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SYNTHESIS CHARACTERIZATION AND APPLICATIONS OF NANOPARTICLES IN ENVIRONMENTAL DETOXIFICATION

Irfan Haidri[1], Nisar Fatima[2], Muhammad Abdullah[3], Aqsa Ilyas [4], Asia Parveen [5], Rabia Afzal[6], Muhammad Shahbaz[7], Minahil Batool[8], Muhammad Qasim*[9]

[1]Department of Environmental Science, Government College University Faisalabad 38000, Punjab Pakistan haidaryirfan807@gmail.com
[2]Department of Physics, GC Women University Sialkot Punjab Pakistan, nisar6699661@gmail.com
[3]Water and Environmental Management, University of Hertfordshire Hatfield abdullahkhansial2@gmail.com
[4]Department of Chemistry, University of Agriculture Faisalabad 38000 Punjab Pakistan aqsajutt305@gmail.com
[5]Department of Chemistry, Government College University Faisalabad 38000, Punjab Pakistan, asiaparveen609@gmail.com
[6]Department of Chemistry, University of Agriculture Faisalabad 38000, Punjab Pakistan, afzalrabia1122@gmail.com
[7]Department of Environmental Science, Government College University Faisalabad 38000, Punjab Pakistan shibazm2@gmail.com
[8]Department of Environmental Science, UET Lahore University of Engineering and Technology minahilbatool171202@gmail.com
*[*9]Department of Environmental Science, Government College University Faisalabad 38000, Punjab Pakistan qasim987khan@gmail.com*

***Corresponding Author:**
qasim987khan@gmail.com

Abstract
The synthesis, characterization, and applications of nanoparticles (NPs) for environmental remediation are reviewed in this review article. An overview of several synthesis techniques—such as precipitation, thermal decomposition, and hydrothermal synthesis—that allow the creation of NPs with precise size, shape, and magnetic properties is given in this work. It also explores methods for characterizing NPs, which are essential for understanding their chemical, magnetic, and physical properties. These methods include vibrating sample magnet magnetometry (VSM), X-ray diffraction (XRD), and transmission electron microscopy (TEM). Most reviews highlight the application of NPs in environmental remediation, emphasizing their efficiency in the adsorption and removal of organic pollutants, heavy metals, and dyes from contaminated water. Case studies demonstrate the use of NPs in real-world ecological remediation situations, highlighting its promise as an environmentally beneficial and long-term method of remediation of soil and water. The review discusses NP-based addresses and prospective future initiatives, such as the need for scalable synthesis methodologies, the development of more advanced functionalization strategies to target specific pollutants and environmental impact assessments.

Keywords: *Heavy metals, Nanoparticles, Water treatment, Environmental pollution, Detoxification, Microbiota, Industrial wastewater*

INTRODUCTION

The surge in pollution affecting water and soil resources with contaminants like heavy metals, organic substances, and dyes is closely linked to rapid urbanization and industrial growth. Certain industries, including those involved in producing paper pulp, spirits, leather, and textiles, contribute significantly to hazardous wastewater. If released into the environment without proper treatment, this wastewater poses severe risks to both human health and ecological balance (Chowdhary et al., 2020). Microorganisms, due to their resilience against metal toxicity, play an essential role in the energy and nutrient cycles within ecosystems. Research has delved into the consequences of heavy metals on biodiversity, the critical function of microbial communities in environmental detoxification, and the identification of reliable indicators to track the success of removing metals from industrial effluents (P. Sharma et al., 2021). The nanoparticles especially magnetic nanoparticles are emerging as a powerful tool in environmental detoxification due to their unique magnetic properties, high surface area, and ability to be manipulated under magnetic fields (Maksoud et al., 2020; Haidri et al., 2023). These nanoparticles are often composed of various coatings to enhance their specificity and affinity for targeted pollutants, including heavy metals, organic compounds, and dyes (Pandiyaraj et al., 2023). The use of NPs in water treatment, for example, allows the rapid and efficient removal of pollutants through the absorption process (Chenab et al., 2020). After binding to pollutants, NPs can be easily separated from water using an external magnetic field, providing a convenient and reusable solution for cleaning polluted water sources (R. K. Sharma et al., 2021). This technology represents a promising approach to addressing the growing challenge of environmental pollution, providing a sustainable and efficient method to clean ecosystems without introducing secondary pollutants (Saravanan et al., 2021). Furthermore, important topics for additional research are also emphasized, along with issues that will need to be handled in the future.

Nanotechnology

Nanotechnology can be defined as a “developing field of science consisting of development and synthesis of different nanomaterials (Ullah et al., 2024). In nanometer scale, nanotechnology consists of manufacturing, processing, and application of structures by monitoring their shape and size. Nanoparticles are fundamental components of nanotechnology, so they can be defined as “particles having a size range between 1 and 100 nm (Batool et al. 2023). The nanoparticles are of different structures, sizes, and shapes. For example, nanoparticles might be sphere-shaped, hollow cylindrical, irregular, tubular, flat, etc (Gatou et al., 2024). At the nanoscale, nanoparticles show exceptional properties (physical, biological, and chemical) as compared to the particles at larger scales (Joudeh & Linke, 2022). Nanotechnology has made huge progress and its usage increased by 25-fold between 2005 and 2010 in different products that require nanoparticles for their manufacturing (Hussein et al., 2023). This is due to their properties of large surface area to volume, greater stability, shape, charge, and reactivity in chemical processes, etc (Shaheen et al., 2023).

Synthesis of Nanoparticles

Many methods are available for the synthesis of nanoparticles. They are broadly categorized such methods into top-down approach and bottom-up approach (Kumari et al., 2023). In a top-down approach destructive method is used, in which large-size molecules are converted into small-size units and then such units are converted into desirable nanoparticles. Grinding, CVD, PVD, etc. are some top-down methods. In the bottom-up method, nanoparticles are formed from simpler substances. Sol-gel, green synthesis, biochemical synthesis, etc. are some bottom-up methods (Hussain et al., 2024; Ullah et al., 2024). Nanoparticles can be produced by various physio-chemical, and biological methods. Some chemical and physical methods for the synthesis of nanoparticles (Mubarik et al., 2022).

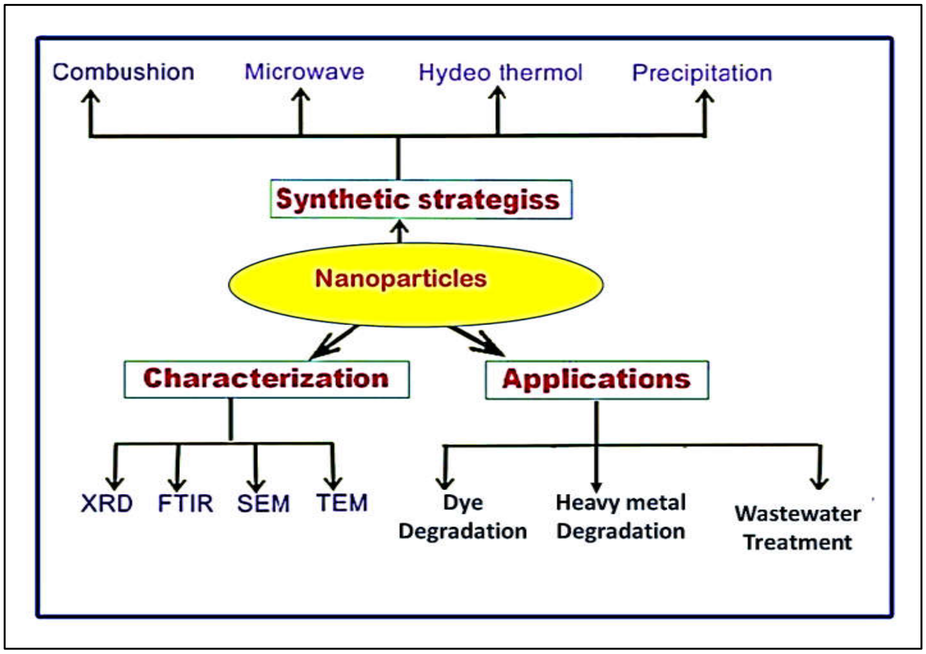

Fig.1 Synthesis and characterization of nanoparticles for detoxification of environmental pollutants

Synthesis of nanoparticles through physical methods

When it comes to the physical methods for the synthesis of nanoparticles, the primary and common ways for the synthesis of nanoparticles are evaporation-thickening and laser-extraction methods (Fatima et al., 2024). Synthesis is carried out with the use of a furnace at atmospheric pressure using the evaporation-condensation process (Sakono et al., 2023). Despite providing high production of nanoparticles, this method has a variety of disadvantages (Waseem et al., 2023). It creates space issues like the furnace takes up a lot of space, a high amount of energy is required in this process, and this enhances the temperature of the surrounding environment (Haidri et al 2023). Finally, this reaction slows down as temperature equals are not easily attained, and it is not easy to reach high temperatures (Ermakova et al., 2001). Another method is a laser-extraction method, in which no chemicals and no machines are used, and it is considered to be effective. When chemical solvents are not present in the process makes it effectively compatible with nature and complies with the 5th Green chemical method which deals with insoluble reactions (Arabi et al., 2021). In addition, controlling the size of nanoparticles is also possible when the numbers of laser pulses are adjusted. Nanoparticles synthesized from the physical method are pure. Laser ablation nanoparticles are considered to show higher regeneration in the field of antimicrobials and anti-bacterial activity than chemically coated nanoparticles (Lazov et al., 2021). Therefore, this reality appears that the laser extraction method is a very effective and extremely environmentally friendly method. While it is believed that, one feature decreases the overall efficiency of this process. In the process of laser emission, the first requirement is very high temperatures and high power consumption (Ouyang et al., 2022). Therefore, it doesn't follow to sixth principle of green chemistry- Chemical processes" Energy requirements must be acknowledged for their economic impact and environmental impact, and they should be reduced as much as possible. Local pressures and temperatures should be taken into account while designing processes. In addition, the use of the laser-ablation method has not been promoted for industrial usage, mainly because of low production from the physical method. As a result, for the time being, this procedure is not the most cost-effective (Zhou et al., 2020; Ummer et al., 2023).

So, the physicochemical methods are nonenvironmentally friendly and costly because combustible, harmful, and toxic chemicals are used which may pose a risk to the environment and they also require high energy for their operations (Ullah et al., 2024). To overcome such limitations, researchers focused on biosynthesis and green synthesis of nanoparticles which are more cost-effective, environmentally friendly, produce safer end products, and require less energy (Fatima et al., 2024).

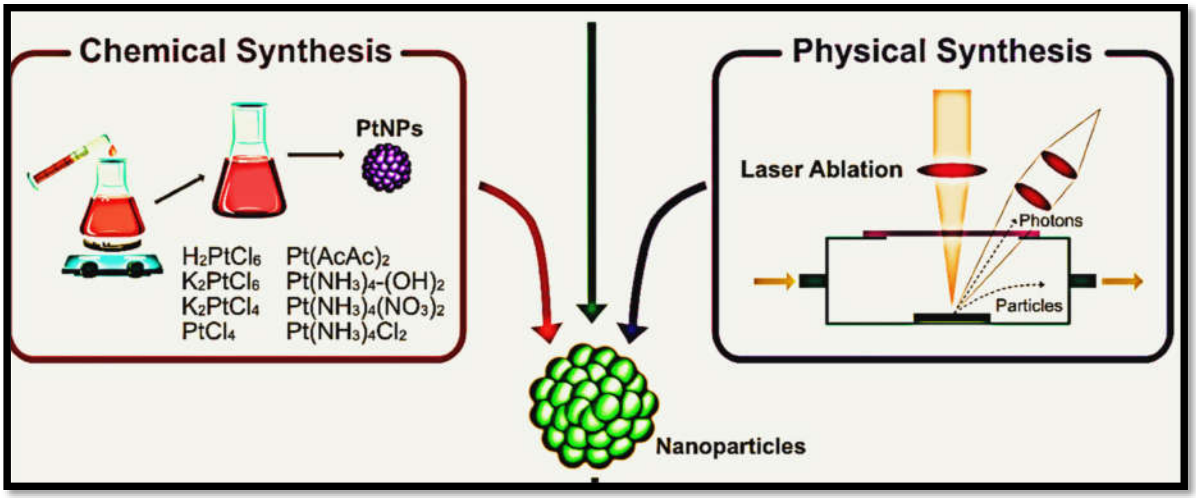

Fig 2 Physiochemical synthesis of nanoparticles

Table 1 Physiochemical Synthesis of Nanoparticles

materials	Methods	Wavelength (nm)	Synthesis technique	Particle size (nm)	Ref.
Carbon-based NPs	Laser ablation	1064	Graphite	80 - 130	(Thongpool et al., 2013)
Carbon-based NMs	-	532	Graphite	200	(Liang et al., 2003a)
CdO NPs	-	1064	Cd sheet	24	(Mostafa et al., 2017)
FePt	-	532	FePt	10-40	(Ishikawa et al., 2006)
Iron Oxide NPs	-	1064	Fe target	2–80	(Uddin et al., 2022)
SnO	-	1064	Sn/Zn	30-60	(Vickers, 2017)
SnO_{2-x}	-	355	Sn	2.5-4	(Liang et al., 2003b)
Oxidized Graphite Nanoparts	Ball milling	600	6h, 16h, 24h + 10min intervals	20-22nm	(Mahmoud et al., 2018)
Iron Oxide Nanoparticles	-	200	24h, 100h	10–15nm	(Velásquez et al., 2018)
Magnesium Hydride (ϒ-MgH_2)	-	750	10h, 50h, 72h	Not specified	(Lobo et al., 2019)
Bornite Nanoparticles	-	1000	5min to 120min intervals	10–40nm	(Azevedo et al., 2018)
Copper Oxide Biochar Composites	-	400	3h to 18h intervals	10-14nm	(Wei et al., 2020)
Nitrogen-Infused Carbon Nanoparticles	-	150	24h	Not specified	(Xing et al., 2013)
ZnO Nanoparticles	sol-gel	NaOH	(0-80 °C)	37 nm	(Altıntıg et al., 2021)
$MnFe_2O_4$ Nanoparticles	-	NaOH	Heated to 70 °C, gel	45 nm	(Rezaei et al., 2021)
Al-doped ZnO Nanoparticles	-	NaOH	60 °C for 2h, and calcined at 200 °C for 2h.	20–50 nm	(Mahdavi & Talesh, 2017)
CuO Nanoparticles	hydrothermal	NaOH	Ethanol washing and drying	~27.7 nm	(Jana et al., 2018)
TiO_2 Nanoparticles	-	BMI.Cl	Ethanol washing, centrifugation, oven drying at 80 °C	35 nm	(Manjunath et al., 2018)
NiO Nanoparticles	-	-	Centrifugation, at 50 °C,	20–50 nm	(Ramasami et al., 2015)
$CoFe_2O_4$ Nanoparticles	Cobalt and iron nitrates	NaOH	Filtration through 0.5 m	20-50 nm	(Prabhakaran et al., 2017)

Chemical synthesis of nanoparticles

Chemical methods for the synthesis of nanoparticles are numerous. They're also quite frequent, and they generate silver nanoparticles with organic water or solvents (Yaqoob et al., 2020). The main advantages of chemical bonding methods are their flexibility, low price, and the ability to generate precise nanoparticles of the desired size and structure (Harish et al., 2023). The reducing agents and the solvents utilized in the production process are poisonous to both the environment and human beings (Lashari et al., 2022). Although in a chemical reaction, polyvinyl alcohol is a common reagent, that is less expensive, it also harms healthy cells of the body where synthesized nanoparticles are generated and employed for medication transformation (Haidri & Qasim, 2023). The harmfulness of the solvents utilized has a long-term impact, which means they harm human life not only during nanoparticle formation but also during their utilization (Ntouros et al., 2021). These nanoparticles are extremely problematic as transporters of hazardous compounds when utilized for antibacterial action, medicine delivery, or any other application that needs nanoparticles to be absorbed into the body of humans. Thus, that is clear the chemical composition of nanoparticles (Nps) is more effective and precise than several green chemical principles, due to their reliance on chemicals that are toxic and harmful to the health of humans (Radulescu et al., 2023). In the electrochemical method, the synthesis of nanoparticles is attained by passing an electric current among both electrodes which are differentiated by electrolyte (Bredar et al., 2020)vv. Normally for the production of nanoparticles, a solution of salt and acid is used. UV radiation is found to be an effective chemical method as it breaks up the metal salts into smaller sizes until they become stable and evenly distributed. Another method discussed in the literature is vacuum drying (Haidri & Khan, 2023). This method is of prime importance for photocatalytic degradation as it produces nanoparticles with oxygen vacancies. Many of the azo dyes have been treated with Nanocomposites synthesized by the sol-gel method (A. K. Sharma & Lee, 2020).

Green synthesis of nanoparticles

The synthesis of nanoparticles through an ecological process. Nanoparticles synthesized from this method were uniform, stable, and pure and they can be used for several medical applications and different biological applications (Ishfaq & Haidri, 2023). These nanoparticles were formulated by two different approaches the most environmentally friendly approach is a green synthesis of nanoparticles. Plants and their derivatives, as well as microbes, are involved in the green synthesis of nanoparticles. Bacteria, fungi, algae, and yeast are examples of microorganisms (Purohit et al., 2019). The skin of Banana was used for this purpose. It is a very cost-effective method for the synthesis of nanoparticles it is environment friendly in a way that the waste of the plant can be used as a useful product (Asiya et al., 2020).

Table 2. Green synthesis of nanoparticles

Bacteria Species	Size (nm)	Shape	References
Bacteria	1.3–62	Round	(Garibo et al., 2020)
Bacteria	210	Triangles, hexagons	(Klaus et al., 1999)
Bacteria	63–70	Round shape	(Malarkodi et al., 2013)
Bacteria	42–92	-	(Korbekandi et al., 2012)
Bacteria	24–50	-	(Korbekandi et al., 2012)
Bacteria	46 ± 0.15	-	(Manivasagan et al., 2013)
Bacteria	21–30	-	(Sadhasivam et al., 2010)
Fungi	1–23	-	(Sagar & Ashok, 2012)
-	33	Round	(Gajbhiye et al., 2009)
-	5–25	Round	(Kathiresan et al., 2009)
-	11–60	Crystalline/ Round	(Basavaraja et al., 2008)
-	51–93	Round	(Arun et al., 2014)
Plants	10	Irregular	(Odeniyi et al., 2020)
-	10.1–70	-	(Niluxsshun et al., 2021)
-	98.47 ± 2.04	-	(Erdogan et al., 2019)
-	2.3–3	Icosahedral	(Gardea-Torresdey et al., 2003)
-	12.4	-	(Ahmad & Sharma, 2012)
-	34	-	(Singh et al., 2010)
-	42–59	-	(Gavhane et al., 2012)
-	11–50	Round /oval	(Velmurugan et al., 2015)
-	20-25	-	(K. Roy et al., 2014)
-	34–10	-	(Kaviya et al., 2011)
-	-	-	(Rout et al., 2012)
-	-	-	(Rout et al., 2012)
-	20-30	-	(Kaviya et al., 2011)

The synthesis of nanoparticles from the biogenic synthesis method is an attractive and alternative approach rather than the chemical methods for the synthesis of nanoparticles (D. Sharma et al., 2019). Numerous sustainable and non-chemical approaches exist for creating nanoparticles (Kumar et al., 2017). In evaluating different nanoparticle production techniques, the biological approach is notably advantageous, utilizing organism enzymes. It was observed that silver nanoparticles produced via biological and chemical processes exhibited significant antibacterial effects, particularly against Escherichia coli and Staphylococcus aureus (Shahverdi et al., 2007).

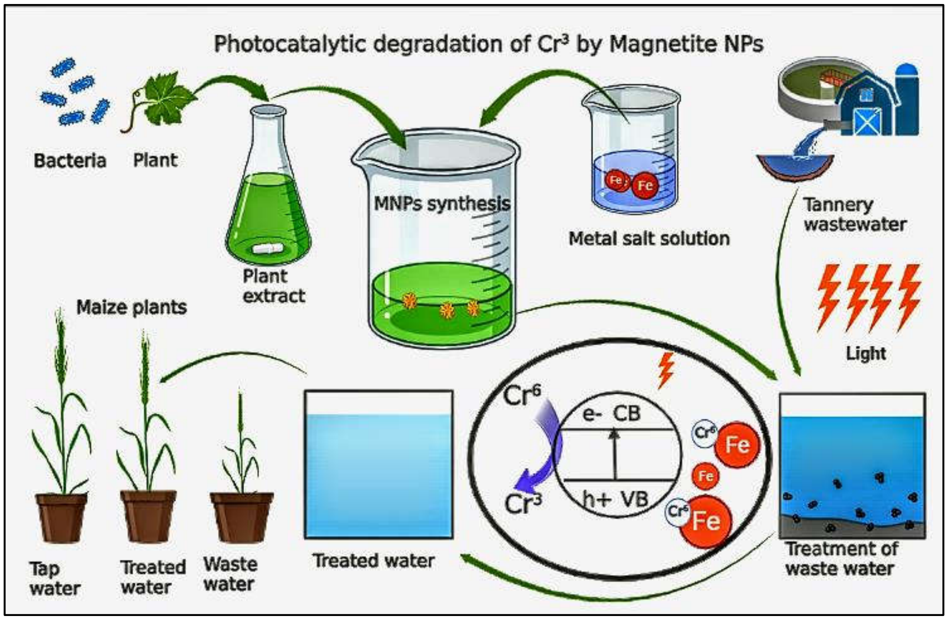

Fig .3 Green synthesis of nanoparticles for the treatment of chromium in wastewater

Factors affecting the synthesis of nanoparticles

The production of nanoparticles through biological methods is influenced by several parameters, including pH, reaction duration, microbial culture concentration, and temperature (Hulkoti & Taranath, 2014). The impact of these parameters on nanoparticle generation has been analyzed. Specifically, pH alterations can significantly modify the size and morphology of the nanoparticles. During the gold nanoparticle production process, different pH values (3, 5, 7, and 9) resulted in varying shapes, sizes, and particle quantities. At a pH of 3, the nanoparticles were mostly spherical and uniform, with sizes less than 10 nm in diameter. When the pH was adjusted to 5, there was a presence of smaller spherical nanoparticles alongside a higher quantity of larger particles in diverse shapes such as hexagons, spheres, triangles, and rods. The nanoparticles produced at pH 7 and 9 demonstrated similarities, featuring small spherical forms and larger particles with irregular, undefined geometries (Patungwasa & Hodak, 2008). Additionally, the nanoparticle yield was lower at pH 9 compared to pH 7.

The influence of temperature, along with pH, plays a critical role in the production of biogenic nanoparticles. As the synthesis reaction temperature rises, the rate of nanoparticle formation and transformation accelerates (Fritz et al., 2022). Observations noted that after a duration of 24 hours, the conversion rates were approximately 70%, 80%, and 90% at temperatures of 25 ℃, 60 ℃, and 95 ℃, respectively. Additionally, an increase in temperature from 25 ℃ to 95 ℃ led to a reduction in particle size from 110 nm to 25 nm. It was theorized that a higher reaction temperature boosts the reaction velocity, enhancing copper ion consumption in nucleus formation and inhibiting secondary reactions on the existing nuclei surfaces. Moreover, the time factor is essential for the synthesis and maintenance of nanoparticle stability (Yaqoob et al., 2020). The accessibility of a maximum number of nuclei at a given time showed a reduction in the size of nanoparticles. This is due to smaller metal nuclei which produce and consume metal ions at the same time (Haidri et al., 2023). The reaction time increased, and size reduction took place. The reaction time of up to 60 minutes resulted in the formation of well-defined nanoparticles during the synthesis of nanoparticles by using the chemical reduction method (Fatima et al., 2024).

It is an easy task to add different types of contaminants to the environment, but it becomes problematic when talking about their elimination (Varsha et al., 2022). The situation becomes more adverse when such pollutants become part of a biological system. Developing countries have limited resources of water for the use of individuals, industry, and agriculture purposes (Chowdhary et al., 2020). With the increase in urbanization and industrialization, the situation has become more adverse. Among other industries, the textile industry produces a large number of dyes-loaded wastewater. Individuals from developing countries use such wastewater for irrigation purposes (Kılıç, 2020). Various types of chemicals are used in different processes of the textile industry and such chemicals are ultimately released into the freshwater bodies without any treatment as industrial effluent (Kishor et al., 2021). However, there is a need to develop effective methods for the treatment of dyes and chemical-loaded wastewater which are eco-friendly before elimination. Nanotechnology is an emerging field that is also used for the treatment of wastewater (W. U. Khan et al., 2023).

Characterization of the synthesized nanoparticles

Upon the creation of nanoparticles, their detailed analysis becomes crucial. This characterization step assesses the nanoparticles' chemical and physical attributes, a vital process for their application across various domains, notably in biomedical sciences. The differentiation of these properties is essential to confirm the nanoparticles' efficacy and safety. Even slight alterations in their intended structure can significantly impact their medicinal effectiveness (Gavas et al., 2021).

Several techniques are available for nanoparticle characterization, among which scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD), and UV-visible spectroscopy, along with nuclear magnetic resonance (NMR), stand out as common approaches (Reaz et al., 2020). Additionally, Fourier transform infrared spectroscopy (FTIR), energy-dispersive X-ray spectroscopy, and X-ray photon spectroscopy are employed for in-depth analysis (Das et al., 2020). Notably, UV/Vis spectroscopy offers a straightforward, rapid, and reliable means to analyze nanoparticles, where their concentration, size, and morphology are inferred from UV/Vis light absorption patterns. Transmission electron microscopy is a technique of Electron scattering that provides information about physical appearance regarded as morphology, size of the nanoparticles, structure, and distribution of Nanoparticles (Arshad et al., 2023). X-ray Diffraction is the pattern of diffraction of the given Nanoparticles that Gives an idea of the size of nanoparticles and also the structure of compact Nanoparticles. It gives us knowledge about crystalline structure (arrangement of lattice) and phases of nanoparticles (Schulz et al., 2021). The strength of nanoparticles and the number of X-rays that are emitted from the excited electrons are measured through Energy Dispersive X-rays. That can help to analyze the local structure of Nanoparticles. TEM is preferred to produce nanoparticles as it provides details about (shape and size) physical properties and chemical properties (Ijaz et al., 2020). In transmission electron microscopy, the beam of electrons is used for measurement. The beam of electrons is empowered to exceed the samples of nanoparticles, which shows the interaction between nanoparticles and the electrons (Siddiqui et al., 2020). This interaction is then translated into the form of an image, which we can read, and information about its features is extracted from the information we got in this interaction (Yao et al., 2021).

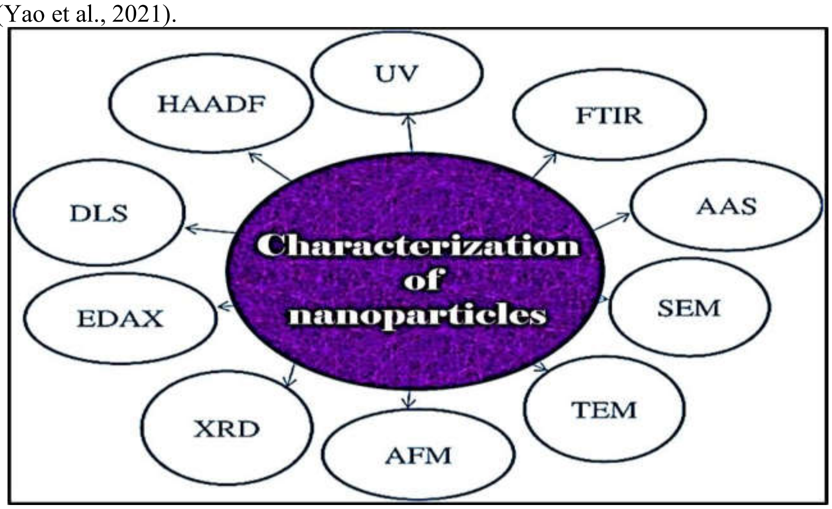

Fig. 4 Characterization of nanoparticles by different techniques

Applications in Environmental Detoxification

Detoxification of textile azo dyes in wastewater

Synthetic dyes find extensive application across various sectors, including paper, leather, oil, pharmaceutical, and food industries, serving as coloring agents. However, the complex and non-biodegradable nature of these dyes, particularly azo dyes, poses significant environmental risks. When these colored substances are directly released into aquatic ecosystems, they can have detrimental effects on the water quality and marine life. (Affat, 2021). Dyes are colored substances that can be natural, synthetic, and semi-synthetic. Natural dyes are nontoxic while synthetic and semisynthetic dyes cause problems (Gill et al., 2023). Different industries like textile, plastic, paper, paints, and plastic are the main sources of synthetic dye pollution. Such industries release dyes loaded water as wastewater. The textile industry uses more dyes than other industries. Among all types of dyes, azo dyes are most commonly used but they are complex and carcinogenic (Alzain et al., 2023).

A variety of methods are used for the decolorization of dye. But all such methods are not environmentally friendly and also, and they are not cost-effective. So, nanotechnology is cost cost-effective and environmentally friendly method for the decolorization of dyes and also for the treatment of wastewater (M. Roy & Saha, 2021). Many methods and techniques are used to treat dye-containing water pollution, but those methods and techniques have their advantages and disadvantages, but adsorption process has been established as superior to other techniques, in terms of expandability and cost. Various adsorbents are advocated for dye adsorption, including molecularly imprinted polymers (MIP), monometallic nanoparticles (NPs) and bimetallic NPs, fly ash, kaolinite, activated clay, hydrogels, metal oxide nanoparticles, activated carbon, altered alumina, and mesoporous zeolite (Nayak et al., 2024).

Table 3. Dye degradation by using nanoparticles

Dyes	Nanoparticles	Synthesis	Characterization	Concentrations	Removal (%)	Ref
Methyl orange	ZnONPS	Green synthesis	XRD, FE-TEM, and SEM	300 min, pH 7	98.1%	(Mohamed Isa et al., 2021)
Methylene blue	ZnONPs	commercial	XRD, XPERT-PRO, and SEM	0.2 g L^{-1} &pH 5.26	33.2%	(Naresh Yadav et al., 2021)
Methyl orange	Zinc-nitroprusside	precipitation method	XRD, SEM, and FTIR	pH 2, 0.5 g L−1 catalyst dose	80.7%	(Djebli et al., 2020)
Methyl orange	Zn-Fe(CN)5NO	Drop by drop method	SEM, and UV–vis	At pH 2, & 0.5 g L^{-1} dose.	80.2%	(Djebli et al., 2020)
Acid Black	ZnO/PUF	Hydrothermal method	SEM, EDX, and XRD	Neutral pH, and 40 mg l−1 dye	86.6%	(Inderyas et al., 2020)
Violet	TiO2/ZnO NP	TiO2	FTIR and XRD,	pH 3 in 60 min	93.2%	(Inderyas et al., 2020)
Eosin	TiO2	Sol-Gel Technique	XRD, FT-IR, and SEM,		72%	(Oliveira et al., 2020)
Malachite green	ZnONPs	Green synthesis	XRD, SEM-EDX, UV–Vis, and FT-IR	load, 20 ppm dye, and pH 9. under 1 h.	90.4%	(Devi et al., 2020)
Blue-KBF	ZnONPs	Green synthesis	XPS, HR-TEM, EDX, , XRD	1.0 g L−1 catalyst, in 159 min	91.2%	(Z. U. H. Khan et al., 2019)
Methyl orange	CuO and ZnO	co-precipitation	XRD, SEM and TEM, UV–vis	0.6 g at pH 6.8.	54.1%	(Jefri, 2017)

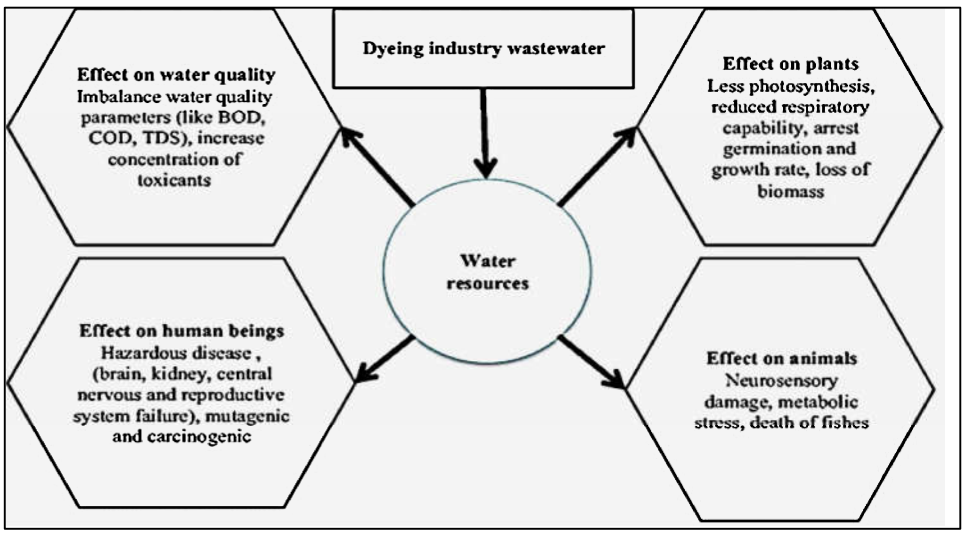

Fig. 5 Effects of dyes on the environment

The nanoparticles have emerged as photocatalysts for synthetic textile dye degradation present in textile wastewater and also show many eco-friendly properties like high efficiency of dye decolorization and lower toxicity (Hashmi et al., 2021). The light source is an important factor in the photocatalytic process. For photocatalytic activity, high surface-to-volume ratio nanoparticles have been preferred. However hollow cages and other structures with larger surface areas are also synthesized depending upon the applications (Ahmed et al., 2020).

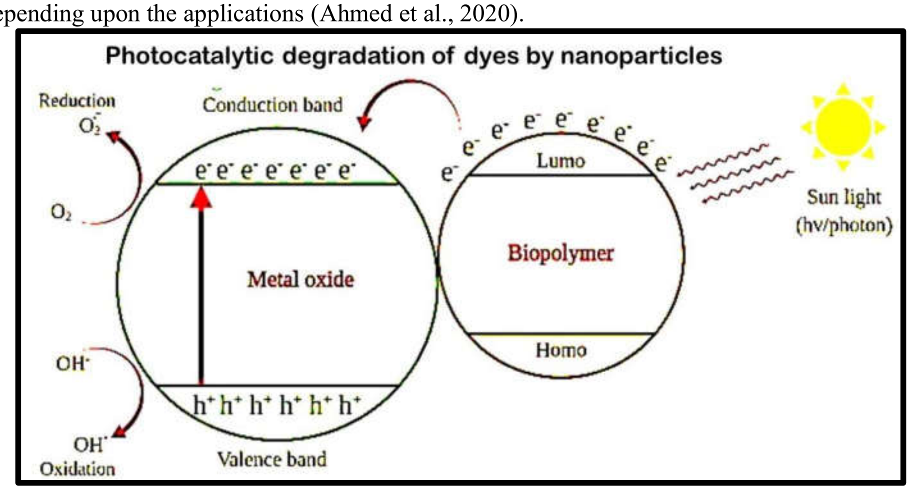

Fig. 6 Photocatalytic degradation of dye by nanoparticles in the presence of sunlight

Wastewater treatment

Due to catalytic properties copper nanoparticles are also used for the treatment of effluent from the textile industry as well as from other industries (Mahadevan et al., 2023). Dlamini et al. (2019) synthesized copper nanoparticles and applied them for the decolorization of dyes and also for the treatment of wastewater. They removed nutrients (such as nitrate, total nitrogen, and phosphate), metals, BOD, and COD from wastewater collected from coal mines, the Mzingazi River, and also from domestic wastewater. They demonstrated that biosynthesized copper nanoparticles had a remarkable ability to remove the P and S from the sample collected from wastewater. They suggested that copper nanoparticles could be an effective alternative to chemical flocculants. Their results showed that the removal efficiency from coal mine wastewater was about 85 % of phosphate, 76 % of sulfate, 96 % BOD, and 93 % of COD. From domestic wastewater, the removal efficiency was about 80 % for phosphate, 89 % for total nitrogen, 63 % for nitrate, 64 % for sulfate, 96 % for BOD, and 72 % for COD (Rajesh Banu et al., 2021). The removal efficiency from the Mzingazi River was about 92 % of phosphate, 52 % of total nitrogen, 89 % of BOD, and 92 % of COD. Similarly, Noman et al. (2020) also used copper nanoparticles for the treatment of wastewater. They reported that nontreated wastewater had large values of pH, hardness, EC, turbidity, TSS, chlorides, TDS, and sulfates. However, after treatment with copper nanoparticles, the values of the above-mentioned parameters were reduced significantly. For bettering wastewater and water purification, nanosize-based adsorbents like metal oxides, graphene, carbon nanotubes, and nanofibers are frequently utilized (Varjani et al., 2020). This is because compared to traditional adsorbents, these nanoparticles are thought to have a better adsorptive ability. The nanoscale metal oxides, like white-yellowish, crystalline zinc oxide dissolve in both acid and base. Its vigorous activity has piqued the curiosity of researchers. ZnO's polarity causes it to aggregate in water, which may cause deposition. It displays three extremely crystalline forms, including rock salt, wurtzite, and zinc blend (Saleh et al., 2020). These nanoparticles' exceptional adsorption capabilities in treating wastewater are a result of their unique characteristics (Yaqoob et al., 2023). Clay, activated carbon, silica, and metal oxides such as titanium oxide, zinc oxide, nickel oxide, iron oxide, tungsten oxide, copper oxide, and alumina are often used materials for wastewater cleanup. TiO2 and ZnO, along with other metal oxide nanoparticles, have caught the attention of researchers working on wastewater treatment techniques. Consequently, nanoparticles have significantly aided in the development of reliable and affordable water adsorption methods (Syahirah Kamarudin et al., 2019).

Table 4. Treatment of wastewater by using nanoparticles

Nanoparticles	Pollutants	Removal process	Time (min)	Removal %	Reference
Fe3O4	malachite green dye	Adsorption	34	97.3%	(Gautam & Tiwari, 2020)
Fe2O3	blue dye	Photocatalytic	60	98.2%	(Fatimah et al., 2020)
Fe3O4SiO	Emulsified oil	Transformation	05	98.7%	(Lü et al., 2020)
Fe3O4	Pharmaceutical	Adsorption	06	99.97%	(D'Cruz et al., 2020)
CT-Fe3O4 NPs	Organic dyes	Adsorption	120	99.2%	(Das et al., 2020)
Co2O3	E. faecalis	Disinfection	05	99.2%	(Abou et al., 2020)
Magnetic Janus	Cooking oil	Phase-separation	15	96.2%	(Khodadadi et al., 2020)
SiO2TiO2	Humic acid	Photocatalytic	30	98.2%	'Cruz et al., 2020)
magnetic	Bio-refinery	Adsorption	90	45.2%	Kumar et al. (2020)
MNP	Colour	Coagulation	07	85.2%	(Triques et al., 2020)
ZrO 2 MNPs	Methyl orange dye	Photocatalytic	100	96.3%	(Reddy et al., 2020)
MOM-Fe3O4	Pharmaceutical	Adsorption	720	95.8%	(Science, 2001)

Conclusion

the environment and human health are seriously threatened by the rising levels of pollutants in water and soil that are a result of fast industrialization and urbanization. Industrial wastewater containing hazardous materials exacerbates the issue. Because microbes are resistant to metals, studies have looked into how heavy metals affect biodiversity and the detoxifying function of microbiota. the environment and human health are seriously threatened by the rising levels of pollutants in water and soil that are a result of fast industrialization and urbanization. Industrial wastewater containing hazardous materials exacerbates the issue. Because microbes are resistant to metals, studies have looked into how heavy metals affect biodiversity and the detoxifying function of microbiota Nowadays, the scientific community throughout the world has been attracted to the nanoparticles and their modification to increase the efficiency of degrading azo dyes and wastewater because of their eco-friendly nature and cost-effectiveness. The nanoparticles also have the potential to treat the actual wastewater by color intensity, pH, EC, and TDS. Therefore, the current paper emphasized on photocatalytic application of Naturally occurring halloysite nanotubes and biosynthesized as chemically synthesized nanocomposite, in the decolorization of azo dyes on a commercial level. To ensure the long-term environmental health of nanoparticle use and address potential consequences, ongoing research is essential.

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