Review Article

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Use of magnetic nanoparticles for the removal of organic and inorganic pollution in wastewater treatment-a review

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Abstract: Magnetic nanoparticles (MNPs) have gained significant attention for their exceptional magnetic properties and nano-level impact, making them highly effective tools for detecting environmental pollutants. This paper provides a comprehensive overview of recent advancements in utilizing MNPs for identifying organic and inorganic contaminants in wastewater. Key aspects discussed include the intrinsic properties of MNPs, strategies for their modification, and production techniques. Emphasis is placed on their potential applications in water pollution detection, highlighting their ability to enhance contaminant concentration and separation efficiency compared to conventional methods. The findings suggest that MNP-based approaches not only improve detection sensitivity but also promote eco-friendly practices, contributing to sustainable environmental management.

Keywords: nanotechnology; surface modification; eco-friendly; wastewater treatment; organic and inorganic pollutants; magnetic nanoparticles

1 Introduction

Effluent that has been either improperly handled or left untreated has polluted the water supply, leading to a dramatic drop in water quality at surrounding sources.[1–3] Additionally, magnetic nanoparticles (NMs) have shown encouraging outcomes when used to purify wastewater. These materials are a huge improvement over older treatment methods because of all the cool things they can do. In addition to features like catalytic activities, great reactivity, great mobility, as well as high adsorption capabilities, some of these qualities include ones that are magnetic, electrical, as well as optical in nature.[4–7] Furthermore, nanotechnology is indeed the solution to several other problems linked with water purification as well as treatment, including economic difficulties and the ability of the materials utilized to be recycled.[2] A word cloud that illustrates the concept of magnetic nanometers provides a visual representation of the topic. The fact that these magnetic nanomaterials have indeed been utilized in the rehabilitation process for virtually every type of contaminant that could be found in water and wastewater is something that can be deduced from the terms.[2,8] Magnetic nanoparticles (MNPs) have played an increasingly important role in a variety of sectors over the last few years, including chemistry, biology, pollution sensors as well as detecting, medications, as well as treatments.[9] This same chronological progression in the ground of nanotechnology is represented in Figure 1, which also indicates that now the meaningful enhancements in the studies began in the year 2010, and indeed a steep rise was indicated in the year 2015 as well as onwards. This is evident from the fact that the findings have been advancing at a rapid rate since the year 2015.

As a result of the exceptional qualities that they possess, nanomaterials have garnered a lot of attention ever since they were discovered. Magnetic nanoparticles, via a range ranging from 0.1 to 100 nm, are referred to as MNPs.[2,10] These particles, due to the particular nanoscale features that they possess, have a major impact on the chemical processes that occur on the surface. Numerous appealing characteristics are possessed by microneedles, which are characterized by their extremely small particle size, enormous specific surface area, and efficient dispersion.[11] Moreover, the technique of copolymerization or surface alterations can be utilized to change MNPs. This is another alternative. One of the most

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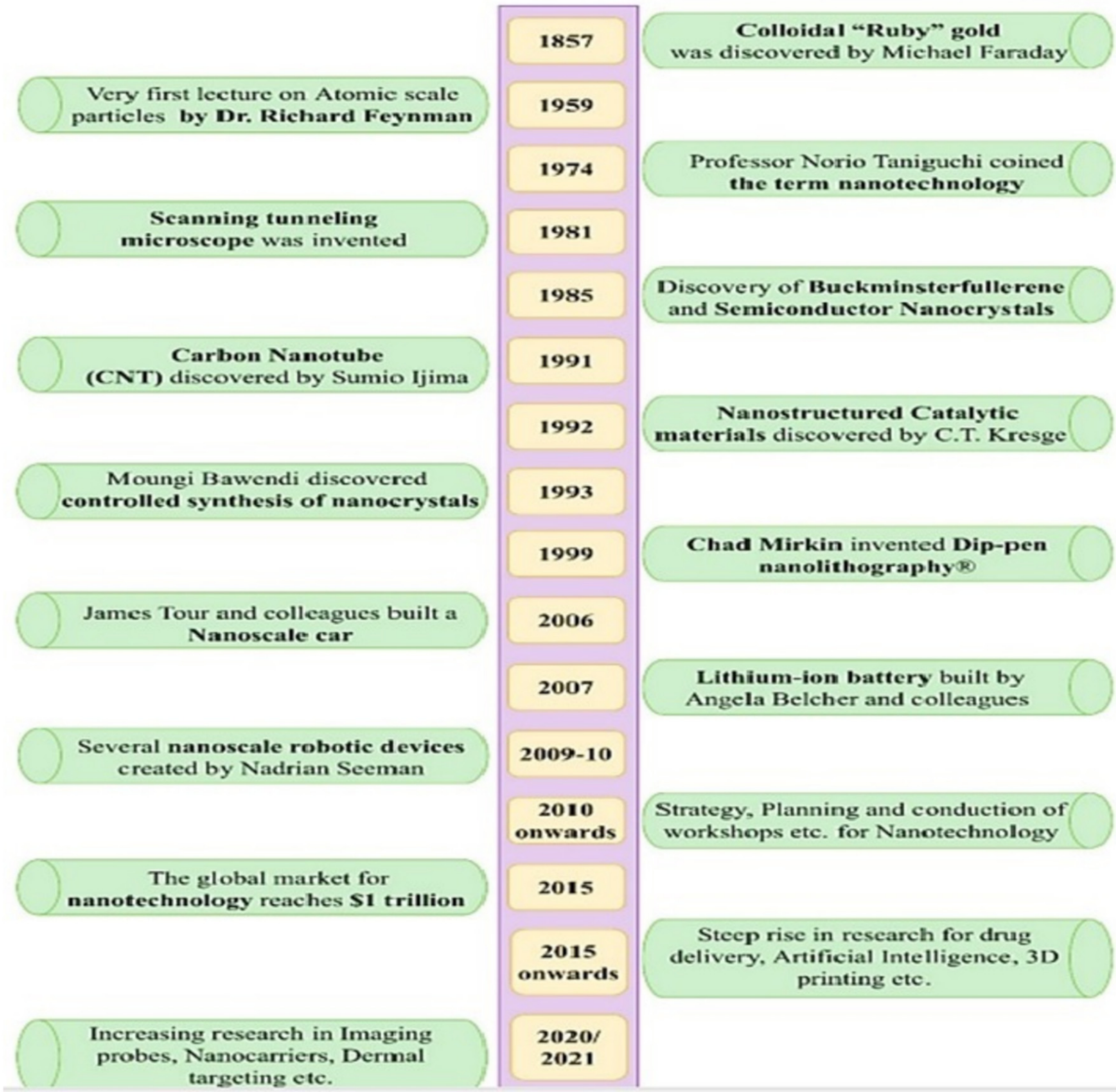

Figure 1: Progress made in the area of nanotechnology in chronological order to date international institute for Nanotechnology.[9]

significant areas of research that has been conducted throughout the past few years is the transformation or functionalization of objects through the utilization of nanomaterials for the purpose of identifying environmental pollutants.[12, 13] From the perspective of adsorption, MNPs are by far the nanoparticles that are utilized the most broadly. They are an intriguing chemical for application in systems that detect water contamination, particularly for the treatment of inorganic salts, heavy metals, and trace pollutants, due to their tendency to adsorb substances.[14] MNPs are superior to other types of pollutants in terms of detection since they possess these qualities. MNPs are characterized by extremely tiny particle sizes, which means that the size effect of these particles is insignificant. Because of their large particular surface area, MNPs enhance the activity of the medicine under evaluation by absorbing more of it. The high magnetic responsiveness makes it possible to separate MNPs effectively when subjected to an external magnetic field.[15] At the moment, the nano zero-valent iron is the most common type of MNP that is frequently employed (nZVI),[16] magnetite (Fe_3O_4),[17] as well as ferric oxide (γ-Fe_2O_3) nanoparticles.[18] While MNPs were introduced to a specimen, the material to be tested can be removed from the specimen by attracting as well as condensing under specific parameters, as well as then isolated as well as detectable by the activity of an external magnetic field.[19] The application of MNPs in the detecting of water as well as soil pollution has received a lot of interest.[20] The enhancement of pollutant enrichment through the modification of MNPs or the direct measurement of sample biological toxicity through the integration of

MNP features and a microbial composition biosensor has emerged as a prominent area of research at present.[20] Nanomaterials have gained significant attention due to their remarkable properties since their discovery. Among them, magnetic nanoparticles (MNPs), ranging in size from 0.1 to 100 nm, exhibit unique nanoscale features that significantly influence surface chemical processes. These particles stand out for their small size, large specific surface area, and efficient dispersion, which can be further enhanced through techniques such as copolymerization or surface modifications. Recent research has focused on leveraging MNPs for detecting environmental pollutants, particularly in water and soil, making them a preferred choice for adsorption-based applications. Their ability to adsorb substances, especially inorganic salts, heavy metals, and trace pollutants, makes MNPs highly effective in water contamination detection systems. Numerous papers have described techniques such as alteration, manufacturing, and others involving magnetic nanoparticles. On the applicability of magnetic nanoparticles to organic pollutants extracted from water specimens, nevertheless, detailed articles are still few. Various techniques for synthesizing MNPs with distinct characteristics are examined in this article. Concurrently, this article examines the methodologies of MNP alteration, the concepts and procedures governing their functional applications, as well as MNP application examples in waterborne environmental detection.

2 The process of producing magnetic nanoparticles

Considerable effort has been devoted to the advancement of innovative techniques for the synthesizing of MNPs. The physicochemical characteristics, stability, mobility, and efficacy of pollutant removal of MNPs can be significantly influenced by the level of precision employed during their manufacture as well as surface functionalization.[21] Overarchingly, the synthesizing of MNPs could be categorized into three fundamental approaches: (a) physical techniques, (b) chemical techniques, as well as (c) techniques involving microbes or biology.[22] The physical processes employ a top-down approach, by which the synthesizing commences with bulk material and progressively depletes it in order to produce NPs. In contrast, chemical as well as biological processes function from the bottom up, assembling atoms as well as molecules to produce NPs of varying sizes (Figure 2). Although other varieties of MNPs exist, the following are the most prevalent:1 Iron oxides, including γ-Fe_2O_3, Fe_3O_4; two metals as well as alloys of metal, including Ni, Fe, Co, cetera; three ferrates, including $MnFe_2O_4$, $MgFe_2O_4$, $CoFe_2O_4$, etc. Furthermore, numerous methods exist for preparing MNPs. One often employed technique for preparation is co-precipitation,[23] pyrolysis at high temperature,[24] microemulsion techniques,[25] and suspension polymerization techniques.[26] An overview is provided of the four frequently employed techniques for synthesizing MNPs. Although it is straightforward and efficient, the co-precipitation process could be utilized to produce the vast majority of MNPs, including ferritic (Co–Zn ferritic, Fe_2O_3, Fe_3O_4, etc.) as well as ferric oxide (Fe_3O_4, Fe_2O_3, and so on.).[27] Metal ions are precipitated from the metal salt solution using this technique, which involves adding an alkaline solution (e.g., sodium hydroxide, ammonia, or sodium) to the solutions. The subsequent description outlines the procedure for producing Fe_3O_4 magnetic particles via chemical co-precipitation. Fe_3O_4 magnetic molecules could be produced by combining a solution containing Fe^{2+} and Fe^{3+} with an alkaline solution precipitant of a specific pH, while being shielded by a gas. The resulting particles could then be separated using an external magnetic field. Commonly utilized due to the accessibility of materials as well as the ease of preparation, chemical co-precipitation is a straightforward process. One way to make magnetic nanoparticles is to use high-temperature pyrolysis, which involves breaking down non-aqueous solutions at high temperatures, using a process that involves burning organic metal molecules in a solvent with a high boiling point at high temperatures as well as pressure to create magnetic nanoparticles.[28] In this technique, metal complexes like iron pentacarbonyl, as well as ferric acetylacetonate, are typically utilized as precursors in order to manufacture metal nanoparticles during the process of high crack propagation. In the event that these metal nanoparticles undergo additional oxidation, it is possible to produce metal oxide nanoparticles. Tomar Dimpal as well as Bellaïd Sarah, together, utilizing this process, monodisperse ferric oxide nanoparticles, as well as $CoFe_2O_4$ nanoparticles, were generated, respectively. Each one of these examples possesses favorable morphological and dimensional properties.[29] Surfactants, oil (hydrocarbon), as well as water (water-soluble electrolyte solution) are the three components that make up a microemulsion, which is a system that is translucent, isotropic, as well as thermodynamically stable. It also has a low viscosity (occasionally alcohol as a co-surfactant).[25] water-in-oil (W/O) and oil-in-water (O/W). As the diameter of microemulsion particles is on the nanoscale, the droplets remain isolated from each other, confining the reaction to the microreactor droplets. When two microemulsions containing reactants are combined, collisions between micelle nanoparticles facilitate the transfer of materials within the water core. This process triggers

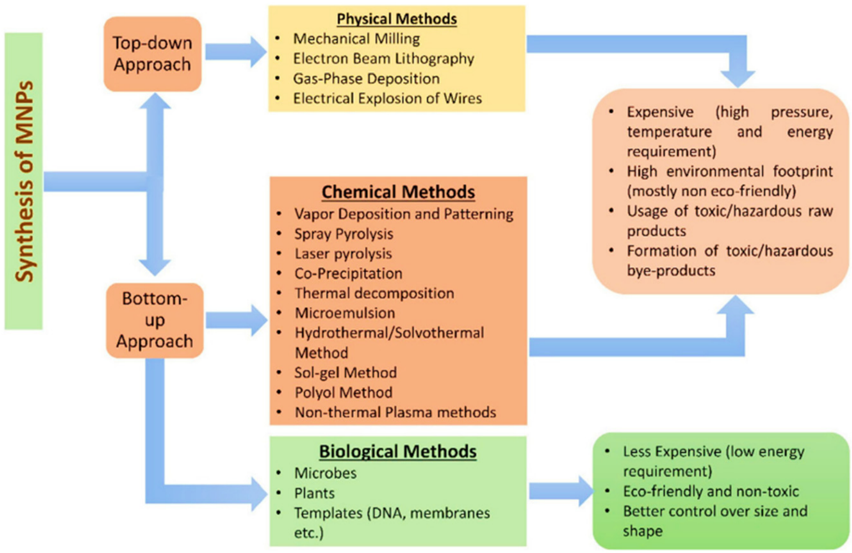

Figure 2: MNP manufacturing techniques and important characteristics.[22]

nuclear chemical reactions that lead to the formation of magnetic particles. Furthermore, the microemulsion method allows for precise control over product particle size and helps prevent the aggregation of magnetic nanoparticles (MNPs) during the manufacturing process.[30] Making $CoFe_2O_4$-based magnetic nanoparticles that work very well is one way that the microemulsion method can be used.[31, 32] We aimed to enhance the ability of these polypeptides for biomimetic mineralization by making them highly elastic and temperature-responsive. Constructing these frameworks allowed us to achieve our objective. The micron nanoparticles (MNPs) that are made have very small, uniform particles, strong crystallinity, high purity, and a unique crystal structure with clear chain formations. When applied to biological systems, these characteristics offer numerous advantages. However, the cost of producing nanocomposites of similar size through the biomineralization method is 18 times higher than that of the co-precipitation approach. Also, growing microorganisms like Magnetospirillum magneticum on a large scale is hard because they have high reproduction requirements, and the equipment needed for production is very expensive. Consequently, the biomineralization mechanism has limited manufacturing capacity due to these issues. Addressing these challenges is crucial for overcoming the technical barriers related to the biomimetic mineralization approach. As illustrated in Table 1, each of the four methods for manufacturing magnetic nanoparticles presents distinct advantages and disadvantages. The co-precipitation technique is well-suited for large-scale production because its preparation process is relatively straightforward. However, the MNPs that are made tend to stick together, have a wide range of particle sizes, and are not biocompatible, so the surfaces need to be changed before they can be used. The pyrolysis and microemulsion methods are both good for making MNPs that are uniform in size, but they produce small amounts of product and cost a lot. The medical field commonly utilizes MNPs produced via the

Table 1: Compare the benefits and drawbacks of MNP manufacturing techniques.

Preparation method	Advantage	Defect	References
Co-precipitation	Short procedure, straightforward reaction conditions, and high product pure	Products that are washed, filtered, and dried are prone to agglomeration.	34
High-temperature pyrolysis	Significant crystallinity, variable particle sizes, as well as narrow particle size distributions	The compound has a hydrophobic component, is insoluble in water, as well as has poor bioavailability.	35
Microemulsion	Large distribution, consistent shape, as well as high dispersion	The yield is minimal, and the preparation method requires a large amount of solvent.	36
Biomimetic mineralization	Excellent biocompatibility as well as bioactivity, excellent stability under physiological settings, as well as protection of the environment and the ecosystem's greenness	Inadequate yield, difficult preparation circumstances, and complicated technology	37

biomimetic mineralization approach due to their high levels of biocompatibility and bioactivity, as well as their environmentally friendly manufacturing process. Furthermore, integrating materials with microbes to develop sensors is an emerging research direction.[33]

3 Modification and functionalization of MNPs

Both the specific surface energy and dipole contact of magnetic nanoparticles (MNPs) are quite high, leading to a tendency for them to clump together and lose their magnetism. However, by modifying MNPs, it is possible to maintain a consistent level of stability in the colloidal system and inhibit the aggregation of nanoparticles. Due to their biocompatibility, water solubility, biological interactions, and cell non-specificity, MNPs have the potential for various applications, including fixed load, biomolecule binding, and biosensing.[38] The majority of modifications and functionalization methods for magnetic nanoparticles can be categorized into the following groups.

3.1 Organic metal-based structures functionalize magnetic nanoparticles

This organic superstructure, also called porous conjugated polymers, is a porous crystal substance that is commonly utilized. Chemical species or metal clusters, in addition to the coordination of organic molecules, are the constituents that make up this substance.[39,40] Therefore, a magnetic organic metal skeleton composite could be produced by combining the advantages of an organic metal frame with magnetic nanoparticles, which would result in a material that has a wider range of applications that could be utilized. Magnetic nanoparticles functionalized with metal-organic frameworks (MOFs) are commonly used to detect organic pollutants in water. a metal-organic structure material called cobalt 2-methylimidazole was organized as the forerunner. Magnetic Co/C particles were prepared through high-temperature pyrolysis, as well as these nanocomposites were then utilized for the identification of the presence of organic dyes in water, like as Congo red. After constructing a one-of-a-kind coil-shell titanium fund organic skeleton surface modification magnetic microsphere Fe_3O_4@Cys@MIL125-NH_2, Lian Lili as well as colleagues using it as a magnetic adsorbent to enrich five fluoroquinolones in water specimens. This magnetic adsorbent has the potential to distinguish fluoroquinolones in both tap water as well as environmental water specimens.[41]

3.2 Ionic liquid functionalized magnetic nanomaterials

The majority of the time, ionic liquids are composed of organic cations as well as either organic or inorganic positive ions. Molten salts that really are liquids at normal temperatures are referred to as ionic liquids. Because of their non-volatile qualities, low melting point, as well as high solubility, ionic liquids find widespread application in the domains of extraction as well as separation. The capabilities of ionic fluids to be used in solid-phase extraction could be improved by combining them via magnetic nanoparticles that depend on phase estrangement as extractant carriers. This will result in the formation of functional magnetic nanoparticles of ionic fluids, which can then be used for the evaluation of trace materials in biological, environmental, as well as food complex specimens. Coating hydrophobic carboxyl functionalized ionic liquid (IL-COOH) in the able to prepare Fe_3O_4@Zr-MOFs, synthesized a novel water-stable IL-COOH/Fe_3O_4@ZRMOF nanocomposite for the very first time, as well as utilized it in the localized adsorbent as well as sensing of fluoroquinolone antibiotics. both of these accomplishments were accomplished.[42] Magnetic solid-state extraction was conducted on specimens by Ping Wenhui and colleagues using ionic liquid-loaded cyclodextrin magnetic nanoparticles, which were synthesized at room temperature. These nanomaterials can be employed to examine the extraction of organic contaminants in water.[43]

3.3 Magnetic nanomaterials functionalized with molecularly imprinted polymers

Molecularly imprinted polymer, also known as MIP, is characterized by the presence of holes that have a certain spatial structure. Several benefits of this type of polymer include its simplicity in creation, its stability, and its potential for reuse. We developed magnetic molecularly imprinted nanoparticles (MMIP NPs) on this premise. These particles are indeed a type of substance that could be selectively enhanced as well as isolated by an external magnetic field.[44] Superparamagnetic Fe_3O_4 nanostructures were effectively prepared by using a silica shell as the carrier and a water-soluble functional monomer, 4-[(4-methacryloyloxy)phenylazo] benzenesulfonic acid, along with sulfadiazine as the template. This approach allowed for the successful creation of a dual-response molecularly imprinted polymer that responds to both photon and magnetic enhancement.[45]

4 Recent applications of magnetic nanoparticles (MNPs) in wastewater treatment

The features of MNPs, which include facile separating, good stability, as well as quick surface encapsulation, have led to their widespread application on a wide range of applications.[46] In the field of environmental detection, the most common applications of MNPs have included the enrichment of compounds that contribute to environmental contamination or the combination of MNPs with bacteria to produce biosensors that can detect environmental properties. MNPs are currently being utilized in water analysis on a regular basis.[47]

4.1 Utilization of MNPs for the elimination of organic pollutants

Wastewater is a significant contributor to pollution due to its wide variety of organic contaminants, including dyes, insecticides, personal care products, phenols, and similar substances. These pollutants negatively impact the health of both people and aquatic life. Moreover, they pose a serious threat to human health. Standard methods for breaking down these contaminants include acidic degradation, heat treatment, and biological therapy. Therefore, selecting the appropriate approach to wastewater treatment is crucial.[48, 49] Hydrogen peroxide was used to aid in the breakdown of organic contaminants using a novel oxidative precipitation-combined educators' synthesis. Both the stability and effectiveness of the generated Fe-MNPs were demonstrated to be exceptional.[50] Scientists uncovered the MNPs' magnetically recoverable nature, great level of recyclability, and outstanding catalytic activity. Multiple contaminants in wastewater have been removed by MNPs coated with poly (ethylenimine, or PEI). Chemical co-precipitation was used to produce PEI-iron oxide MNPs, which were then stabilized with trisodium citrate. Within 60 minutes, MNPs can remove half of the entire organic material (TOC) from 0.5 L wastewater. Further, microbial content decreased by 90 %, total nitrogen by 24 %, color by 86 %, and turbidity by 89 %.When PEI-MNPs were added to the treatment process, they reduced processing, intricacy, sludge production, and chemical requirements. An alternative study proved the viability of a practical as well as eco-friendly method for synthesizing copper-doped Fe_3O_4 MNPs (Fe_3–$xCuxO_4$). These MNPs have the capacity to induce H_2O_2.[51] The findings indicated that the breakdown of H_2O_2 on Cu-doped MNPs occurred at a velocity that was significantly faster than that of undoped MNPs. An environment applicability of the improved activation capability of hydrogen peroxide was detailed through the removal of rhodamine B (RhB) from textile effluent. More than 97 % of the target population was successfully eliminated. Dye is indeed a persistent organic substance that could persist in the environment for extremely long durations of time, which could have an effect on the process of photosynthesis. As previously mentioned, investigating methods for removing colored wastewater is an important area of study. A study found that by combining kaolinite with nanoscale zero-valent iron (K-nZVI), it is feasible to remove over 97 % of crystal violet.[52] The researchers discovered that by analyzing various adsorption and reduction kinetics, isotherms, and thermodynamic properties, they could achieve an elimination efficiency of over 99.9 percent in treating wastewater with K-nZVI MNPs. Additionally, they found that a straightforward method for producing betaine-modified magnetic iron oxide nanoparticles (BMNPs) was effective in degrading methylene blue (MB) dye.[53] The magnetic nanoparticles (BMNPs) had remarkable super-magnetic characteristics, which indicated a higher degree of recyclability (about 73 % up to five cycles). At room temp, the maximum adsorption of MB dye was determined to be 136 mg/g, and the data on adsorption were found to be in close agreement with Langmuir adsorption isotherm theory. The goal of this investigation was to determine if Fe_3O_4 MNPs produced by the co-precipitation approach using glutaraldehyde could effectively remove reactive red azo dyes, direct green azo dyes, or a combination of the two. The MNPs showed no signs of degradation even after 90 days, and they maintained their peak performance even after 100 recycling cycles. The red and green azo dyes were entirely extracted from the textile effluent samples shortly after 4 h, and therefore by 6 h, the blending of the two colors had vanished. The writers publicly released this data. In a separate investigation, silicon-coated Fe_3O_4 nanoparticles were grafted with poly (ionic liquid) (PIL) using the polymerization process. As a result, a selective adsorbent that is both economical and efficient was developed.[54] In order to evaluate the efficacy of the created MNPs as a removal agent, a variety of colors were put through their paces.[55] As revealed by the results, which discovered that 93 percent of the convictions were attained, it was demonstrated that the adsorption of MG dye was caused by a spontaneous and endothermic process. Magnesium nanoparticles demonstrated superparamagnetic characteristics even after being maintained in the method that was considered to be adequate. In designed to be easy to synthesise, having a high specific surface region, and being environmentally benign, they were also quite lightweight. The need for pharmaceutical as well as personal care products, or PPCPs, has skyrocketed alongside the advancement of science as well as technologies. The byproducts of these products, especially the pharmaceutically active compounds (PhACs) comprised of hormones, antibiotics, and other such molecules. Due to their detrimental impacts on human and environmental health, has recently emerged as a major worry for professionals in the field. A new adsorbent for wastewater elimination was developed by an inquiry that combined two-dimensional graphene oxide (GO) and graphite carbon nitride (g-C_3N_4) with the help of Fe_3O_4 nanoparticles.[56,57] The study publications that have been provided are summarized in Table 2 as of the year 2020. The use of MNPs in wastewater treatment has the potential to produce extremely effective pollutant removal. If one were to analyze the various removal techniques, one could conclude that magnetic nanosorption is the best approach for cleaning up wastewater. One more efficient way to eliminate hazardous pollutants is the photocatalytic degradation that employs MNPs.

4.2 Utilization of MNPs for the elimination of inorganic pollutants

Because heavy metals have harmful impacts on human health, it is crucial to determine and pre-concentrate them at detectable levels from an aquatic environment. Cu(II) is a well-known inorganic contaminant that is present in water from mining, smelting, battery production, home plumbing systems, and pipe corrosion.[72] As a result of Cu(II)'s ability to infiltrate both surface and ground water systems, environmental researchers are increasingly concerned about water contamination. Cu(II) can endanger human health and can potentially find its way into drinking water. Cu(II) is known to be a necessary micronutrient at low concentrations, but at excessive concentrations, it may become hazardous.[73] A thorough evaluation of Cu(II) toxicity at high concentrations has revealed that it is exceedingly dangerous. Heavy metals, arsenic, nitrates, and phosphates are among the most prevalent inorganic pollutants that are detected in wastewater.[74] A novel chrysin-functionalized silica core–shell magnetic nanoparticle (FeO_4@SiO_2–N–chrysin) that is intended to collect copper ions from water samples. This nanoparticle combines effective adsorption capabilities with

Table 2: Remediation of various types of organic pollutants from wastewater by MNPs and their removal mechanism.

Name of MNP	Contaminant removed	Removal mechanism	Contact time	Removal efficiency	Reference
Humicacid functionalized Fe_3O_4	Carcinogenic malachite green dye	Adsorption	35 min	97 %	58
Combination of Fe_3O_4 and Fe_2O_3	Bromophenol blue dye	Photocatalytic degradation	60 min	98 %	59
Silica coated ferro-ferric oxide (Fe_3O_4@SiO_2)	Emulsified oil	Transformation	05 min	98 %	60
Magnetic activated carbon-Fe_3O_4 AC-Fe_3O_4)	Pharmaceutical substance	Adsorption	06 min	99.97 %	61
JC-Fe_3O_4 and CT-Fe_3O_4 NPs	Organic dyes	Adsorption	120 min	99 %	62
Nano porous Co_2O_3/Cu_2O_3: Al_2O_3:SiO_2	*E. faecalis*	Disinfection	05 min	100 %	63
Magnetic Janus nanoparticles (M-Janus NPs)	Cooking oil and crude oil	Phase-separation	15 min	96 %	64
$FeNi_3$@SiO_2@TiO_2	Humic acid (HA)	Photocatalytic degradation	30 min	100 %	65
Chitosan-coated magnetic nanoparticles (cMNPs),	Bio-refinery wastewater containing phenol	Adsorption	90 min	46.20 %	66
Moringa extract modified MNP	Color	Coagulation	07 min	89 %	67
MOM-Fe_3O_4	Pharmaceutical substance	Adsorption	720 min	93.90 %	68
NovelMNP-alum conjugate	Adsorption cum enhanced coagulation – flocculation	Natural organic matter	30 min	98.70 %	69
MCPEI (polyethyleneimine andmagnetic nanoparticle)	Black 5 dye	Adsorption	180 min	100 %	70
Magneticsilica-based nanoadsorbents	Pharmaceutical substance	Adsorption	200 min	80 %	71

magnetic solid-phase extraction (MSPE) to provide a novel approach to water purification. With a recovery rate of almost 98 % under ideal circumstances, the study illustrates the remarkable removal efficiency of Cu(II) ions through the synthesis, characterization, and optimization of this adsorbent. The technique offers intriguing uses for environmental water treatment and heavy metal ion recovery since it is inexpensive, extremely sensitive, and readily recyclable.[75] To improve MNPs' selectivity and adsorption ability for particular contaminants, their surface can be coated with additional materials or altered with functional groups. For instance, the capacity of Fe_3O_4 nanoparticles to adsorb heavy metals such as lead (Pb), cadmium (Cd), and chromium (Cr^{6+}) has been the subject of much research. Furthermore, MNPs can be readily extracted from treated water with the use of an external magnetic field, negating the necessity for filtration steps that are frequently involved in traditional treatment techniques.[76] In industrial wastewater, heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr^{6+}), and mercury (Hg^{2+}) are common inorganic contaminants. These metals can bioaccumulate in living organisms and lead to significant health issues, even at low concentrations. Iron oxide-based nanoparticles, particularly Fe_3O_4, are effective for removing heavy metals from aqueous solutions.[77] For instance, magnetite (Fe_3O_4) nanoparticles exhibit impressive adsorption capabilities for lead (Pb) and cadmium (Cd) through surface adsorption and ion exchange mechanisms. The adsorption process is influenced by several factors, including pH, contact time, and the initial concentration of the metal ions. One study found that Fe_3O_4 nanoparticles were able to remove 95–99 % of lead within 60 min.[78] Using iron oxide magnetic nanoparticles (MNPs) also achieved cadmium ion removal efficiencies between 80 % and 96 %. These high removal rates demonstrate the potential of MNPs for treating wastewater contaminated with heavy metals. Reports indicate that Fe-MNPs can remove 90–95 % of arsenic (As) within 60 min of contact time.[79] The strong interaction between arsenic species and the hydroxyl groups on the surface of iron oxide nanoparticles is responsible for the high affinity of these particles for arsenic. Arsenic's concentration in the water is lowered as a result of this interaction, which makes it easier for the metal to adsorb onto the surface of the nanoparticle. Inorganic nutrients like phosphates (PO_4^{3-}) and nitrates (NO_3^-) cause water bodies to become eutrophic, which lowers oxygen levels and causes toxic algal blooms. MNPs' high adsorption capacity and adjustable surface characteristics have drawn attention to their use in the removal of phosphate and nitrate from wastewater. It has been demonstrated that iron-doped MNPs and magnetic biochar are efficient at removing phosphates and nitrates from wastewater. In a single research, magnetic biochar removed 75–90 % of the nitrate in 60–90 min of contact time.[80] Similarly, it has been reported that iron-doped MNPs can use ion exchange and surface adsorption to remove up to 95 % of phosphate from aqueous solutions.[81] These findings demonstrate how MNPs may be used to treat wastewater nutrient contamination. Table 3 provides a summary of the study articles that have been supplied over the years.

5 Conclusions

The application of magnetic nanoparticles (MNPs) in wastewater treatment has gained significant attention, with numerous studies highlighting their effectiveness in removing or degrading a wide range of organic and inorganic pollutants. Comparative analyses reveal that MNPs not only achieve rapid and efficient pollutant clearance – exceeding 95 % within minutes – but also outperform other types of nanoparticles in removal effectiveness. Techniques such as photocatalytic degradation, adsorption, and redox transformations have proven to be successful and stable strategies for pollutant elimination. Notably, some MNPs

Table 3: Overview of MNPs used to remove different inorganic contaminants from wastewater, including efficiency, contact time, and removal process.

Pollutant type	MNP material	Removal mechanism	Contact time (min)	Removal efficiency (%)	References
Copper (Cu^{2+})	Chrysin-functionalized Fe_3O_4	Adsorption, ion exchange	30	98	[75]
Chromium (Cr^{6+})	Mn-doped Fe_3O_4 nanoparticles	Reduction and adsorption	30–180	70–98	[82]
Lead (Pb)	Fe_3O_4 nanoparticles	Surface adsorption, ion exchange	60	95–99	[83]
Cadmium (Cd)	Iron oxide MNPs	Adsorption, co-precipitation	30–90	80–96	[84]
Arsenic (As)	Fe_3O_4 nanoparticles	Adsorption, surface complexation	60	90–95	[85]
Nitrate (NO_3^-)	Magnetic biochar	Adsorption, reduction	60–90	75–90	[86]
Phosphate (PO_4^{3-})	Iron-doped Fe_3O_4	Surface adsorption, ion exchange	45–90	85–95	[87]
Zinc (Zn^{2+})	Coated Fe_3O_4	Adsorption, surface complexation	45	85–90	[88]
Mercury (Hg^{2+})	Thiol-functionalized Fe_3O_4	Adsorption, coordination bonding	120	90–98	[89]

exhibit exceptional magnetic saturation values exceeding 70 emu/g, contributing to their ease of separation, reusability, and stability, with removal efficiencies remaining above 95 % even after multiple recycling cycles. Despite these promising results, challenges remain that warrant further investigation. For instance, the scalability of MNP synthesis methods, especially those involving chemical synthesis, must be addressed to ensure their viability for large-scale industrial applications. Additionally, the environmental impact of MNP production and disposal requires comprehensive evaluation to mitigate potential risks associated with their widespread use. Future research should also focus on optimizing cost-effectiveness while exploring eco-friendly and sustainable synthesis routes. Moreover, the long-term economic and toxicological implications of MNP deployment in wastewater treatment systems need to be systematically examined to enable their safe and effective integration into global wastewater management strategies.

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