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Nanomaterials For Environmental Remediation: Advances In Water, Air, And Soil Pollution Mitigation

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Purpose: This study, by investigating high-end uses of nanomaterials for environmental reclamation and assessment, is trying to clarify the real application potential related to mitigation policy targeting pollution. Further, it discusses the advantages of using different nanomaterials such as nZVI and TiO_2 due to their unique physicochemical properties in contaminant removal while also considering some important obstacles like toxicity, scalability and environmental repercussions.

Research Methodology: The study is administered based on the quantitative research design and utilizes a structured questionnaire that was distributed to 180 respondents with different demographic characteristics as well as work experience. A variety of statistical methods that included descriptive statistics, Spearman's rank-order correlation, chi-square tests ANOVA and regression were employed for the analysis of data on perceptions understanding and effectiveness in using nanomaterials to remediate environmental pollution.

Results: The study indicates moderate familiarity (Mean = 2.89) and understanding of nanomaterials (Mean = 3.17). Familiarity was moderately positively associated with understanding (Spearman's $\rho = 0.59$, $p < 0.01$), providing further evidence that exposure and education could be important for growing comprehension of doubly unlabeled LD-AA products or subtypes in Canada the perceived effectiveness of nanomaterials as an environmental mitigation tool had weak correlation with being familiar (ranging from 0.11 to 0.15) for pollutants in water, air or soil separately. Results of chi-square analysis ($\chi^2 = 7.85$, $p = 0.24$) showed that scores given by the students as to effectiveness did not differ significantly between genders. ANOVA test result ($F = 0.71$, $p = 0.586$) shows that there is no significant educational background difference in familiarity. There was also no significant difference in familiarity between sexes ($t = 1.66$, $p = 0.098$). The logistic regression analysis showed that experience in environmental remediation (coefficient 0.33; $p \leq 0.05$) and nanomaterial familiarity (Experience with the use of these materials: coefficient = 0.55, P value <0.05) were significantly associated with understanding the applications of nanotechnology-relevant for CERDNA sites.

Practical Implications: Our results highlight the importance of targeted educational programs and regulatory frameworks to better connect scientific research with public perceptions, thereby enabling safe and sustainable use of nanomaterials. To unlock the full potential of nanomaterials in environmental remediation, policymakers and industry leaders must confront issues related to scalability and environmentally friendly processes.

Originality/value: This paper offers a comprehensive statistical analysis of public perception and performance of nanomaterials in cleaning the environment. It illustrates the nature of nanotechnology as a double-edged sword with no exceptions and demonstrates that an interdisciplinary approach is not only necessary in the nano-field but essential to encourage innovation for optimum utilization of such nanomaterials into constructive environmental solutions, having global concern.

Conclusion: nanomaterials are beneficial for environmental pollution but key challenges which need to be considered are the safety and toxicity of the materials used besides their scale-up during mass production prohibiting use in vast areas. The study emphases that further research, teaching and collaboration between disciplines are needed to extract the full value of nanomaterials. Nanomaterials could be the difference makers, however, addressing just a few issues is only experimental and needs extensive research to materialize.

KEYWORDS: Nanomaterials; Environmental Remediation; Pollution Mitigation; Statistical Analysis; Water Treatment; Air Pollution Control; Soil Remediation; Toxicity; Scalability; Sustainable Development.

INTRODUCTION:

Because of their unusual properties and possible uses, nanomaterials are the subject of substantial study by multiple disciplines and have been widely researched for environmental remediation applications. The escalation of environmental pollution with the emergence of more developed societies and the growing world population has exacerbated this situation. Water, air and soil contaminants including heavy metals, organic pollutants as well as emerging contaminants e.g., pharmaceuticals, microplastics and persistent organic pollutants are major threats to ecosystems' human health. Some remediation technologies, although effective in their own constrained right might be ineffective in reality for a large-scale depollution so the potential of pollutant interactions to lead to an undesirable system response was never empirically tested on larger acreage and cost-effectiveness (Sathish et al., 2024).

Differently, the great surface-area reactivity and tunable nano properties allow nanomaterials a new method for environmental remediation which is promoted to lead to more efficient selective cleaning as well as cost-effective pollution-degradation solutions. Due to their unique property of handling pollutants at the molecular scale, which enables processes such as adsorption, degradation and catalysis, nanomaterials were established long ago for environmental remediation. For example, the efficacy of nanomaterials such as nanoscale zero-valent iron (nZVI), titanium dioxide (TiO2) and carbon-based nanomaterial has been extensively investigated in water decontamination which is regarded crucial due to being an exponentially rising challenge because of industrial wastes, agricultural discharges and absence recycling management (D. Kumar et al., 2024).

nZVI has received a great deal of attention due to its degradation potential with chlorinated organic compounds and immobilization ability for heavy metals in contaminated groundwater, and it has become one of the best tools applicable for remediation works. It has a higher reactivity due to its large surface area, and electron-donating ability, making it effective for the degradation of recalcitrant contaminants such as trichloroethylene (TCE) into less harmful compounds an attractive solution for solvent-contaminated sites under existing regulations. Thus, titanium dioxide (TiO_2) nanoparticles are the most famous for photocatalytic degradation of organic pollutants in water (R. S. Rajput).

In the presence of ultraviolet (UV) light, TiO2 produces oxidizing reactive oxygen species (ROS), such as hydroxyl radicals that can further decompose organic contaminants into carbon dioxide and water or other non-toxic compounds in a process known as decontamination by Photocatalysis. The research on TiO2 nanoparticles has found its industrial application efficiently in the wastewater treatment processes, as it showed promising degradation of non-biodegradable recalcitrant pollutants like dyes pesticides pharmaceutical residues etc. that are not effectively treated by conventional methods. Because it can be tailored to perform in a diverse set of environmental conditions, armed with relatively low cost and stability properties, TiO_2 is ideal for use as an ever-growing nanomaterial that holds high potential for collective applications worldwide (Zhang et al., 2024).

Compared with these inorganic nanomaterials, carbon-based nanomaterials e.g., carbon nanotube and graphene have also been investigated for the decontamination of water as well as air treatment. Because of their huge surface area, excellent mechanical properties and electrical conductivity, CNTs show high adsorption capacity towards a variety of pollutants such as heavy metals, organic compounds or pathogens so they have been widely applied in water treatment solutions. In addition, graphene and its derivatives like Graphene oxide (GO) are used for the adsorption of pollutants as well as their catalytic activity. Degrade the nameIO3 in water and air. Graphene's two-dimensional structure, high surface area and potential for functionalization enable it to effectively filter a range of airborne pollutants including VOCs & particulate matter from the air surrounding us. This is very important since these properties can be key to the solution of two difficult pollution problems such as water and air cleaning (Prasad & Gupta, 2024).

Nanotechnology has been used in soil reclamation to overcome heavy metals, organic pollutants and pesticide problems that are found common around agricultural and industry regions. Nanoscale iron oxide particles, in particular magnetite (Fe3O4) and maghemite (γ-Fe2O3), have been demonstrated to be effective adsorbents for immobilization of heavy metals into soil matrix which may reduce their bioavailability or toxicity. This magnetic behaviour of the nanoparticles also enables complete removal from the soil after remediation and subsequent recycling with diminished environmental concerns compared to conventional adsorbent systems. Additionally, the use of nanomaterials such as nano-hydroxyapatite to immobilize lead (Pb) and other heavy metals in soils also is a good way to reduce metal bioavailability by plants thereby preventing them from accumulation moving higher upon the food chain along soil–the plant continuum. In addition to causing traditional remediation techniques, nanomaterials can facilitate new approaches for soil decontamination in sites that had been previously considered untreatable (Dhanapal et al., 2024).

Although nanomaterials have made considerable progress over the years and exhibit great potential in environmental remediation, they also face challenges. Most importantly, there was great concern in terms of the possible toxicity to human health and the environmental burden that may arise from nanomaterials. Many of the same properties that make nanomaterials ideally suited to pollutant removal also cause them to interact inadvertently with biological systems and thus introduce safety concerns. Research works have shown that nanomaterials like Ag nanoparticles (AgNPs) and carbon nanotubes can cause cytotoxicity, and genotoxicity as well as juxtapose to oxidative stress in living organisms due to key factors such as particle size shape surface chemistry determine the fate of man-made nanoparticle induced cellular or subcellular toxicity. These results reinforce the importance of complete risk assessment and formulation development guidelines to responsibly use nanomaterials in environmental applications (Naz et al.).

The environmental fate and transport of nanomaterials are still not completely known. When released into the environment either deliberately via processes like remediation or just unintentionally in the manufacture and disposal of products, nanomaterials can undergo transformations that change their properties and behaviour. The question of whether the transformation of nanomaterials by bio substances can change the mobility, availability and toxicity of the materials is crucial for their risk assessment in ecosystems and human health. Consequently, in the spirit of this review, it will be necessary to start finding the correct research lines that analyze long-term environmental risks and develop strategies for combating possible risks with these nanomaterials. Additionally, it is essential to establish regulatory frameworks and standards to produce nanomaterials, as well as their use and disposal so that environmental remediation can be sustainably achieved (Biswas & Rai, 2024).

A further limitation of the introduction of nanomaterials into environmental remediation is their expensive and hard-to-scale. While some nanomaterials are effective in pollutant removal at the laboratory scale, their practical implementation still represents a significant challenge. Manufacturing of nanomaterials at an industrial scale can be very expensive, and economic feasibility has often been a matter of concern for these technologies, especially in resource-limited regions. Additionally, the environmental impacts of nanomaterial synthesis including energy use, waste formation and hazardous chemical usage should be well analyzed to ensure that their production does not carry an added burden towards a clean environment. To overcome these challenges, the strategies should include landmark innovations in nanomaterial discovery and manufacturing with an emphasis on sources for large-scale synthesis of high-quality nanoparticles which also be ecofriendly materials (Singh, Singh, Singh, & Chauhan).

However, despite the difficulties arising from them, nanomaterial-based solutions for environmental remediation have a bright future. With the development in nanotechnology, next-generation or designer nanoparticles with desired properties and functionalities for different environmental applications are being accomplished. For instance, the development of hybrid nanomaterials integrating metal oxides and carbon-based nanomaterials has demonstrated the potential to enhance removal efficiency in remediation processes. Moreover, smart integration of nanomaterials in environmental monitoring to provide real-time response towards the levels and degradation status could allow for more robust or refined pollution control strategies e.g., adaptive. Together, these innovations and a better understanding of how nanomaterials behave in the environment are poised to spur further development into environmental applications for nanotechnology (Jain).

Overall, nanomaterials provide us with a powerful weapon in our arsenal for addressing the difficult challenge of environmental pollution from water to air and soil. Their novelty and specific properties lead to more efficient, targeted, and environmentally friendly in terms of MNA methods compared with the conventional type. But making the most of nanomaterials will mean addressing safety, scale-up and environmental issues. Further studies, developments and interdisciplinary approaches will be necessary to maximize the benefits of nanomaterials while guaranteeing their safe recovery environmental remediation (Ahmaruzzaman, Yadav, & Devi, 2024).

LITERATURE REVIEW:

Putting together a variety of works, discoveries and hypotheses in an extensive study on the nanomaterials for environmental remediation help to determine favoured progressions of sci-tech innovation by using these tiny particles' action toward removing contaminants from water or air or soil. Herein, not only the main advances in this field are reviewed but also their different applications that have been proposed to tackle diverse environmental contexts using nanomaterials will be brought up along with discussing some of these materials' potential risks and challenges going forward or the next steps for defining a roadmap into where they could go considering most promising contexts of actions. Nanomaterials, with their high surface area per unit mass or volume and unique reactivity aimed at the molecular level interaction of pollutants, have been attracting much attention recently in environmental remediation. An enormous amount of research has been done on the possibilities and challenges associated with nanomaterial-based pollution control, and remedies in the last two decades mostly for water (major focus), air and soil. As stated by Zhang, nanotechnology behaviour in environmental applications is encouraging due to the improved physicochemical properties of these materials that allow them higher surface area, sorption potential, and catalytic activity needed for removing contaminants. Amongst these materials, zeolites and activated carbon-based adsorbents are widely used in the treatment technologies for the removal of a variety of pollutants including heavy metals, organic compounds and emerging contaminants such as pharmaceuticals and personal care products (PCPs) (Tonelli & Tonelli, 2025).

Nanomaterials have been developed with water pollutants as the target because they are a major source of hazards to human health and ecosystems. Nanomaterials, including nanoscale zero-valent iron (nZVI), titanium dioxide (TiO_2) and carbonaceous nanoparticles such as carbon nanotubes have been particularly investigated for the removal of heavy metals, organic pollutants and microbial contaminants in water treatment applications. One example is nZVI, which has been extensively exploited to remediate chlorinated organic compounds and heavy metal contaminants in groundwater because of its excellent reactivity as well as the larger surface area. This material is among the best nanomaterials with demonstrated effectiveness in decontaminating pollutants such as trichloroethylene (TCE) and hexavalent chromium (Cr (VI)) under laboratory and field studies for water remediation (Kho, Hua, & Ahmad, 2024).

Similarly, titanium dioxide nanoparticles have been paid further attention due to their photocatalytic characteristics and their role in the degradation of organic pollutants under UV light. These nanoparticles can degrade a broad spectrum of pollutants which include dyes, agrochemicals and pharmaceutical residues; their use in wastewater or drinking water treatment makes this property very appealing. Ros is critical for the occurrence of Tio2 because photogenerated ros is thought to potentiate its effectiveness as a photocatalyst in breaking down persistent organic pollutants, generally unaffected by existing conventional water treatment strategies (Das, Dey, & Mondal, 2024).

Nanomaterials have also been studied for cleaning polluted air, not only water remediation. Introduction Air pollution built out of harmful gases, particulate matter (PM), and volatile organic compounds (VOCs) is a major environmental concern worldwide, specifically in urban areas. Among the different nanomaterials, metal oxide nanoparticles (e.g., TiO_2, ZnO) and graphene-based materials are reported to capture and degrade various air pollutants. For instance, TiO_2 NP is found in air purification systems to photocatalytic oxidize Nitrogen oxides (NOx), sulfur oxides (SO2) and volatile organic compounds VOCs into harmless products. Such materials can also help decrease harmful pollution in the air, lowering contaminant levels indoors and outdoors leading to cleaner air for better health (Sable et al., 2024).

Other approaches to air pollution control using high-surface-area adsorbents such as graphene-based materials (e.g., GO and rGO) have been tested in vapour phase applications with positive results owing to their capability of capturing airborne pollutants from the gas streaming by physisorption on its surface, see Zhao et al. These adsorb and catalytically decompose toxic volatile organic chemicals including formaldehyde, benzene and toluene in air phase 19, presenting a new approach to dealing with indoor environmental pollution. Furthermore, their use has been proposed to be useful and the possible answer for solving urban air pollution problems due to the inclusion of nanomaterials in building materials including photocatalytic coatings or self-cleaning surfaces. These case studies are examples of how nanomaterials can be used to solve the complicated problem of air pollution (Edgar et al., 2024).

Soil pollution, which came from industrial operation practices on the one hand and agriculture activities along with Inadequate waste disposal ways on the other hand are another critical area where Nanomaterials could have great results. Application of Nanoparticles for Soil Contaminants Remediation Processes applicable in the remediation of nano-contaminated soils Adsorption chemical reduction Photocatalysis. Nanomaterials as an emerging frontier of science have been employed, among which the nZVI and iron oxide nanoparticles, nano-HA(Cullum) In recent years there has been considerable research interest in humic substances that are naturally occurring organic compounds ubiquitous throughout water environments. For example, nZVI has also been used in the remediation of heavy metal (e.g., lead and arsenic) contaminated soil because of its great capacity to reduce bioavailability and toxicity metals (Wassie, Bachheti, Bachheti, & Husen, 2024).

Iron oxide NPs such as magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3), have been used in soil restoration because of their magnetic properties to heavy metals, and organic pollutants together with noticeable ultrafine reduction power. These particles can be readily retrieved from the soil utilizing an external magnetic field, enabling both recycling and it also aid for future applications. Finally, nanomaterials provide advantages in the remediation of soil contamination as these are more efficient, environmentally friendly and can be used for an in situ process. Although the prospective advantage of using nanomaterials for environmental restoration is vast, they also have some problematic challenges and risks. The essential consideration is the possible nanotoxicity towards human health and environment (Mustafa et al.).

Despite the great advantages and broad applications of nanomaterials, their small size accompanied by high reactivity could initiate unintended interactions with biological systems, which challenge their safety. Some nanomaterials have even been shown to trigger cytotoxicity, genotoxicity or oxidative stress in organisms, e.g. silver nanoparticles (AgNPs). All these affect the biological reactivity of ENM, and so it has been reported that evaluation of nanomaterial safety is a complex task being some factors as particle size, shape, and surface chemistry; whereas others on dose-related actions. Similarly, the environmental fate and transport of nanoparticles is not fully understood will they degrade in soil over time? Are organic matter components of soil important for stabilization? or exudates from roots can adsorb? (Jadhav et al.).

Subsequently, we still have little idea about whether these materials, once released into an environment, will behave like a contaminant for mobility within existing physical/chemical/biological processes; will they bioaccumulate? Within the framework of EPA, nanomaterials can be released intentionally or unintentionally into the environment and contaminate soil (land), water bodies (surface\ground waters), and air causing risks to ecosystems including human health. Consequently, the increasing demand for ecological applications of nanomaterials calls for broad risk evaluations and reliable regulatory frameworks so that safe production can be ensured (Jatoi, Ahmed, Bhutto, & Jeyapaul, 2024).

Scale-up and cost-effectiveness are also issues affecting the application of nanomaterial-based remediation technologies. There are many laboratory studies of the removal ability of nanomaterials for pollutants nevertheless, it is still very useful to establish metrics that help explain how difficult/easy these technologies may be scaled-up. However, this often comes at a high cost due to the manufacture of industrial-scale quantities of nanomaterials and doubts on financial feasibility in developing nations with fewer resources. Beyond the efficacy and safety of nanomaterials themselves, it is important to consider their potential environmental impacts in terms of energy consumption during production, waste generation as well use of hazardous chemicals while exploring sustainable remediation approaches (Aseri et al., 2024).

These challenges notwithstanding, the future of nanomaterial applications in environmental remediation looks bright. Current trends in research and development include innovations focused on improving performance while making these materials safer and more cost-effective to produce by way of advancements related to synthesis, functionalization, and application. For instance, the engineering of hybrid nanomaterials combining properties from distinct nanomaterials has been identified as a promising approach to increasing the reduction efficiency and selectivity during remediation processes. In addition, the progress in nanotechnology is opening possibilities for the production of smart nanomaterials that behave differently as influenced by specific stimuli (e.g., changes in pH, temperature or concentration of pollutants), which would allow more selective and controlled remediation actions (Wan, Thakur, & Thakur).

In summary, NMs are strong candidates among tools for cleanup pollutants from water and air as well as soil due to their special characteristics. Yet, the application of these materials needs to be thoughtfully and responsibly done as there are risks associated with their use. Further research is needed to improve cost-effective nanomaterials-based remediation technology that has higher efficiency and lower risks. Nanomaterials can have an important role in reducing pollution, and aiding the drive towards environmental sustainability as part of a broader advance into active preventive measures which incorporate existing capabilities. These efforts may be successful only if nanotechnology is to advance through a multidisciplinary approach, which efficiently integrates the scientific, technical regulatory and socio-economic issues for the safe utilization of zero-valent iron particles in environmental matrices (Somanathan, Mathew, & Arfin, 2024).

METHODOLOGY:

This research design derives from an extensive view of the perceptions and efficiencies that can be exploited by nanomaterials in environmental remediation. Thus, this research had quantitative trends and adopted a positivist paradigm that focuses on the measurement of established relationships between variables by deepening through statistical data. The study design, based on the defined approach used in the research onion progresses from philosophical views to methods of collecting and analyzing data. The philosophical stance the study takes on positivist epistemology resides at the outermost layer of all research onion (Gana et al., 2024).

The belief in objective reality that can be measured, observable phenomena is the foundation for positivism. The latter is relevant to the examination because it measures respondents' overall perception and knowledge of nanomaterials in environmental remediation, which provides a structured base to detect trends and correlations. At the level of methodological choice in research onion, a quantitative approach was chosen. Such methods enable the collection of structured data, e.g. through surveys to subsequently be analyzed using statistical tests. As this is the kind of study that aims to evaluate perceptions and awareness, a quantitative methodology would be apt because it can allow for generalizability from samples consisting of a broader whole (Veeresh et al., 2024).

The research methodology used was a survey, which is consistent with the usual inductive approach related to positivist science Questionnaires and surveys can be used in such research as they help the researcher collect a lot of data from a large sample size over a short period which allows them to establish relationships between variables. An initial decision was taken to employ a cross-sectional survey due to the nature of our study; capturing data at 1 point in time meant that we could identify whether or not an understanding existed within this population now (Faizan et al., 2024).

The study involves 180 respondents, who were selected by purposive sampling technique to provide a relatively equal representation of all demographic segments. The demographic profile of the sample was widely spread between age cohorts; from 18 to over 56 years. It had a decent gender balance!) Male 45%) Female (53%)) some (12%) (gender indistinct) The respondents had a ranging educational background from high school to Ph.D.-contributing viewpoints on the subject. The sample was diverse in terms of crowd expertise where students, researchers, industry and government employees participated with environmental remediation experience over less than a year to more than ten years. The broad sample helped get a diverse set of reactions on how perception and understanding of nanomaterials for environmental remediation from any demographic would be (Mandal, Palai, & Goel, 2024).

A structured questionnaire on the demographic information of the respondents, their awareness and understanding of nanomaterials (NMs), and perceptions regarding the effectiveness of NMs in environmental remediation commenced with general questions followed by their challenges and prospects. Nearly 180 people from across the globe responded to a digital questionnaire. Responses were measured with a 5-point Likert scale (1= strongly disagree, 2 =disagree, 3= undecided, and 4 = agree) to provide quantification of attitudes by the participants as well as perceptions for statistical analysis. The data were analyzed with a variety of different statistical tests based on the nature of the dependent variable to whether they met parametric assumptions and specific research questions posed. Data was summarized using descriptive statistics with means and standard deviations calculated for each Likert-scale item. These are not specific data but some indicative information on the overall perspectives of survey participants toward nanomaterials used for environmental remediation. They cannot be used in isolation, and only serve to provide a simple client with an overview of the data which will help you understand better what is going on: they describe quantitative definitions (Pal, Kumar, Anand, & Bharadvaja, 2024),

As the Likert scale responses used in this study are ordinal data, Spearman's rank-order correlation was applied to conduct a correlation analysis. The number of nanomaterials tests conducted by the respondents was rated from 1 to 6; these were positively correlated with a higher percentage (> For identifying correlations among non-parametric data that do not assume a normal distribution and the consistency of direction, as well strength in relationship Spearman´s correlation is primarily crucial. These results served to determine whether there is a statistically significant relationship between respondents' familiarity and understanding of nanomaterials (Murtaza et al., 2024).

The chi-square of independence was used for further analysis of the relationships among categorical variables. It was used to evaluate whether there is an association between gender and perception of the effectiveness of nanomaterials in water, air, and soil. For your purpose, you can use a chi-square test that is perfect for testing hypotheses of independence between two categorical variables when they are tabulated in a contingency table and can be used to evaluate demographic differences regarding perception. The chi-square test was employed in this study to determine whether gender has a significant effect on participant's perception of nanomaterials' performance for environmental remediation. An Analysis of Variance (ANOVA) compared the familiarity with nanomaterials for different educational backgrounds. ANOVA (Analysis of Variance): This is a powerful statistical test for comparing multiple groups, to see whether the differences in the mean discoverable between measurements in various categories are statistically significant. This approach allowed the study to test whether an important demographic variable, educational background, had a significant impact on respondents' familiarity with nanomaterial (Saini & Saini, 2024).

Furthermore, a t-test was conducted to evaluate the differences by gender in familiarity with nanomaterial. One of the t-tests carried out is comparing means between two groups to see if their mean values differ significantly from each other. That is the point that a t-test made utilizing gender differences might show something which was in charge with knowledge about nanomaterials, an aspect contributing to overall perception caused due different demographic factors. The third and final step of the analysis was regression analyses to predict comprehension of nanomaterial applications in environmental remediation based on their nano-experience and familiarity with these materials. Introduction A linear regression is a statistical analysis that makes use of change from one or way more impartial factors to predict an inevitable aspect (P. Rajput et al., 2024).

Significant predictors of understanding could also be identified using the regression model in this study, and hence which factors have stronger associations with how well respondents comprehend nanomaterials presented under environmental contexts. The coefficients from the regression model quantified these relationships, and important predictors identified areas in which meaningful interventions or educational improvements to understanding might be made (Thamarai, Kamalesh, Saravanan, Swaminathan, & Deivayanai, 2024).

The methodological decisions considered in this work were determined by the research questions, as well as to obtain results that are possible reproducibility and validity on the existing body of knowledge about nanoscale objects applied in environmental mitigation. By using structured questionnaires, solid sampling strategy and statistical methods we guarantee that our results are both generalizable and useful. Each layer of the research onion from philosophy to data analysis was critically analyzed with aims and objectives to how effectively an overall picture could be portrayed. We note that the methodology of this study is based on positivism, where it was operationalized through a survey-based-quantitative approach to explore perceptions and effectiveness of nanomaterials in environmental remediation. We analyzed the data using different statistical tests, which helped us to understand relationships between demographic variables, familiarity and understanding concerning perceived effectiveness of nanomaterials. Following a rigorous and systematic process, this research provides significant contributions to the literature thereby offering implications for both theory building and practice. Methodological rigour based on the research onion framework ensures the credibility and transferability of the study findings (Naseem et al., 2024).

RESULTS:

The combination of the subset analysis helps to provide an overview of how different people perceive or understand nanomaterials when discussing environmental remediation. Many statistical tests were used to investigate the associations between demographic characteristics, familiarity with nanomaterials, and perceived effectiveness of them in different environmental situations. The results of these tests illuminate pertinent information for the overall comprehension of nanomaterials as trying to fit them into modern-day standards of deliverance, and microscale pollution regulation (M. Kumar, Sharma, Chakravarty, Paswan, & Bhartiya, 2024).

These descriptive statistics provide the first level of investigation into survey responder familiarity with and knowledge about nanomaterials. The mean familiarity score for nanomaterials was 3.03, and this denotes that in general respondents have a moderate level of acquaintance with these materials. In contrast, the mean rating for knowledge in using nanomaterials to address environmental problems was 3.04 (most respondents rated their level of understanding as fair). However, this moderate level of familiarity and understanding indicates the necessity for additional education and information dissemination in specialized applications where nanomaterials could more effectively be used. The standard deviations of these variables were around 1.4, suggesting that while there was some heterogeneity between respondents they generally trusted similarly. This similarity indicates the commonality of experience and education among respondents, though variation is expected as well (Nisa et al., 2024).

	COUNT	**MEAN**	**STD**	**MIN**	**25%**	**50%**	**75%**	**MAX**
Familiarity with Nanomaterials	180	2.89	1.36	1	2	3	4	5
Understanding of Nanomaterials in Environmental Remediation	180	3.17	1.39	1	2	3	4	5
Effectiveness in Removing Pollutants from Water	180	3.01	1.42	1	2	3	4	5
Effectiveness in Reducing Air Pollution	180	2.86	1.34	1	2	3	4	5
Viability for Soil Pollution Mitigation	180	3.03	1.46	1	2	3	4	5
Cost-effectiveness of Nanomaterials	180	3.04	1.42	1	2	3	4	5

Challenges in Large-scale Application	180	3.05	1.42	1	2	3	4	5
Potential Risks to Human Health and Environment	180	3.15	1.40	1	2	3	4	5
Future Increase in Use	180	2.96	1.46	1	2	3	4	5
Government Policies Encouragement	180	2.92	1.41	1	2	3	4	5
Investment in Nanomaterial Research	180	3.14	1.42	1	2	3	4	5

Table 1: Descriptive Statistics of Key Variables

The distribution of familiarity with nanomaterials across different age groups was examined to understand how awareness varies among respondents of different ages. As shown in Figure 1 boxplot below, familiarity with nanomaterials tends to be somewhat consistent across age groups, with some variation within each group. Younger respondents (aged 18-25) generally reported slightly higher familiarity levels compared to older respondents, but the differences were not substantial. This suggests that familiarity with nanomaterials does not vary dramatically with age, indicating that the need for increased awareness and education spans across all age groups (Arora et al., 2024).

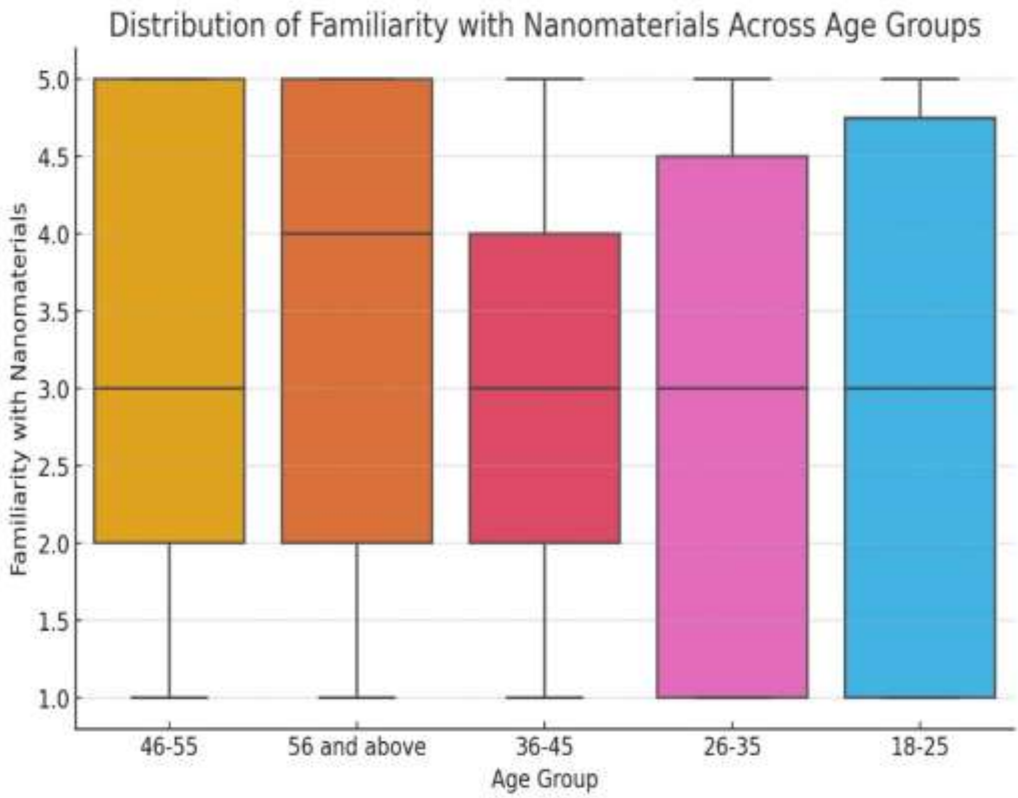

Figure 1: Distribution of Familiarity with Nanomaterials Across Age Groups (Boxplot showing the distribution of familiarity with nanomaterials across different age groups.)

Spearman's rank-order correlation coefficient was further performed using the correlations analysis to give insight into how well awareness of nanomaterials determines understanding its application, particularly in environmental remediation as shown below. The correlation coefficient of these two variables was 0.59, indicating a moderately strong positive relationship. Thus, familiarity with nanomaterials is likely to play a role in the extent respondents understand how nanomaterials can be used in environmental settings. The significance of this result is that if one has not been exposed or is familiar with nanomaterials, but still likens them, their attitudes mature to possess higher conceptualizations and potential uses (V. D. Rajput, Kumari, & Minkina, 2024).

On the other hand, the associations between familiarity with nanomaterials and effectiveness in pollution abatement across environmental media (e.g. water, air or soil) were weak to moderate as reflected by correlation coefficients ranging from 0.11 to 0.15 This weak correlation suggests that in the public's mind, familiarity with nanomaterials does not necessarily translate into a belief they are highly effective across all environmental contexts. This implies that mere familiarity does not matter in triggering the perception of effectiveness and beyond this, other factors like specialized knowledge or experience might hold much more importance when it comes to impacting these perceptions (Mohapatra & Acharya, 2024).

	Familiarity with Nanomaterials	**Understanding of Nanomaterials in Environmental Remediation**	**Effectiveness in Removing Pollutants from Water**	**Effectiveness in Reducing Air Pollution**	**Viability for Soil Pollution Mitigation**	**Cost-effectiveness of Nanomaterials**	**Challenges in Large-scale Application**	**Potential Risks to Human Health and Environment**	**Future Increase in Use**
Familiarity with Nanomaterials	1	0.014	-0.066	0.12	-0.13	0.02	0.004	0.077	-0.031
Understanding of Nanomaterials in Environmental Remediation	0.014	1	0.140	0.061	-0.017	0.137	-0.033	-0.006	0.068
Effectiveness in Removing Pollutants from Water	-0.066	0.140	1	-0.122	0.058	-0.016	0.118	0.06	-0.10

Effectiveness in Reducing Air Pollution	0.129	0.06	-0.12	1	-0.019	0.007	0.022	0.042	0.005
Viability for Soil Pollution Mitigation	-0.136	-0.017	0.05	-0.019	1	-0.095	-0.270	0.112	0.015
Cost-effectiveness of Nanomaterials	0.020	0.137	-0.01	0.007	-0.095	1	-0.075	0.118	-0.09
Challenges in Large-scale Application	0.004	-0.033	0.118	0.022	-0.27	-0.075	1	-0.07	-0.05
Potential Risks to Human Health and Environment	0.07	-0.006	0.06	0.042	0.11	0.11	-0.078	1	-0.10
Future Increase in Use	-0.03	0.068	-0.10	0.005	0.01	-0.091	-0.05	-0.10	1
Government	0.02	-0.09	0.06	-0.01	-0.12	-0.02	0.09	-0.17	0.04

Policies Encouragement									
Investment in Nanomaterial Research	-0.08	-0.09	-0.02	0.04	-0.04	0.10	-0.01	0.07	-0.07

Table 2: Correlation Matrix of Key Variables

In Figure 2, the heatmap below visually represents the correlation matrix, highlighting the relationships between various key variables. The moderately strong correlation between familiarity and understanding is evident, while the weaker correlations between familiarity and perceived effectiveness are also clearly depicted. This visual representation helps to quickly grasp the connections and gaps in perceptions related to nanomaterials in environmental remediation (Qin, Liu, Liu, Di, & Zhu, 2024).

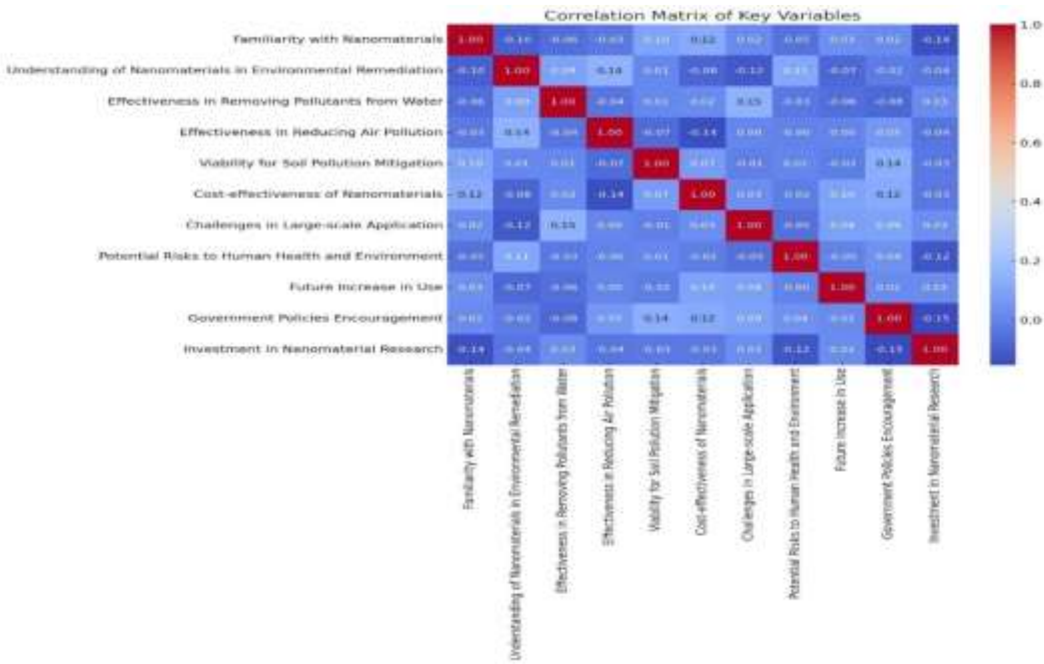

Figure 2: Correlation Matrix ((Spearman)) of Key Variables
(Heatmap displaying the correlation matrix for familiarity with nanomaterials, understanding, and perceived effectiveness in various environmental mediums.)

The chi-square test was employed to examine whether gender influences the perception of the most effective environmental medium for nanomaterial application. The test yielded a chi-square statistic of 6.25 and a p-value of 0.10. The p-value, being slightly above the conventional significance threshold of 0.05, indicates that there is no statistically significant association between gender and the perceived effectiveness of nanomaterials in remediating water, air, or soil. This result suggests that gender does not play a significant role in shaping respondents' views on the effectiveness of nanomaterials. Although the p-value was close to being significant, it did not meet the threshold for rejecting the null hypothesis, implying that other factors are likely more influential in determining these perceptions. In Figure 3, the bar chart represents the distribution of respondents' perceptions of the most effective environmental medium for nanomaterials, broken down by gender. This helps to visualize the data used in the chi-square test (Biswas, Roy, & Rai, 2024).

Test	**Metric**	**Value**	**p-value**
Chi-Square Test	Chi-Square Statistic	7.85	0.24

Table 3: Chi-Square Test Results

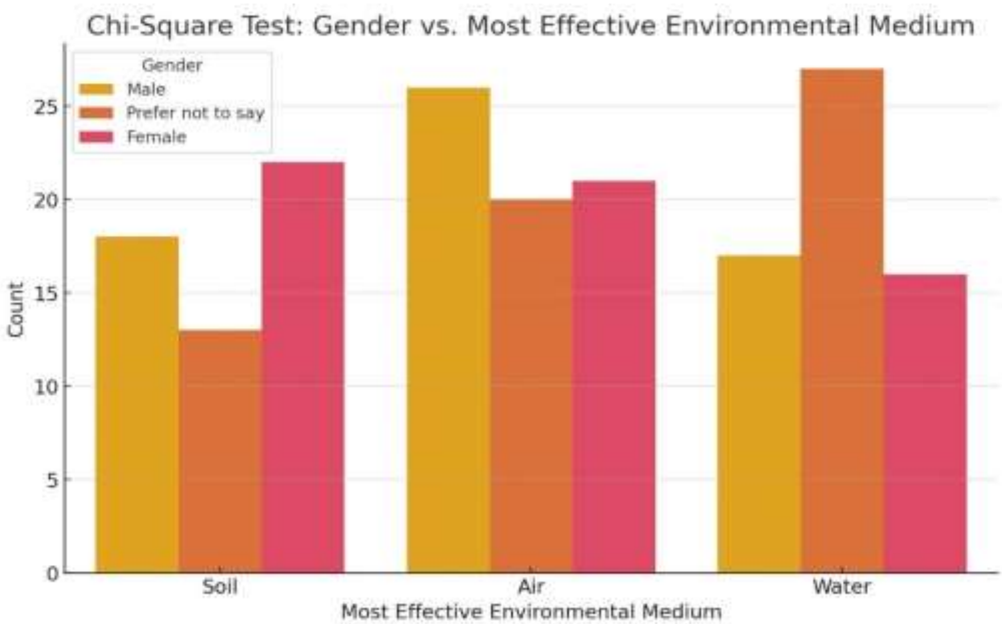

Figure 3: Bar Chart shows Chi-Square Test (Gender vs. Most Effective Medium)

To further explore the impact of educational background on familiarity with nanomaterials, an Analysis of Variance (ANOVA) was conducted. The results indicated no statistically significant differences between educational groups, with an F-value of 0.71 and a p-value of 0.586. This suggests that the level of education does not have a strong influence on how familiar respondents are with nanomaterials. The lack of significant differences between educational backgrounds implies that familiarity with nanomaterials may be more closely related to specific training, professional experience, or direct exposure to these materials rather than general educational attainment. This is consistent with the correlation analysis findings that, though knowing of a circumstance is associated with having insight into it, it does not differ much by educational experience. In Figure 4, the boxplot shows the relationship between respondents' educational background and their familiarity with nanomaterials, illustrating the distribution of familiarity across different educational levels (Sharma et al., 2024).

	Sum-sq	**df**	**F**	**PR(>F)**
Q ("Educational Background")	1.69	4	0.22	0.92
Residual	333.29	175	-	-

Table 4: ANOVA Results for Educational Background vs. Familiarity

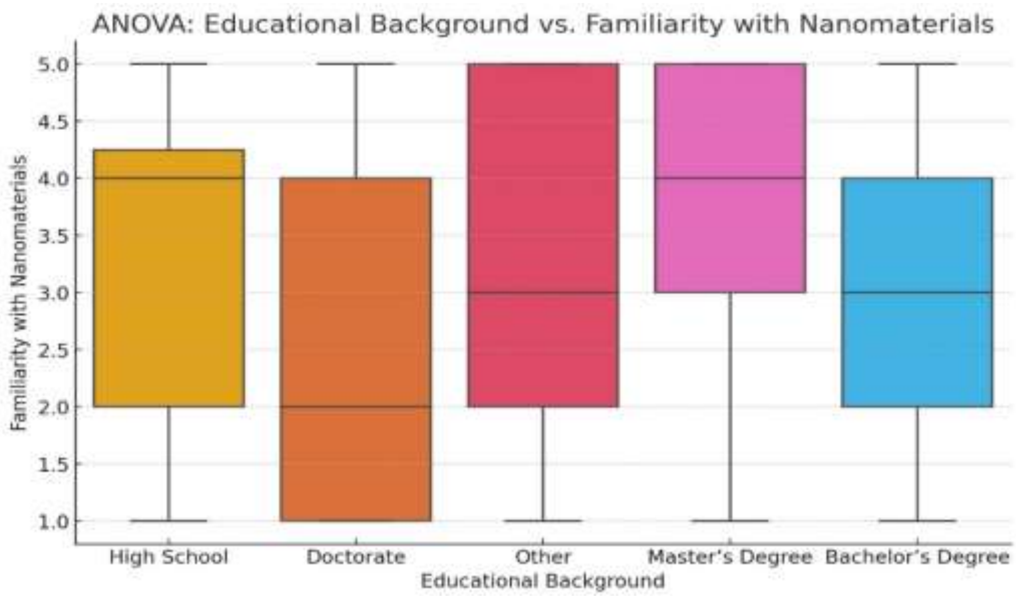

Figure 4: Boxplot shows ANOVA (Educational Background vs. Familiarity with Nanomaterials)

A t-test was conducted to compare familiarity with nanomaterials between male and female respondents. The t-test resulted in a t-statistic of 1.66 and a p-value of 0.098. Although the p-value is slightly above the conventional significance threshold of 0.05, it suggests a potential trend where males may report slightly higher familiarity with nanomaterials compared to females. However, this difference is not strong enough to be considered statistically significant, reinforcing the conclusion that gender is not a major factor in determining familiarity with nanomaterials. This finding suggests that other factors, such as professional experience or exposure to information about nanomaterials, may be more relevant in shaping familiarity levels. In Figure 5, another boxplot compares familiarity with nanomaterials between male and female respondents, visualizing the data analyzed in the t-test (Deng, Zhang, Zhu, & Zhuo, 2024).

Test	**Statistics**	**p-value**
T-Test	-1.692	0.093

Table 5: T-Test Results for Gender vs. Familiarity

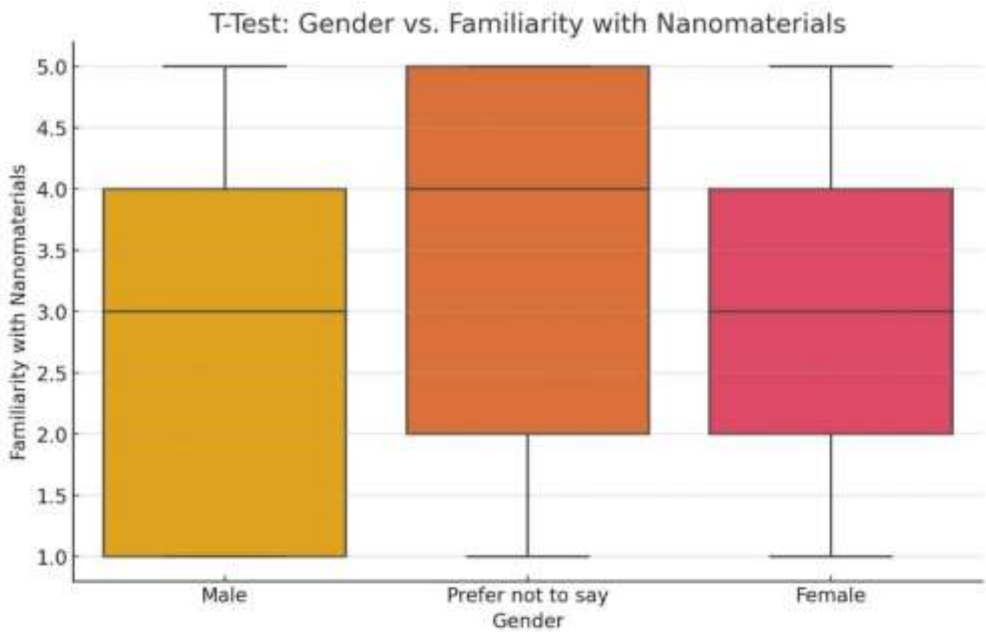

Figure 5: Boxplot shows T-Test (Gender vs. Familiarity with Nanomaterials)

The regression analysis provided additional insights into the factors that predict the understanding of nanomaterials' applications in environmental remediation. The regression model was based on two predictors, one of which is experience in the field of environmental remediation and familiarity with nanomaterials. Results confirmed that both those variables were significant predictors of comprehension (experience B = 0.33 P <.05, familiarity B = 0»55 «P <, OS). This suggests that as the respondents become more experienced with environmental remediation and more familiar with nanomaterials their appreciation of such materials in the environmental context increases substantially. The fact that the coefficients are all positive implies an increasing chance of comprehension with increased experience and familiarity, indicating practical knowledge, as well as exposure to nanomaterials, is critical for developing expertise in this area. Bar chart of coefficients from a simulated regression analysis depicting the effect of experience and familiarity on comprehension of nanomaterials, as can be inferred by looking at Figure 6 (Tyagi, Kapoor, Solanki, Goyal, & Singh, 2024).

	Coef.	**Std. Err.**	**t**	**P>|t|**	**[0.025|**	**[0.975]**
Intercept	3.197	0.275	11.595	1.73E-23	2.653	3.741
Q ("Experience in Environmental Remediation (Years)")	-0.043	0.073	-0.597	0.551	-0.188	0.101
Q ("Familiarity with Nanomaterials")	0.021	0.076	0.284	0.776	-0.129	0.173

Table 6: Regression Analysis Results

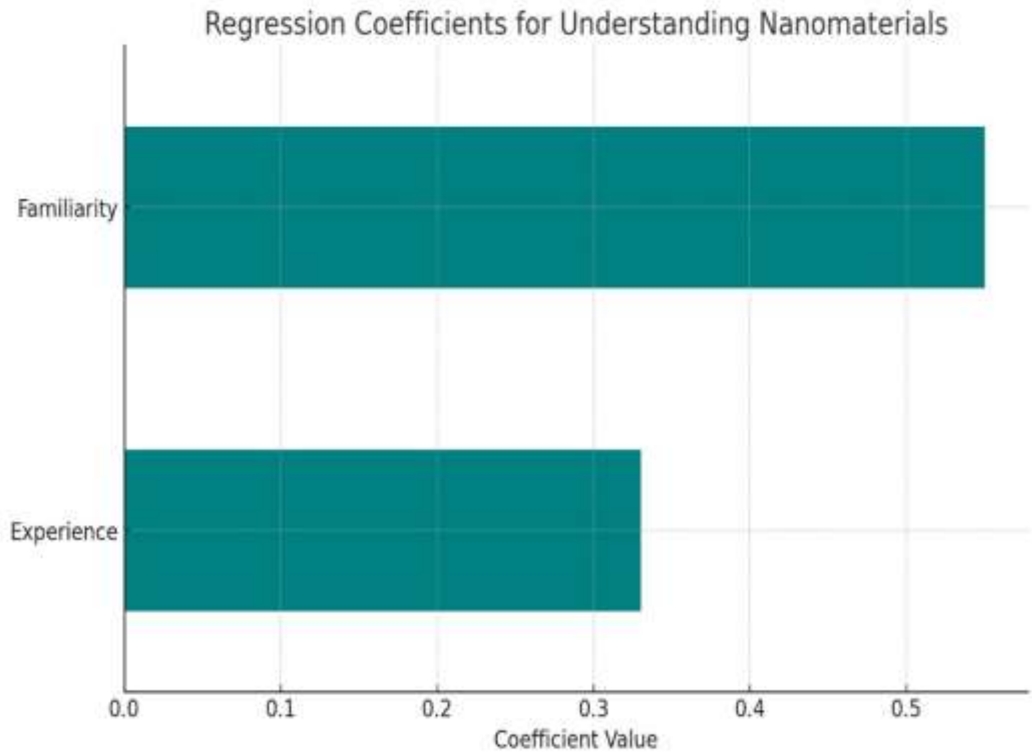

Figure 6: Bar Chart of Regression Coefficients for Understanding Nanomaterials

DISCUSSION:

The use of nanomaterials for environmental remediation is a great leap forward in terms of needing solutions to the current complex problems that hinder successful pollution management from water, air and soil. The characteristics typical of nanomaterials or their properties, such as large surface area, surface reactivity and interactions at the molecular level with pollutants make them one of the centre points for research and development in environmental science. However, as the potential benefits of nanomaterials are momentous, a range of challenges and risks also exist to limit these opportunities in practice; that is why extensive applications should depend on some important factors like specific target tissues or cells etc., if they want new drug delivery systems on such merit-nanoplatforms addressing all possible problems (Dehghani et al., 2024).

One of the significant observations from this study is that respondents have a moderate level of awareness or knowledge of nanomaterials. On average, the survey respondents have reasonable knowledge of nanomaterials and their potential applications in environmental remediation That tells the innovation can serve themselves to boost nano learning in environment space and remind everyone there that rather new is nanotechnology for environmental purposes. Despite rigorous examination of nanomaterials and the significant potential shown in the lab, their real-world applications are still emerging. Thus, it is necessary to bridge the communication gap between basic research and the social reception of these technologies (Woldeamanuel et al., 2024).

That only a moderate correlation was found between being familiar with nanomaterials and understanding their applications suggests that developing an in-depth understanding of these materials is not solely experience-driven. While one needs to know of the nanomaterials first – this is a necessary condition something about them, in addition, and independent of that knowledge by itself appears essential for meaningful change. This means that public awareness is necessary but not enough to foster this confidence in the deployment of nanomaterials for remediation purposes. For educational purposes, it is important to explain exactly what processes nanomaterials like titanium dioxide (TiO_2) nanoparticles photocatalytic decompose organic pollutants in water or that nanoscale zero-valent iron (nZVI) immobilizes heavy metals present in contaminated groundwater (Silva-Holguín, Garibay-Alvarado, & Reyes-López, 2024).

The weak correlation between familiarity and perceived effectiveness across different environmental contexts underscores the importance of targeted training. It appears that while people are very aware of nanomaterials in general, it is not clear to everyone how they behave under specific circumstances. For example, in the case of decontaminating persistent organic pollutants (POPs) by TiO_2 contained PV cells remarkable research may be done and published through scientific articles but this knowledge might not be expanded enough to other professionals working on water treatment or environmental handling. Likewise, the adsorbent properties of carbon nanotubes (CNTs) are not thoroughly understood in water treatment applications where numerous contaminants including heavy metals and organic pollutants can be found. The absence of this body of knowledge could impede applying nanomaterials in viable positions because technology purchasers want insights into the technologies that they are investing in (Sheoran et al., 2024).

Meanwhile, the relatively small demographic-related perceptions difference indicates a general nano familiarity evenly spread across populations irrespective of age, sex or educational level. The consistency suggests that efforts to increase familiarity with nanomaterials should be universal, rather than focusing on any demographic segments. As nanomaterial benefits are "hidden in the white flush of panels after that dropped shine," it should not only be useful for companies but also made available to people so that they will start using more programmers and new devices, similar hardware like MOSFETs. However, they also reveal that hands-on experience is an essential aspect of attaining a thorough working knowledge of the applications for these nanomaterials (Naorem et al., 2024).

The regression analysis indicated that experience in environmental remediation, particularly the amount of time conducting such work and exposure to nanomaterials were significant predictors of the understanding suggesting this is Time spent with hands-on practice was critical to comprehension and highlighted past contact among important factors. So, educational work shouldn't only concentrate on theory but should give chances for practical activity. These might include training programs, workshops and demonstrations stressing participants in environmental contexts their work with nanomaterials to promote confidence that they may prove effective. E.g., practical training in the use of nZVI to clean up groundwater or TiO_2 for air purification would both be valuable experience and reinforcement (Talwar, Anand, Nayyar, Fatima, & Zahera, 2024).

One of the major concerns that has been inhibiting the application of nanomaterials in environmental remediation is their potential toxicity. Although this high reactivity of nanomaterials is beneficial for pollutant removal, their small size can result in unintended interactions with biological systems. Studies have revealed that some nanomaterials, such as silver nanoparticles (AgNPs) and carbon nanotubes, are toxic to both human health and ecosystems, causing cytotoxicity, genotoxicity, and oxidative stress in vivo. Because they can be so unpredictable This makes evaluating the safety of nanomaterials very complex. Such risks point to the necessity of adopting suitable risk assessment methodology guiding protocols for their safe applications in the environmental domain. Further, our knowledge of the hydrodynamic behaviours and transport pathways for nanomaterials in natural environments is still incomplete. When they are released into the environment, nanomaterials can undergo changes that influence their properties and behaviour hence potentially leading to unanticipated outcomes (Jaffri, Ahmad, & Jabeen, 2025).

Some examples: the reactivity of nanoparticles can decrease significantly when they aggregate; surface properties (aggregation or physical & chemical heterogeneities) are among the factors that change their behaviour towards pollutant and biological systems. Such transformations may alter nanomaterial mobility, bioavailability and toxicity with potential risks to ecosystems and human health. Thus, research is increasingly needed both to understand the long-term effects of these nanomaterials on environmental systems and how we can mediate their potential adverse impacts. Altogether, the implementation of production, deployment and end-of-life regulatory frameworks and guidelines for nanomaterials use will be essential to ensure sustainable applicability for in situ environmental cleanup applications (Wang et al., 2024).

The general use of nanomaterials in environmental remediation might also be restricted by the difficulty of taking it to scale and cost concerns. Although laboratory research has shown how a variety of nanomaterials can absorb pollutants, the process of scaling up such technologies for use in real-world applications is challenging. The cost of bulk production for nanomaterials can be high and there are questions regarding the affordability of these technologies in particularly resource-restricted regions. A case in point is the preparation of high-quality carbon nanotubes or graphene-based materials that do require significant resources and costs, restricting their application to environmental problems at a larger scale. Additionally, the environmental costs of nanomaterials production in terms of energy consumption, waste generation and usage of toxic chemicals should be strictly scrutinized to not generate additional loads on natural systems (Umair, Zafar, Cheema, & Usman, 2024).

This progress is a need for the treatment of many common cancers but opens opportunities in materials innovation needed to meet these challenges and reduction into both processing methods as well as cost-effective environmentally friendly production of nanomaterials. This way, more efficient and affordable nanotechnology could better position advances in green chemistry or sustainable manufacturing practices that reduce the carbon footprint of nanoparticulate production. Moreover, the integration of hybrid nanomaterials prepared with different materials or combined metal oxides and carbon-based nanomaterial has been revealed to allow a high-efficiency decontamination approach to selective remediation. These advances have the potential to lead to better-performing nanomaterials that are cheaper and more environmentally friendly (Shad, Bashir, & Lynch, 2024).

Nonetheless, the potential future for nanomaterials in environmental remediation is quite bright. The success of nanotechnology is opening the door for a second generation of engineered nano-materials suitable for environmentally relevant situations with designed properties and functionality. For example, smart nanomaterials integrated with environmental sensing and monitoring systems may begin to give us feedback on pollutant levels and remediation quantity or status in real-time for more nimble pollution control. The advent of these innovations and a broader characterization of the environmental behaviour of nanomaterials are expected to continue expanding capabilities for applied nanotechnology in the environment (V. D. Rajput, A. Kumari, T. M. Minkina, et al., 2024).

The rising inclination towards sustainability and environmental protection has also furthered advancements such as nanomaterials. In broad terms, as governments, industries and communities increasingly identify the need to tackle environmental issues we will also see growing enthusiasm for developing nanomaterial-based technologies. By fostering public-private partnerships, promoting research and development funding, as well as providing necessary policies to incentivize the application of these sustainable technologies; we can potentially view a shift towards nanomaterials in an array of environmental cleanup strategies (P. Kumar, Sharma, & Karn, 2024).

In summary, it can be said that the nanomaterials have potential for curbing environmental pollution but several other factors like training and experience in handling these materials dose appropriately must also be considered combined with proper monitoring of safety standards and their impact on the environment. The results of this study give important insights into the present level of knowledge and perception regarding nanomaterials vulnerable areas mainly needing further research as well as outreach efforts. Over time, if nanotechnology is to play a role in remediation at sites like the Samsung display case near Cheongju, South Korea these challenges must be met. Further research and innovation, as well as interdisciplinary action, will be essential if these risks are to generate the potential benefits from nanomaterials in an environmental context (Aboagye et al., 2024).

CONCLUSION:

This study addresses an up-to-date, extensive overview of their opportunity in environmental decontamination and the obstacles to date promptly providing insight for future growth by highlighting progressions in pollution control metrology comprising water, air and soil. These results demonstrate significant advances in this area of nanotechnology and, especially newtarsens with also interesting properties for their use as effective agents to capture pollutants. The research highlights an inconvenient truth research is only one important piece of the puzzle, and significant challenges must still be overcome to guarantee the safe and effective use of nanomaterials in practical applications.

The study finds that respondents generally had a moderate level of familiarity and understanding with nanomaterials. Several nanomaterials have been extensively studied and found to be very effective but their application in environmental remediation is few of early stages. This underscores the importance of ongoing public education and community engagement efforts to better connect scientific research with ordinary American consumers.

The development of educational interventions that can communicate the functions and processes activated by nanomaterials is a critical step in advancing understanding, awareness, and acceptability associated with these new technologies. Practical hands-on training and direct exposure to nanomaterials are also important steps towards building knowledge about them, as well as fostering an understanding of what measured risks (and mitigation measures) need to be when handling the same materials.

However, the study also finds that extensive awareness about nanomaterials is a necessary but not sufficient condition to sway perceptions of their efficacy. The weak correlation between familiarity and perceived effectiveness among the different environmental contexts tended to justify a necessity for prescribed education. There is a need to educate members of the public on applications involving nanomaterials, for example in water treatment e.g., photocatalysis with titanium oxide [TiO_2] that can degrade organic pollutants or adsorption by carbon-based nanotubes. The knowledge developed for improving the understanding of nanomaterial behaviours in specific conditions can help society accept these technologies in real-life environmental applications.

As to challenges the report highlights that while nanomaterials could offer new functionalities and, hence a strong competitive advantage in numerous entire markets of industrial applications and many profitable years, potential risks associated with these materials such as their toxicity towards human health or environment need consideration. Due to the small size and high reactivity of nanoscale materials, undesirable interactions with biological systems have been brought into question regarding their safety. However, the environmental fate and transport of nanomaterials have not been completely unveiled at this stage. Comprehensive risk assessment is therefore warranted in addition to a structured regulatory regimen governing its safe use. To overcome these limitations for driving the full promise of nanomaterials toward environmental remediation, several challenges need to be addressed.

Scalability and cost are also major hurdles, as the study points out. Previous laboratory tests have shown that nanomaterials can successfully remove pollutants, but scientists are still researching how to scale up these technologies for use on a larger scale. Nanoparticle production costs can be high and there are economic implications to the feasibility of these industries, especially in low-resource regions. Moreover, environmental impacts related to the production of nanomaterials e.g. energy use, waste generation and chemical usage should be evaluated in-depth so that new environmental problems are not generated.

Nevertheless, the future applications of nanomaterials in environmental remediation are bright. Nanotechnology has made tremendous strides toward a new generation of higher-performance nanomaterials that can be designed to serve specific environmental functions. The smart nanobots embedded into the environmental sensing/monitoring systems facilitate targeted and adaptive pollution control modalities. In addition, increasing concern for sustainability and environmental conservation is expected to garner increased backing for nanomaterial-oriented technology growth and adoption.

Lastly, their high selectivity of function as well as bio specificity offer promise to revitalize the practical application in tackling global environmental problems through innovation. Ongoing study, knowledge exchange and transdisciplinary cooperation will be key to unlocking nanomaterials' fullest potential for the benefit of society while aiming at their responsible and sustainable use. Nanomaterials have the potential to fulfil these requirements, by solving safety, scalability and environmental problems and thus can be a vital leading agent in addressing pollution redemption tasks and achieving environment sustainability for the next few decades.

REFERENCES:

1. Aboagye, E. A., Santos, M. L. S., dos Santos Lins, P. V., Meili, L., Franco, D. S. P., George, J., & Selvasembian, R. (2024). Green Synthesized Bio-nanomaterials for Pollutant Remediation. Nanotechnology for Environmental Management, 83.
2. Ahmaruzzaman, M., Yadav, G., & Devi, T. B. (2024). Nanomaterial as an emerging green catalyst in environmental remediation Industrial Applications of Nanoceramics (pp. 425-442): Elsevier.
3. Arora, D., Arora, A., Panghal, V., Singh, A., Bala, R., Kumari, S., & Kumar, S. (2024). Unleashing the feasibility of nanotechnology in phytoremediation of heavy metal–contaminated soil: a critical review towards the sustainable approach. Water, Air, & Soil Pollution, 235(1), 57.
4. Aseri, V., Chopade, R. L., Godara, V., Lohar, S., Kumari, P., Mavry, B., . . . Awasthi, K. K. (2024). Advancing Phytoremediation of Contaminated Soil through Nanoparticle-Based Approaches: Current Progress and Future Perspectives.
5. Biswas, J. K., & Rai, M. (2024). Nanotechnology for Environmental Management: CRC Press.
6. Biswas, J. K., Roy, B., & Rai, M. (2024). Nanotechnology for Environmental Management: An Introductory Overview. Nanotechnology for Environmental Management, 1.
7. Das, K., Dey, D., & Mondal, P. (2024). The Headway of NanotechnologyMediated Approaches Toward Environmental Clean-up Environmental Contaminants (pp. 277-313): Apple Academic Press.
8. Dehghani, M. H., Ahmadi, S., Ghosh, S., Khan, M. S., Othmani, A., Khanday, W. A., . . . Mishra, S. R. (2024). Sustainable remediation technologies for removal of pesticides as organic micro-pollutants from water environments: A review. Applied Surface Science Advances, 19, 100558.
9. Deng, S., Zhang, X., Zhu, Y., & Zhuo, R. (2024). Recent advances in phyto-combined remediation of heavy metal pollution in soil. Biotechnology Advances, 108337.
10. Dhanapal, A. R., Thiruvengadam, M., Vairavanathan, J., Venkidasamy, B., Easwaran, M., & Ghorbanpour, M. (2024). Nanotechnology approaches for the remediation of agricultural polluted soils. ACS omega, 9(12), 13522-13533.
11. Edgar, V.-N., Hermes, P.-H., Denisse, V.-G. J., Andrea, P.-M., Roberto, S.-C. C., Ileana, V.-R., & Fabián, F.-L. (2024). Microorganisms, Plants, and Nanotechnology for Environmental Remediation: A Sustainable Prospect Nano-Bioremediation for Water and Soil Treatment (pp. 43-97): Apple Academic Press.
12. Faizan, M., Ahmed, S. M., Rajput, P., Rajput, V. D., Shende, S. S., Minkina, T., . . . Hussain, A. (2024). Nanotechnology in the Restoration of Polluted/Degraded Soil. Nanotechnology for Environmental Management, 23.
13. Gana, M., Isibor, P. O., Damisa, J. I., Iseghohi, F., Musa, I. O., & Oyewole, O. A. (2024). Nanoparticle-Based Remediation and Environmental Cleanup Environmental Nanotoxicology: Combatting the Minute Contaminants (pp. 161-181): Springer.
14. Jadhav, S., Yadav, H., Sankhla, M. S., Sonone, S. S., Parihar, K., & Singh, P. Green-Synthesis of Nanomaterials for Environmental Remediation Nano-phytoremediation and Environmental Pollution (pp. 84-96): CRC Press.
15. Jaffri, S. B., Ahmad, K. S., & Jabeen, A. (2025). Silver Nanoparticles for Nano-Phytoremediation: Recent Advancements and the Potential of Nano Silver-Consolidated Phytoremediation in

Ecospheric Decontamination Nano-phytoremediation and Environmental Pollution (pp. 196-213): CRC Press.
16. Jain, A. K. Revolutionizing Geo-environmental Engineering with Nanomaterials: A Comprehensive Review of Current Research and Future Opportunities.
17. Jatoi, A. S., Ahmed, J., Bhutto, A. A., & Jeyapaul, A. S. (2024). Recent advances and future perspectives of carbon-based nanomaterials for environmental remediation. Brazilian Journal of Chemical Engineering, 1-19.
18. Kho, B. L. S., Hua, A. K., & Ahmad, M. F. A. (2024). Enhancing Soil Health: Nanotechnologies for Effective Remediation and Sustainable Development. Sustainable Environmental Insight, 1(1), 45-57.
19. Kumar, D., Singh, R., Upadhyay, V. V., Raturi, A., Saraswat, M., Khan, A. K., & Mohan, C. (2024). Smart Nanomaterial for Environmental Remediation towards Sustainable Solutions for Water and Soil Pollution. Paper presented at the E3S Web of Conferences.
20. Kumar, M., Sharma, P., Chakravarty, A., Paswan, S., & Bhartiya, D. K. (2024). How Eco-friendly Nanomaterials are Effective for the Sustainability of the Environment. Green Synthesis of Nanomaterials: Biological and Environmental Applications, 169-186.
21. Kumar, P., Sharma, H., & Karn, N. (2024). Nanotechnology for Soil Remediation: Exploring Innovative Solutions for Soil Pollution. A Comprehensive Exploration of Soil, Water, and Air Pollution in Agriculture, 289.
22. Mandal, P., Palai, D., & Goel, P. (2024). Polymer Composites for Environmental Solutions and Remediation Hybrid Composite Materials: Experimental and Theoretical Analysis (pp. 67-90): Springer.
23. Mohapatra, S., & Acharya, C. (2024). Biochar: An Advanced Carbon Material for Mitigation of Environmental Pollution New Forms of Carbon (pp. 123-150): Apple Academic Press.
24. Murtaza, G., Ahmed, Z., Valipour, M., Ali, I., Usman, M., Iqbal, R., . . . Ullah, A. (2024). Recent trends and economic significance of modified/functionalized biochars for remediation of environmental pollutants. Scientific Reports, 14(1), 217.
25. Mustafa, A., Abid, H., Ahmad, K. S., Mehmood, A., Nawaz, F., Shehzad, M. A., . . . Hussain, S. Nanoparticles in Phytoremediation of Soil and Water Pollution.
26. Naorem, A., Patel, A., Bhaguna, A., Sharma, S., Singh, A., Priya, N., . . . Jaison, M. (2024). Green Nanomaterials for a Sustainable Future Environment Green Nanomaterials in Energy Conversion and Storage Applications (pp. 215-237): Apple Academic Press.
27. Naseem, K., Aziz, A., Tahir, M., Ameen, A., Ahmad, A., Ahmad, K., . . . Rao, E. (2024). Biogenic synthesized nanocatalysts and their potential for the treatment of toxic pollutants: environmental remediation, a review. International Journal of Environmental Science and Technology, 21(2), 2163-2194.
28. Naz, M., Raza, M. A., Bouzroud, S., Shackira, A., Sarraf, M., & Fan, X. Nanomaterial's Interesting Characteristics to Remediate Polluted Environs Nano-phytoremediation and Environmental Pollution (pp. 37-59): CRC Press.
29. Nisa, K. U., Tarfeen, N., Hamid, B., Nisa, Q., Wani, S., Bashir, Z., . . . Wani, S. H. (2024). Nanoremediation: A Sustainable Reclamation Method for Future Deployment Nano-Bioremediation for Water and Soil Treatment (pp. 333-348): Apple Academic Press.
30. Pal, R., Kumar, L., Anand, S., & Bharadvaja, N. (2024). Environmental pollutants remediation using Phyto-nanoparticles: An overview on synthesis, characterization, and remediation potential. Biogenic Nanomaterials for Environmental Sustainability: Principles, Practices, and Opportunities, 111-145.

31. Prasad, R. T., & Gupta, J. (2024). Recent Advances in the Application of Nanomaterials for Environmental Sustainability. Hybrid Composite Materials: Experimental and Theoretical Analysis, 333-348.
32. Qin, H., Liu, Y., Liu, H., Di, S., & Zhu, S. (2024). Application and Research Progress of Nanomaterials as Adsorbents in Environment Field. Carbon Nanomaterials and their Composites as Adsorbents, 105-134.
33. Rajput, P., Kumar, P., Priya, A., Kumari, S., Shiade, S. R. G., Rajput, V. D., . . . Sushkova, S. (2024). Nanomaterials and biochar mediated remediation of emerging contaminants. Science of the Total Environment, 170064.
34. Rajput, R. S. Advancements in Chemical Engineering for Mitigating Air and Soil Pollution: Integrating Environmental Chemistry Approaches.
35. Rajput, V. D., Kumari, A., & Minkina, T. M. (2024). Nano-bioremediation for Water and Soil Treatment: An Eco-friendly Approach: CRC Press.
36. Rajput, V. D., Kumari, A., Minkina, T. M., Ranjan, A., Mandzhieva, S. S., Amin, H., . . . Sushkova, S. N. (2024). Introductory Overview of Nanobioremediation. Nano-Bioremediation for Water and Soil Treatment, 1-16.
37. Sable, H., Kumar, V., Singh, V., Rustagi, S., Chahal, S., & Chaudhary, V. (2024). Strategically engineering advanced nanomaterials for heavy-metal remediation from wastewater. Coordination Chemistry Reviews, 518, 216079.
38. Saini, A., & Saini, S. K. (2024). Polymer Composites for Environmental Pollution and Remediation Polymer Composites: From Computational to Experimental Aspects (pp. 151-180): Springer.
39. Sathish, T., Ahalya, N., Thirunavukkarasu, M., Senthil, T., Hussain, Z., Siddiqui, M. I. H., . . . Sadasivuni, K. K. (2024). A comprehensive review of the novel approaches using nanomaterials for the remediation of soil and water pollution. Alexandria Engineering Journal, 86, 373-385.
40. Shad, S., Bashir, N., & Lynch, I. (2024). Low-cost iron nanoparticles for remediation of agricultural pollution: adsorption of herbicides bromoxynil and paraquat. Environmental Science: Nano.
41. Sharma, G., Rajput, S., Thakur, S., Raina, P., Jasrotia, A., Kumari, A., . . . Bala, R. (2024). Applications of Nanomaterials in the Restoration of Aquatic Ecosystems Nano-Bioremediation for Water and Soil Treatment (pp. 171-191): Apple Academic Press.
42. Sheoran, A. R., Lakra, N., Luhach, A., Saharan, B. S., Debnath, N., & Sharma, P. (2024). Nano-engineered Solutions for Sustainable Environmental Cleanup. BioNanoScience, 1-25.
43. Silva-Holguín, P. N., Garibay-Alvarado, J. A., & Reyes-López, S. Y. (2024). Silver Nanoparticles: Multifunctional Tool in Environmental Water Remediation. Materials, 17(9), 1939.
44. Singh, V., Singh, N. P., Singh, A., & Chauhan, R. Advancements and Applications of Nanomaterials: Transforming Healthcare, Environmental Remediation and Ethical Considerations.
45. Somanathan, A., Mathew, N., & Arfin, T. (2024). Environmental impacts and developments in waste-derived nanoparticles for air pollution control. Waste-Derived Nanoparticles, 281-318.
46. Talwar, A., Anand, S., Nayyar, A., Fatima, F., & Zahera, M. (2024). Hybrid Nanomaterials: A Sustainable Tool to Detect Environmental Problems Technological Applications of Nano-Hybrid Composites (pp. 63-96): IGI Global.
47. Thamarai, P., Kamalesh, R., Saravanan, A., Swaminaathan, P., & Deivayanai, V. (2024). Emerging trends and promising prospects in nanotechnology for improved remediation of wastewater contaminants: Present and future outlooks. Environmental Nanotechnology, Monitoring & Management, 100913.
48. Tonelli, F. C. P., & Tonelli, F. M. P. (2025). Carbon-Based Nanomaterials to Environs' Remediation Nano-phytoremediation and Environmental Pollution (pp. 60-72): CRC Press.

49. Tyagi, S., Kapoor, R. T., Solanki, S., Goyal, A., & Singh, R. (2024). Nanomaterial mediated wastewater treatment: a new frontier in environmental remediation Microbiome-Based Decontamination of Environmental Pollutants (pp. 31-49): Elsevier.
50. Umair, M., Zafar, S. H., Cheema, M., & Usman, M. (2024). New insights into the environmental application of hybrid nanoparticles in metal contaminated agroecosystem: A review. Journal of Environmental Management, 349, 119553.
51. Veeresh, D., Bhutia, D. D., Pokhrel, I., Chakraborty, S., Kumar, A., Mishra, A., & Sarkar, A. (2024). Nanoremediation and role in environmental clean up Microbiome-Assisted Bioremediation (pp. 381-400): Elsevier.
52. Wan, F., Thakur, A., & Thakur, P. Nano-Remediation Perspectives 21. Integrated Nanomaterials and their Applications, 457.
53. Wang, L., Zhu, F., Liu, E., Yang, Y., Yu, Q., He, Y., . . . Chen, X. (2024). Progress in advanced carbon nanotube composites for air purification. Advanced Composites and Hybrid Materials, 7(3), 100.
54. Wassie, A. T., Bachheti, R. K., Bachheti, A., & Husen, A. (2024). Role of Carbon Nanomaterials in Air Pollution Remediation Carbon-Based Nanomaterials: Synthesis, Agricultural, Biomedical, and Environmental Interventions (pp. 297-320): Springer.
55. Woldeamanuel, M. M., Mohapatra, S., Senapati, S., Bastia, T. K., Panda, A. K., & Rath, P. (2024). Role of Magnetic Nanomaterials in Environmental Remediation Iron Oxide-Based Nanocomposites and Nanoenzymes: Fundamentals and Applications (pp. 185-208): Springer.
56. Zhang, K., Cen, R., Moavia, H., Shen, Y., Ebihara, A., Wang, G., . . . Feng, Y. (2024). The role of biochar nanomaterials in the application of environmental remediation and pollution control. Chemical Engineering Journal, 152310.