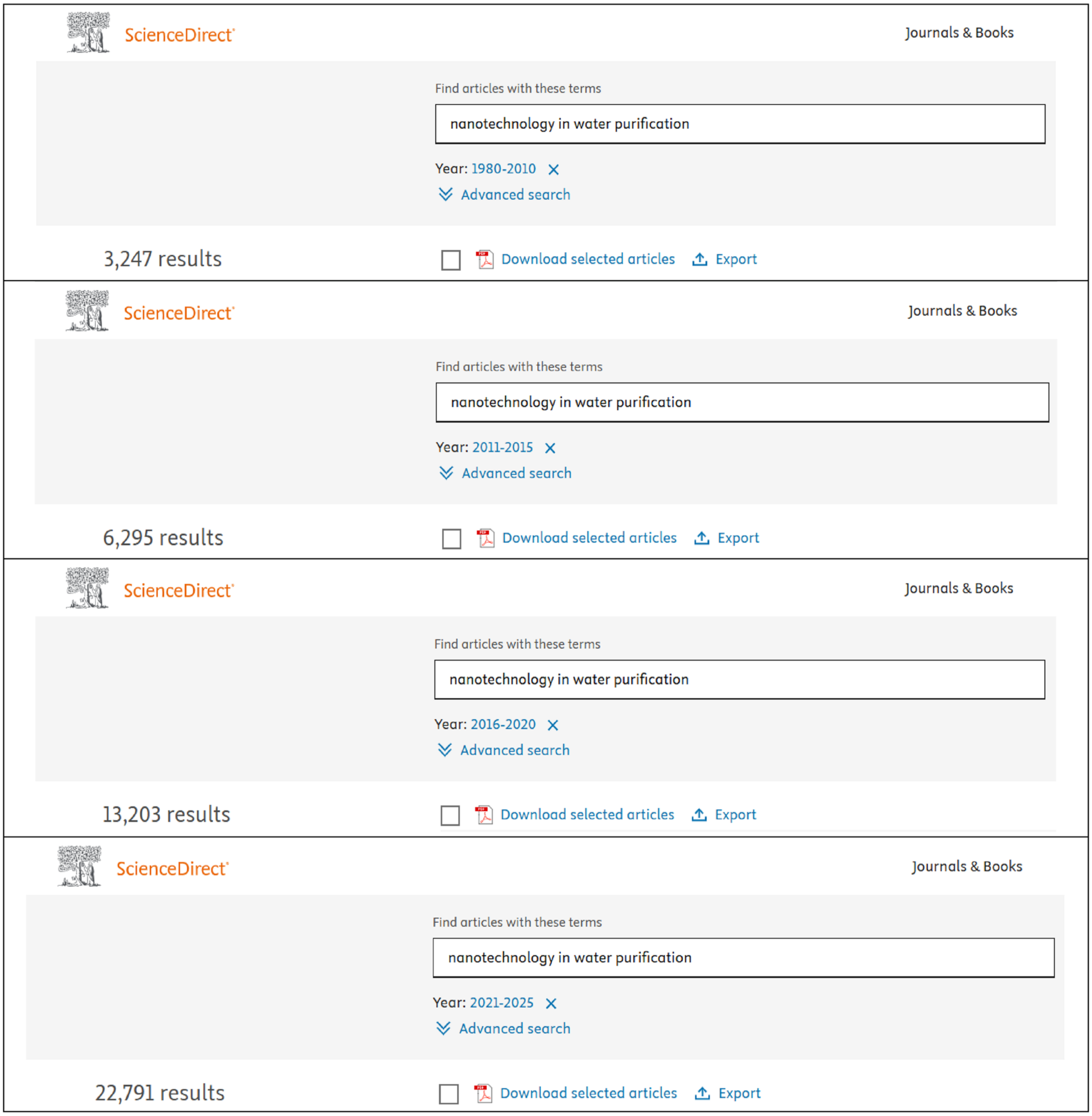
Conclusion

The current study examined the role of nanotechnology in water sector, specifically, its application in addressing challenges such as water scarcity and pollution. Through the expert opinion, it became clear that nanotechnology offers significant potential in water purification, particularly in its ability to remove contaminants more efficiently than traditional methods. Nanofiltration membranes, nanocatalysts, and nano-adsorbents emerged as the most frequently encountered technologies, demonstrating their effectiveness in water purification. However, despite the recognized benefits of nanotechnology, several barriers such as including high initial costs, health and safety concerns, and regulatory challenges hinder its widespread adoption. These barriers limit the broader application of nanotechnology, particularly in residential water treatment, where cost-effectiveness and scalability are key concerns. Experts also emphasized the need for clear regulatory frameworks to ensure the safe implementation of nanomaterials in water management without causing unintended environmental or health risks. Interdisciplinary collaboration was another key insight, with more than 80% of experts stressing its importance. Bringing together scientists, engineers, policymakers, and industry stakeholders is essential for developing holistic solutions that align with societal and environmental needs. Clear regulatory frameworks are also crucial for ensuring the safe implementation of nanomaterials, addressing nanoparticle toxicity concerns, and streamlining approval processes. While the study collected detailed data on experts' years of experience and number of scientific publications, it did not capture information on patents or direct industrial project involvement. Future research should include such metrics to provide a more comprehensive assessment of expert experience, innovation contributions, and real-world application potential.

In conclusion, nanotechnology holds immense promise for transforming water management systems, offering sustainable and scalable solutions to global water challenges. By addressing barriers such as cost, health risks, and regulatory hurdles, and fostering interdisciplinary collaboration, nanotechnology can play a central role in ensuring resilient and sustainable water management systems for the future.

Appendix 1

Evolution of research



Appendix 2

Correlation analysis output

Correlations

		Years of Experience in Academia	Number of Publications	Nanotechnologies Encountered in Water Purification Projects	Benefit Most Related to Enhanced Efficiency	Major Barrier to Widespread Adoption of Nanotechnology	Prevalence of Nanotechnology in Industrial vs. Residential Water Treatment
Years of Experience in Academia	Pearson Correlation	1	.148	-.085	-.073	-.094	-.226
	Sig. (2-tailed)		.445	.663	.707	.627	.238
	N	29	29	29	29	29	29
Number of Publications	Pearson Correlation	.148	1	-.034	.114	.198	.126
	Sig. (2-tailed)	.445		.862	.557	.303	.516
	N	29	29	29	29	29	29
Nanotechnologies Encountered in Water Purification Projects	Pearson Correlation	-.085	-.034	1	-.120	-.380*	-.227
	Sig. (2-tailed)	.663	.862		.534	.042	.237
	N	29	29	29	29	29	29
Benefit Most Related to Enhanced Efficiency	Pearson Correlation	-.073	.114	-.120	1	.431*	.129
	Sig. (2-tailed)	.707	.557	.534		.019	.503
	N	29	29	29	29	29	29
Major Barrier to Widespread Adoption of Nanotechnology	Pearson Correlation	-.094	.198	-.380*	.431*	1	.384*
	Sig. (2-tailed)	.627	.303	.042	.019		.039
	N	29	29	29	29	29	29
Prevalence of Nanotechnology in Industrial vs. Residential Water Treatment	Pearson Correlation	-.226	.126	-.227	.129	.384*	1
	Sig. (2-tailed)	.238	.516	.237	.503	.039	
	N	29	29	29	29	29	29

*. Correlation is significant at the 0.05 level (2-tailed).

Appendix 3

Correlation analysis

Notes		
Output Created		29-AUG-2024 00:40:27
Comments		
Input	Data	C:\Users\jemis\OneDrive—UCLan\BN 4609 Masters Dissertation\Role of Nanotechnology in Water Project Management An Expert Opinion.sav
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	Split File	<none>
	N of Rows in Working Data File	29

Notes		
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing
	Cases Used	Statistics for each pair of variables are based on all the cases with valid data for that pair
Syntax		CORRELATIONS /VARIABLES = Experience Publications NanoTechnologiesEncountered BenefitRelatedToEfficiency BarrierToNanoAdoption PrevalenceIndustrialVsResidential /PRINT = TWOTAIL NOSIG FULL /MISSING = PAIRWISE
Resources	Processor Time	00:00:00.00
	Elapsed Time	00:00:00.00

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Data availability Data will be available upon request from first author.

Declarations

Conflict of interest This manuscript has not been previously published and is not under consideration, in whole or in part, by any other peer-reviewed publication. To the best of our knowledge, there are no conflicts of interest or other competing interests to declare.

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