



Plant-Derived NiO Nanoparticles with Enhanced UV Absorption and Photocatalytic Efficiency for Sustainable Dye Degradation

C.Ramalakshmi¹, S.Thanga parameshwari², R.Mariselvam³, S.Shibila⁴, A.Sabaridasan^{5*}

¹Department of Food and Nutrition, St.Eugene University, Zambia.

²Tamil Institute of Science and Technology, Seeniyapuram, Tenkasi, India.

³Saraswathi Institute of Lifescience, Therkkumadatthur, Tenkasi, India.

⁴Department of Biotechnology, Meenaakshi Ramasamy Arts and Science College, Thathanur, Ariyalur, India.

⁵PG & Research Department of Biotechnology, Sri Vinayaga College of Arts & Science, Ulundurpet, Kallakurichi (Dt), India.

*Corresponding author Email: sabari.biotech@gmail.com

Abstract

The UV–Visible absorption analysis of synthesized nickel oxide (NiO) nanoparticles through *Emblica officinalis* plant extracts confirms their successful formation and notable optical characteristics. A dominant absorption peak at 250.01 nm is attributed to charge transfer transitions between oxygen 2p and nickel 3d orbitals, reflecting the material's semiconductor nature and high photoactivity. Additional peaks at 296.71 nm and 370.05 nm likely arise from interband transitions or structural defects, such as oxygen vacancies, common in nanostructured systems. The shoulder near 370.05 nm may indicate plasmonic resonance or scattering effects influenced by particle size. Mie theory, which relates light scattering to particle size and refractive index, can be applied to the absorption data for nanoparticle size estimation, suggesting sizes within the 10–100 nm range. Broad absorption from 200 to 400 nm and the absence of peaks beyond 400 nm underscore the wide bandgap and strong UV absorption, making NiO suitable for applications in UV shielding, photocatalysis, and energy devices. Complementary UV–Vis spectra of Bismarck brown dye show a strong peak between 400–500 nm, linked to $\pi \rightarrow \pi^*$ transitions in azo and aromatic groups, with minor UV peaks from $n \rightarrow \pi^*$ transitions. Upon visible light irradiation in the presence of NiO, a steady decline in absorbance over 48 hours indicates effective photocatalytic degradation. The fading of both major and minor peaks suggests full mineralization without stable intermediates. This confirms the efficiency of NiO nanoparticles in breaking down complex dye molecules, reinforcing their potential in treating dye-laden wastewater and advancing sustainable environmental remediation technologies.

Keywords: nickel oxide (NiO) nanoparticles; UV/Vis spectrophotometer; photocatalytic degradation.

Introduction

Nickel is a lustrous, silvery-white transition metal that holds significant importance in modern industry due to its unique combination of physical and chemical properties. It is known for its strength, corrosion resistance, and ability to withstand high temperatures, making it an indispensable material in a variety of industrial applications (Genchi *et al.*, 2020). Discovered in the 18th century by Axel Fredrik Cronstedt, nickel's utility has expanded immensely, especially with the advancement of metallurgy, electronics, and chemical industries. Naturally occurring in the Earth's crust and often found in combination with iron, nickel is extracted mainly from ores such as pentlandite, garnierite, and laterite. The demand for nickel has grown consistently due to its vital role in producing alloys, batteries, and coatings (Briffa *et al.*, 2020). Its essential role in the global economy is underscored by its wide-ranging applications in sectors such as construction, transportation, electronics, energy production, and healthcare. However, while nickel has enabled technological and industrial progress, its extensive use has also raised serious environmental and health concerns due to contamination and toxicity issues (Wang *et al.*, 2025). With the advancement of nanotechnology, innovative strategies are now emerging to address nickel pollution through targeted degradation and remediation techniques, offering a more sustainable approach to managing its environmental impact (Rather *et al.*, 2023).

The uses of nickel are extensive and diverse, making it a critical material for various industries. One of the primary uses of nickel is in the production of stainless steel, where it imparts durability, resistance to oxidation and corrosion, and enhances the mechanical properties of steel alloys (Mankins & Lamb, 1990). Approximately 65% of the world's nickel production is utilized in manufacturing different grades of stainless steel, which are widely used in kitchenware, medical instruments, architecture, and construction (IARC, 1990). Nickel is also an essential component in the production of other alloys such as Inconel, Monel, and Hastelloy, which are used in extreme environments like aerospace, marine engineering, and chemical processing plants (Marenych & Kostryzhev, 2020). Besides its metallurgical applications, nickel is critical in the battery industry, particularly in the production of nickel-cadmium (NiCd), nickel-metal hydride (NiMH), and the more recent nickel-rich lithium-ion batteries. The transition towards electric vehicles and renewable energy storage has further increased the demand for nickel, as it contributes to battery performance and longevity (Zhang *et al.*, 2023). Furthermore, nickel is used in electroplating

to create corrosion-resistant coatings on various products, including coins, electronic components, and automotive parts. Its catalytic properties also make it valuable in hydrogenation reactions in the chemical and food industries, where nickel catalysts are employed to produce margarine and other products (Mankins & Lamb, 1990).

Beyond traditional uses, nickel's applications extend into critical technological domains. In electronics, nickel is used in the production of sensors, capacitors, and transistors, where its conductivity and stability under varying conditions are highly valued (Kaushal *et al.*, 2023). The aerospace industry relies heavily on nickel-based superalloys for the production of jet engines, turbine blades, and other high-performance components that must withstand extreme thermal and mechanical stress (Satyanarayana & Eswara Prasad, 2016). In healthcare, nickel-titanium alloys, commonly known as nitinol, are used in medical devices such as stents, orthodontic wires, and surgical instruments due to their unique shape memory and superelastic properties (Uysal *et al.*, 2022). Moreover, nickel finds application in water treatment systems, desalination plants, and chemical plants where resistance to aggressive chemicals and harsh environments is crucial. The versatility of nickel continues to drive research into new applications, particularly in emerging fields such as renewable energy, where nickel-based catalysts are investigated for hydrogen production and carbon dioxide reduction processes, potentially playing a vital role in addressing climate change challenges (Skuse *et al.*, 2021).

However, the extensive use of nickel has not come without environmental consequences. Nickel mining and processing activities contribute significantly to environmental degradation, including habitat destruction, soil erosion, and contamination of water bodies (Loet *et al.*, 2024). The release of nickel into the environment occurs through various pathways, such as industrial emissions, mining effluents, and the disposal of nickel-containing products. Once released, nickel can persist in soils and sediments, where it may become bioavailable to plants and microorganisms, leading to bioaccumulation and potential entry into the food chain (Begum *et al.*, 2022). Elevated concentrations of nickel in soils can impair plant growth by disrupting nutrient uptake and causing phytotoxic effects such as chlorosis, necrosis, and inhibited photosynthesis. In aquatic environments, nickel toxicity can adversely affect fish, invertebrates, and algae, resulting in reduced biodiversity and ecosystem dysfunction (Hassan *et al.*, 2019). Moreover, atmospheric emissions of nickel,

often from smelting operations and the combustion of fossil fuels, contribute to air pollution and can lead to human exposure through inhalation (Tian *et al.*, 2012).

The environmental issues associated with nickel contamination are compounded by its health implications for humans. Chronic exposure to nickel compounds has been linked to a range of adverse health effects, including respiratory problems, skin allergies, cardiovascular diseases, and cancers, particularly lung and nasal cancers (Genchi *et al.*, 2020). Nickel is classified as a human carcinogen by the International Agency for Research on Cancer (IARC), especially when exposure involves soluble nickel compounds and inhalable particulate forms. Occupational exposure is a significant concern in industries involved in mining, refining, and manufacturing nickel-based products, necessitating stringent occupational health measures (Guo *et al.*, 2019). Public exposure can also occur through contaminated water supplies, food, and air, particularly near industrial sites. Nickel-induced allergic reactions, such as contact dermatitis, are among the most common immunological responses, affecting millions of individuals worldwide (Riedel *et al.*, 2021). The persistence of nickel in the environment and its potential for biomagnification through food webs present long-term challenges for both ecological health and human safety (Kumar *et al.*, 2021).

The challenges posed by nickel contamination have prompted significant interest in developing effective remediation technologies, and nanotechnology has emerged as a promising tool in this regard. Nanotechnology offers innovative approaches to the degradation, removal, and recovery of nickel from contaminated environments (Ningthoujam *et al.*, 2022). Nanomaterials, due to their high surface area-to-volume ratio, tunable surface properties, and reactivity, are particularly effective in adsorbing and immobilizing heavy metals like nickel. Various types of nanomaterials, such as nanoparticles, nanotubes, and nanocomposites, have been explored for nickel remediation (Baby *et al.*, 2022). For instance, iron-based nanoparticles, including zero-valent iron (nZVI) and iron oxide nanoparticles, have demonstrated strong affinity for nickel ions, enabling their removal from contaminated water through adsorption and co-precipitation mechanisms. Functionalized carbon nanotubes and graphene oxide sheets are also investigated for their exceptional adsorption capacities and rapid kinetics in binding nickel ions from aqueous solutions (Yang *et al.*, 2019).

In addition to adsorption, photocatalytic degradation using semiconductor nanomaterials like titanium dioxide (TiO₂) and zinc oxide (ZnO) has been explored to

degrade organic complexes of nickel or to facilitate redox reactions that immobilize nickel in less bioavailable forms (Farooq *et al.*, 2024). Nanotechnology also enables the development of biosensors for real-time detection and monitoring of nickel concentrations in environmental samples, allowing for more precise and timely intervention. Furthermore, biogenic nanoparticles produced by microorganisms offer an eco-friendly alternative for nickel remediation (Ramesh *et al.*, 2022). Microbial reduction of nickel ions to elemental forms or their sequestration within biomass or biogenic mineral phases presents a low-cost and sustainable approach for treating nickel-contaminated sites (Newsome *et al.*, 2021).

Another promising area is the use of magnetic nanomaterials, which allow for easy separation and recovery after treatment. Magnetic iron oxide nanoparticles functionalized with specific ligands can selectively bind nickel ions, and after adsorption, they can be retrieved using an external magnetic field, minimizing secondary pollution. The regeneration and reuse potential of nanomaterials further enhances their economic viability for large-scale applications (Eivazzadeh-Keihan *et al.*, 2021). Research into hybrid systems, combining nanomaterials with biological or chemical treatment methods, is ongoing to enhance the efficiency, selectivity, and sustainability of nickel remediation processes (Ji *et al.*, 2024).

Despite the significant potential, the use of nanotechnology in nickel degradation also poses certain challenges, including the risk of introducing new nanomaterial-related environmental and health issues (Singh *et al.*, 2024). Therefore, it is essential to conduct comprehensive risk assessments, develop green synthesis methods, and design nanomaterials that are biodegradable or easily recoverable to minimize unintended consequences. Regulatory frameworks guiding the safe production, use, and disposal of nanomaterials are critical to ensuring that nanotechnology contributes positively to environmental remediation efforts without creating additional risks (Dhall *et al.*, 2024).

Nickel is a metal of immense industrial significance, with applications spanning from stainless steel production to battery manufacturing and medical devices. Its versatile properties have made it indispensable in modern society. However, the environmental and health challenges associated with nickel extraction, use, and disposal are serious and require immediate attention. Nickel contamination affects ecosystems, reduces biodiversity, and poses carcinogenic risks to humans (Kandasubramanian, 2024). The rise of nanotechnology provides promising new tools for addressing nickel pollution through advanced detection,

removal, and recovery techniques. Continued research, responsible development of nanomaterials, and stringent environmental regulations are essential to leverage nanotechnology effectively while minimizing potential risks. As industries move toward sustainable practices, integrating nanotechnological solutions for nickel remediation represents a crucial step toward balancing industrial growth with environmental stewardship and public health protection (Guerra *et al.*, 2018).

The present study deals with the *Emblica officinalis* leaf extract based NiO nanoparticles used to analyse the photocatalytic degradation of AZO dye.

Materials and Methods

Plant collection and extraction: Leaves of *Emblica officinalis* were harvested from an agricultural area in the Coutrallam hills. The collected leaves were shade-dried and ground into a fine powder using a mechanical grinder. For extract preparation, 10 grams of the dried powder were mixed with 100 mL of distilled water and heated at 60–80 °C for approximately 20 minutes. The mixture was then cooled to room temperature and filtered using Whatman No.1 filter paper to obtain a clear aqueous extract.

Synthesis of NiO Nanoparticles: A 0.1 M aqueous solution of nickel nitrate hexahydrate $[\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}]$ was prepared by dissolving the required amount in distilled water. To this solution, the prepared *Emblica officinalis* leaf extract was added dropwise under constant stirring at room temperature. The mixture was then heated at 70–80 °C and continuously stirred for 2–3 hours. A gradual color change indicated the formation of nickel oxide nanoparticles.

Characterization of NiO nanoparticles: The synthesized nickel oxide (NiO) nanoparticles were characterized using UV–Visible spectroscopy to confirm their optical properties and estimate particle size. A stable colloidal suspension was prepared by dispersing a small quantity of the calcined NiO nanoparticles in distilled water using ultrasonication. The absorbance spectrum of the suspension was recorded in the range of 200–800 nm using a UV–Vis spectrophotometer, with distilled water as the reference blank and a 1 cm quartz cuvette.

Photocatalytic degradation of AZO dye using NiO nanoparticles: The photocatalytic activity of the synthesized NiO nanoparticles was evaluated by monitoring the degradation of

Bismarck Brown dye under visible light irradiation. A stock solution of the dye was prepared by dissolving an appropriate amount in distilled water to obtain a concentration of 10 mg/L. In a typical experiment, 100 mL of the dye solution was placed in a beaker, and a specific amount of NiO nanoparticles (e.g., 50 mg) was added as the photocatalyst. The suspension was stirred in the dark for 30 minutes to establish adsorption–desorption equilibrium between the dye molecules and the catalyst surface. Following this, the suspension was exposed to visible light using a halogen lamp or natural sunlight, with continuous stirring to ensure uniform irradiation. At regular time intervals (e.g., every 30 minutes), 5 mL aliquots were withdrawn, centrifuged to remove the catalyst particles, and the absorbance of the clear solution was measured using a UV–Visible spectrophotometer. The decrease in the intensity of the characteristic absorption peak of Bismarck Brown (typically around 460 nm) was used to track the degradation efficiency. The process was continued for up to 48 hours.

Result and Discussion

The UV–Visible absorption spectrum of the synthesized nickel oxide (NiO) nanoparticles reveals distinct peaks, indicating successful synthesis and significant optical activity. A major absorption peak at 250.01 nm is attributed to charge transfer transitions between the oxygen 2p and nickel 3d orbitals, a hallmark of NiO's semiconductor behavior. This prominent UV absorption reflects the high photoactivity of NiO, supporting its applicability in photocatalysis and optoelectronic devices. Additional peaks at 296.71 nm and 370.05 nm may arise from interband electronic transitions or defect states induced by oxygen vacancies or lattice disorders. These features point to structural irregularities often encountered in nanostructured materials and confirm the nanoscale nature of the particles. The subtle shoulder at 370.05 nm, near the visible region, could also indicate particle size-dependent plasmonic resonance or Mie scattering effects (Figure 1).

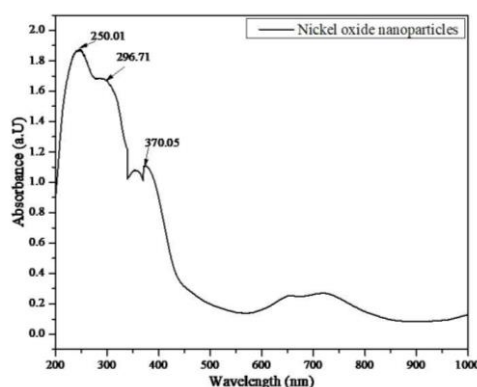


Figure 1: UV/Vis spectral data of green synthesized nickel oxide nanoparticles.

To quantitatively interpret the optical absorption and estimate the size of the nanoparticles, Mie theory can be employed. Mie theory provides a theoretical framework for understanding how spherical particles interact with light, particularly when the particle size is comparable to the incident light wavelength. It relates the extinction efficiency to particle size, refractive index, and wavelength. By fitting the experimental UV–Vis absorption data with Mie scattering models, one can estimate the average diameter of the synthesized NiO nanoparticles. The presence of broad absorption features and the shift in spectral peaks may be influenced by such scattering effects, suggesting that the nanoparticles are within the optimal size range (typically 10–100 nm) for significant light-matter interactions (Figure 1).

The broad absorption from 200 to 400 nm and absence of distinct peaks beyond 400 nm underscore the wide bandgap and strong UV absorption capacity of NiO nanoparticles. These attributes make them highly suitable for applications in UV shielding, photocatalytic degradation of dyes, and renewable energy systems such as solar cells and supercapacitors.

The UV–Visible absorption spectrum of Bismarck brown dye exhibits distinct optical features that highlight its strong light-absorbing capabilities in the visible region (Figure 2). A prominent and broad absorption peak is observed between 400–500 nm, with a maximum absorbance of approximately 1.4 absorbance units. This peak can be attributed to $\pi \rightarrow \pi^*$ transitions in the conjugated system of the azo functional groups and aromatic rings that are characteristic of the dye's molecular structure. These chromophores are responsible for the vivid coloration of the dye and its ability to absorb visible light efficiently.

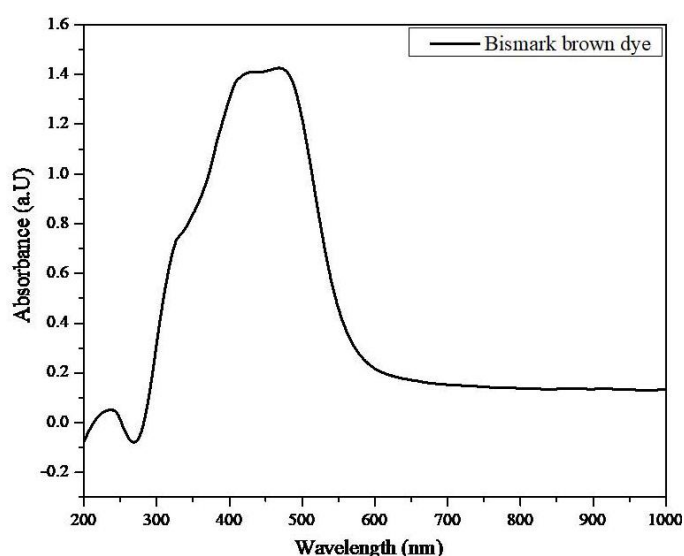


Figure 2: AZO dye (Bismarck brown).

In addition to the major peak, minor absorption features are visible in the ultraviolet region (around 250–300 nm), which may correspond to $n \rightarrow \pi^*$ transitions involving lone pair electrons on nitrogen atoms or other auxiliary functional groups. These peaks further confirm the presence of aromatic and heteroatomic groups within the dye's structure. The sharp rise in absorbance in the UV region and its sustained intensity in the visible range suggest that Bismarck brown has a complex conjugated system that allows for effective light harvesting.

The baseline flattening beyond 550 nm indicates minimal absorption in the red and near-infrared regions, consistent with its classification as a brown azo dye. This spectral behavior underlines its suitability for colorimetric applications and makes it an ideal candidate for photocatalytic degradation studies, where its strong absorbance can be monitored over time (Figure 2).

The UV–Vis spectrum confirms the presence of characteristic electronic transitions of Bismarck brown dye, especially in the visible region. The strong absorption properties provide a useful baseline for evaluating dye degradation under photocatalytic conditions and reinforce its applicability in environmental monitoring and textile wastewater treatment studies.

The time-resolved UV–Visible absorption spectra of Bismarck brown dye demonstrate a clear trend of photocatalytic degradation under visible light in the presence of a nickel oxide nanoparticle catalyst. Initially, the dye exhibits a strong absorption peak between 400–500 nm, characteristic of $\pi \rightarrow \pi^*$ transitions in its azochromophores and aromatic structures. The maximum absorbance is observed around 1.5 absorbance units at 0 minutes, indicating a high concentration of dye molecules in solution (Figure 3).

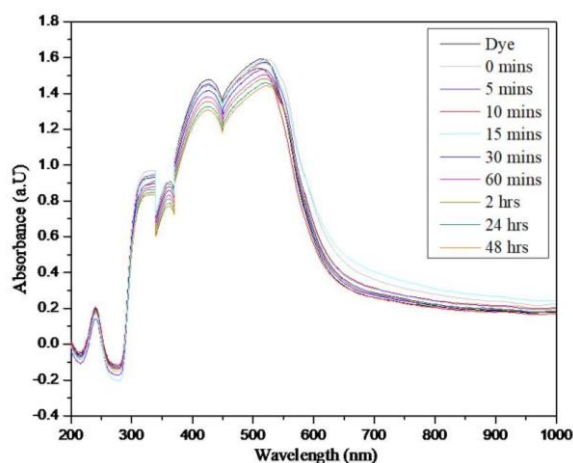


Figure 3: Dye degradation by nickel oxide nanoparticles.

As the reaction proceeds, a gradual and consistent reduction in peak intensity is observed at subsequent time intervals—5, 10, 15, 30, and 60 minutes—extending further to 2 hours, 24 hours, and eventually reaching minimal absorbance at 48 hours. This decline in absorbance reflects the progressive breakdown of the dye's conjugated system, particularly the degradation of the azo bonds and aromatic rings responsible for its coloration.

The sustained decrease in absorbance without the emergence of new peaks suggests a complete mineralization process rather than the formation of stable intermediate products. The disappearance of additional UV region peaks between 250–300 nm further supports the idea that side groups and minor chromophores are also being degraded over time. By the 48-hour mark, the absorbance drops to near-baseline levels, indicating a significant reduction in dye concentration and potential transformation into non-toxic end products like CO₂, H₂O, and other simple molecules (Figure 3).

These spectral results confirm the effective photocatalytic activity of the nickel oxide nanoparticles, highlighting their potential in the degradation of persistent organic dyes from industrial effluents. The steady decline in absorbance across all time points underscores the reliability and sustainability of the photocatalytic process for environmental remediation purposes.

Conclusion

The UV–Visible spectral analysis provides strong evidence for the successful synthesis and optical functionality of nickel oxide (NiO) nanoparticles using *Emblica officinalis*, as indicated by distinct absorption features in the ultraviolet region. The primary peak at 250.01 nm confirms the expected charge transfer transitions, while additional features at 296.71 nm and 370.05 nm suggest the presence of structural defects and size-dependent effects. The observed spectral characteristics align with Mie theory, which aids in estimating particle size by modeling light interaction with spherical nanoparticles, affirming their nanometric dimensions and efficient light-scattering behavior. The broad UV absorption and absence of peaks beyond 400 nm support the material's wide bandgap and make it suitable for photocatalytic and optoelectronic applications. Complementing this, Bismarck brown dye exhibited strong absorption in the visible region, primarily due to $\pi \rightarrow \pi^*$ transitions in its azo-linked aromatic structure. Upon exposure to visible light in the presence of NiO nanoparticles, the dye's absorbance steadily declined over time, indicating effective

photocatalytic degradation. The lack of emerging peaks and the complete fading of UV-visible absorption signals suggest comprehensive mineralization rather than partial breakdown. These results collectively highlight the high photocatalytic potential of NiO nanoparticles, underscoring their environmental relevance in degrading toxic dyes from wastewater and their broader applicability in sustainable remediation technologies.

Reference

Briffa, J., Sinagra, E., & Blundell, R. (2020). Heavy metal pollution in the environment and their toxicological effects on humans. *Heliyon*, 6(9).

Wang, Q., Li, Y., & Li, R. (2025). Integrating artificial intelligence in energy transition: A comprehensive review. *Energy Strategy Reviews*, 57, 101600.

Rather, M. A., Bhuyan, S., Chowdhury, R., Sarma, R., Roy, S., & Neog, P. R. (2023). Nanoremediation strategies to address environmental problems. *Science of the Total Environment*, 886, 163998.

Mankins, W. L., & Lamb, S. (1990). Nickel and nickel alloys.

IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. Chromium, Nickel and Welding. Lyon (FR): International Agency for Research on Cancer; 1990. (IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, No. 49.) Nickel and Nickel Compounds.

Marenych, O., & Kostyryhev, A. (2020). Strengthening mechanisms in nickel-copper alloys: A review. *Metals*, 10(10), 1358.

Zhang, C., Yan, J., & You, F. (2023). Critical metal requirement for clean energy transition: A quantitative review on the case of transportation electrification. *Advances in Applied Energy*, 9, 100116.

Kaushal, J. B., Raut, P., & Kumar, S. (2023). Organic Electronics in Biosensing: A Promising Frontier for Medical and Environmental Applications. *Biosensors*, 13(11), 976.

Satyanarayana, D. V. V., & Eswara Prasad, N. (2016). Nickel-based superalloys. In *Aerospace Materials and Material Technologies: Volume 1: Aerospace Materials* (pp. 199-228). Singapore: Springer Singapore.

Uysal, I., Yilmaz, B., Atilla, A. O., & Evis, Z. (2022). Nickel titanium alloys as orthodontic archwires: A narrative review. *Engineering Science and Technology, an International Journal*, 36, 101277.

Skuse, C., Gallego-Schmid, A., Azapagic, A., & Gorgojo, P. (2021). Can emerging membrane-based desalination technologies replace reverse osmosis?. *Desalination*, 500, 114844.

Lo, M. G., Morgans, C. L., Santika, T., Mumbunan, S., Winarni, N., Supriatna, J., & Struebig, M. J. (2024). Nickel mining reduced forest cover in Indonesia but had mixed outcomes for well-being. *One Earth*, 7(11), 2019-2033.

Begum, W., Rai, S., Banerjee, S., Bhattacharjee, S., Mondal, M. H., Bhattarai, A., & Saha, B. (2022). A comprehensive review on the sources, essentiality and toxicological profile of nickel. *RSC advances*, 12(15), 9139–9153.

Hassan, M. U., Chattha, M. U., Khan, I., Chattha, M. B., Aamer, M., Nawaz, M., Ali, A., Khan, M. A. U., & Khan, T. A. (2019). Nickel toxicity in plants: reasons, toxic effects, tolerance mechanisms, and remediation possibilities-a review. *Environmental Science and Pollution Research International*, 26(13), 12673–12688.

Tian, H. Z., Lu, L., Cheng, K., Hao, J. M., Zhao, D., Wang, Y., & Qiu, P. P. (2012). Anthropogenic atmospheric nickel emissions and its distribution characteristics in China. *Science of the Total Environment*, 417, 148-157.

Genchi, G., Carocci, A., Lauria, G., Sinicropi, M. S., & Catalano, A. (2020). Nickel: Human Health and Environmental Toxicology. *International Journal of Environmental Research and Public Health*, 17(3), 679.

Guo, H., Liu, H., Wu, H., Cui, H., Fang, J., Zuo, Z., Deng, J., Li, Y., Wang, X., & Zhao, L. (2019). Nickel Carcinogenesis Mechanism: DNA Damage. *International Journal of Molecular Sciences*, 20(19), 4690.

Riedel, F., Aparicio-Soto, M., Curato, C., Thierse, H. J., Siewert, K., & Luch, A. (2021). Immunological Mechanisms of Metal Allergies and the Nickel-Specific TCR-pMHC Interface. *International Journal of Environmental Research and Public Health*, 18(20), 10867.

Kumar, A., Jigyasu, D. K., Subrahmanyam, G., Mondal, R., Shabnam, A. A., Cabral-Pinto, M. M. S., & Bhatia, A. (2021). Nickel in terrestrial biota: Comprehensive review on contamination, toxicity, tolerance and its remediation approaches. *Chemosphere*, 275, 129996.

Ningthoujam, R., Singh, Y. D., Babu, P. J., Tirkey, A., Pradhan, S., & Sarma, M. (2022). Nanocatalyst in remediating environmental pollutants. *Chemical Physics Impact*, 4, 100064.

Baby, R., Hussein, M. Z., Abdullah, A. H., & Zainal, Z. (2022). Nanomaterials for the Treatment of Heavy Metal Contaminated Water. *Polymers*, 14(3), 583.

Yang, J., Hou, B., Wang, J., Tian, B., Bi, J., Wang, N., Li, X., & Huang, X. (2019). Nanomaterials for the Removal of Heavy Metals from Wastewater. *Nanomaterials* (Basel, Switzerland), 9(3), 424.

Farooq, N., Kallem, P., urRehman, Z., Khan, M. I., Gupta, R. K., Tahseen, T., & Shanableh, A. (2024). Recent trends of titania (TiO₂) based materials: A review on synthetic approaches and potential applications. *Journal of King Saud University-Science*, 103210.

Ramesh, M., Janani, R., Deepa, C., & Rajeshkumar, L. (2022). Nanotechnology-Enabled Biosensors: A Review of Fundamentals, Design Principles, Materials, and Applications. *Biosensors*, 13(1), 40.

Newsome, L., & Falagán, C. (2021). The Microbiology of Metal Mine Waste: Bioremediation Applications and Implications for Planetary Health. *GeoHealth*, 5(10), e2020GH000380.

Eivazzadeh-Keihan, R., Bahreinizad, H., Amiri, Z., Aliabadi, H. A. M., Salimi-Bani, M., Nakisa, A., & Madanchi, H. (2021). Functionalized magnetic nanoparticles for the separation and purification of proteins and peptides. *TrAC Trends in Analytical Chemistry*, 141, 116291.

Ji, W., Liu, J., Sha, C., Yong, Y. C., Jiang, Y., & Fang, Z. (2024). Nanomaterial-biological hybrid systems: Advancements in solar-driven CO₂-to-chemical conversion. *Green Carbon*.

Singh, G., Thakur, N., & Kumar, R. (2024). Nanoparticles in drinking water: Assessing health risks and regulatory challenges. *Science of The Total Environment*, 174940.

Dhall, S., Nigam, A., Harshavardhan, M., Mukherjee, A., & Srivastava, P. (2024). A comprehensive overview of methods involved in nanomaterial production and waste disposal from research labs and industries and existing regulatory guidelines for handling engineered nanomaterials. *Environmental Chemistry and Ecotoxicology*.

Kandasubramanian, B. (2024). Sustainable approaches and advancements in the recycling and recovery of metals in batteries: A Review. *Hybrid Advances*, 100271.

Guerra, F. D., Attia, M. F., Whitehead, D. C., & Alexis, F. (2018). Nanotechnology for Environmental Remediation: Materials and Applications. *Molecules (Basel, Switzerland)*, 23(7), 1760.