

Review Article

Recent Developments on Magnetically Separable Ferrite-Based Nanomaterials for Removal of Environmental Pollutants

Shreyas Pansambal^(b),¹ Arpita Roy^(b),² Hamza Elsayed Ahmed Mohamed,^{3,4} Rajeshwari Oza^(b),⁵ Canh Minh Vu^(b),⁶ Abdolrazagh Marzban^(b),⁷ Ankush Chauhan^(b),⁸ Suresh Ghotekar^(b),⁹ and H. C. Ananda Murthy^(b)^{10,11}

¹Department of Chemistry, Shri Saibaba College, Savitribai Phule Pune University, Shirdi, 423109 Maharashtra, India ²Department of Biotechnology, School of Engineering & Technology, Sharda University, Greater Noida, India

³UNESCO UNISA Africa Chair in Nanosciences and Nanotechnology, College of Graduate Studies,

University of South Africa, South Africa

⁴Nanosciences African Network (NANOAFNET), Material Research Department, IThemba LABS, Cape, South Africa

⁵Department of Chemistry, S.N. Arts, D.J.M. Commerce and B.N.S. Science College, Savitribai Phule Pune University, Sangamner, 422605 Maharashtra, India

⁶Advanced Institute of Science and Technology, The University of Da Nang, Da Nang 550000, Vietnam

⁷Razi Herbal Medicines Research Center, Lorestan University of Medical Sciences, Khorramabad, Iran

⁸Chettinad Hospital and Research Institute, Chettinad Academy of Research and Education, Chengalpattu District, Kelambakkam, 603103 Tamil Nadu, India

⁹Department of Chemistry, Smt. Devkiba Mohansinhji Chauhan College of Commerce and Science, University of Mumbai, Silvassa, 396 230 Dadra and Nagar Haveli (UT), India

¹⁰Department of Applied Chemistry, School of Applied Natural Sciences, Adama Science and Technology University, P.O. Box 1888, Adama, Ethiopia

¹¹Department of Prosthodontics, Saveetha Dental College & Hospital, Saveetha Institute of Medical and Technical Science (SIMATS), Saveetha University, Chennai, 600 077 Tamil Nadu, India

Correspondence should be addressed to Suresh Ghotekar; ghotekarsuresh7@gmail.com and H. C. Ananda Murthy; anandkps350@gmail.com

Received 15 July 2022; Revised 4 September 2022; Accepted 8 September 2022; Published 26 September 2022

Academic Editor: Pounsamy Maharaja

Copyright © 2022 Shreyas Pansambal et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The current water supply situation demonstrates the predominance of contamination caused by industrial effluent runoff. Polluted waters have contributed to significant health and environmental risks, calling for an acceptable alternative to address the effects. However, diverse chemical and treatment physical stages commonly used for dye effluent processing are more cost-intensive, less effective, and time-consuming. Instead, nanomaterials have developed as a good alternative for dye removal and degradation because of their special chemical reactivity and superior surface features/properties. In this regard, the ability of modified or hybrid ferrite-based magnetically recoverable nanomaterials in dye effluent treatment has been extensively explored. The present study especially emphasizes magnetic ferrite (Fe₃O₄ + X) or metal-doped ferrite (MFe₂O₄ + X) nanocomposite for dye degradation (where M consists of Co, Cu, Zn, Mg, Mn, Ni, etc., and X consists of reduced graphene oxide, graphene oxide, metal, or metal oxide). Several dye degradation efficiencies of various ferrite and metal ferrite nanomaterial were discussed. Degradation is carried out using direct sunlight, and various lamps (e.g., visible light/UV-C lamp/halogen lamp/Mercury-Xenon lamp/UV lamp with UV filter for visible light) are used as a source. This review article covers the degradation of various dyes from wastewater using ferrite-based nanomaterial as an efficient catalyst and making water pollution free.

1. Introduction

The first commercially effective synthetic dye was explored in 1856, and till now, numerous dyes have been synthesized [1]. The reseals of synthetic dyes in natural water sources increase pollution, causing severe harm to humans [2]. According to Jin et al., textiles discharged 280,000 tons of industrial effluents worldwide [3]. The effluent encompasses a wide range of pollutants, including organic and inorganic salts, surfactants, heavy metals, enzymes, oxidizing, and reducing agents [2, 4]. The human being swallows such contaminated water persuades respiratory tract, gastrointestinal tract irritation, and skin and eye irritation. Furthermore, the reports also prove the developmental, chronical, and neurotoxicity effects of dyes on human beings [5]. A huge volume of freshwater is essential to carry out the daily process in the textile industry. Scrutiny of the literature reveals that for the treatment of 1 kg of textile materials, about 100 L of water is essential [2]. Therefore, to avoid such environmental degradation due to synthetic dyes, the degradation of dyes is essential.

Diverse techniques are used for the effluent treatment [6–8], which are listed in Figure 1. Traditional techniques for the dye degradation used are adsorption utilizing activated carbon, reverse osmosis, ion exchange employing resins, etc. However, the technique mentioned earlier can only transform the phase creating secondary pollution, which needs additional treatment to regenerate the adsorbent [9]. Traditional technologies for the treatment of west water were unsuccessful by Forgacs et al. [10]. Furthermore, the report also states that these techniques are insufficient to degrade/treat certain azo dyes selected for the study. Recently, the advanced oxidation process (AOPs) has been used mostly to treat polluted water. Reactive oxygen species (ROS) produced using AOPs quickly oxidize dyes in the industrial effluent and make the water pollution free [11].

Magnetic nanomaterials are of massive enthusiasm for scientists from a vast variety of domains, including catalysis [12–14], magnetic fluids [15], biomedicine [16], data storage [17], magnetic resonance imaging [18, 19], biosensors [20], and environmental remediation [21-25]. While several effective approaches for the fabrication of selective magnetic nanomaterials of diverse compositions have been developed, the efficient uses of certain magnetic nanomaterials in the fields mentioned above are strongly reliant on the stability of the nanomaterials under a variety of situations. The nanomaterial works perfectly in most planned applications when the size of the nanomaterials is around a particular value, which relies on the nanomaterial. Then, when the temperature is beyond the so-called blocking temperature, each nanomaterial becomes a unified magnetic field and exhibits superparamagnetic conduct. These nanomaterials have a broad stable magnetic moment and operate as a large paramagnetic atom with a quick reaction with negligible coercivity and remanence to applied magnetic fields. These features render superparamagnetic nanomaterials very appealing for such a large scope of bioengineering uses since the possibility of agglomerations at room temperature is negligible [26].

Various strategies have been created, including adsorption, biological, electrochemical, ion exchange, membrane

processes, and solvent extraction techniques. These methods have a variety of disadvantages, including as high operating costs, pollution transfer from one phase to another, and the challenge of eliminating biologically or chemically persistent contaminants. Advanced oxidation processes (AOPs) are the most effective way to remove pollutants from water because they can produce powerful oxidizing agents at ambient temperature and normal atmospheric pressure [27-30]. Heterogeneous photocatalysis has proven to be a more successful method for addressing energy and environmental concerns as an oxidation mechanism. Heterogeneous photocatalysts can remove persistent nonbiodegradable organic pollutants by supplying strong oxidizing agents and converting them into mineral salts, H₂O, and CO₂. Intriguing materials for CO₂ photoreduction, microbial disinfection, N₂ photofixation, and organic compound synthesis are also heterogeneous photocatalysts. An ideal heterogeneous photocatalyst will have a high quantum efficiency, be physiologically and chemically inert, have a considerable capacity to absorb solar energy, be nontoxic, be resistant to photocorrosion, and be inexpensive. Despite heterogeneous photocatalysts' potential for addressing energy and environmental problems, removing and recycling these parts from the reaction solution is difficult. Centrifugation and filtration techniques are used to separate used photocatalysts from systems that have been treated. Meanwhile, these methods are time- and money-consuming, restricting the widespread application of heterogeneous photocatalysts [31-33]. The fixation of heterogeneous photocatalysts has addressed this issue with an inert substrate. Despite the fact that this method lessens particle aggregation and makes it simpler to separate heterogeneous photocatalysts, photocatalytic performance is anticipated to suffer as a result of the decreased photocatalyst active sites. In order to separate and recover heterogeneous photocatalysts on a large scale, this problem is solved by combining photocatalysts with magnetic materials. Magnetic materials are more desirable in photocatalytic applications because they may show considerable photocatalytic activity and separability [34, 35].

Thus, this perspective review article intends to present reports on photocatalytic degradation of various dyes using ferrite-based nanocomposites.

2. Hazards of Dyes to Environment and Human Health

In addition to having adverse effects, the dye materials are often aesthetically undesirable in water. Several structure varieties are used in the textile industry, such as basic, acidic, disperse, reactive, azo, anthraquinone-based, diazo, and metal complex dyes [36]. Having more or less destructive consequences, it puts up. Increased heart rate, shock, vomiting, cyanosis, Heinz body formation, quadriplegia, human tissue necrosis, and jaundice are associated with extreme exposure to dyes [37]. Dyes such as metanil yellow seem to have a tumor-producing effect [38] and can generate human body enzyme disorders [39]. However, it is nonmutagenic, but it can change gene expression sequences [40]. It produces harmful methaemoglobinaemia [41] and cyanosis



FIGURE 1: Classification of methods of effluent treatments.

[42] in humans when taken orally, while skin interaction leads to allergic dermatitis [43]. Testicular lesions are caused by intratesticular and intraperitoneal administration or oral feeding of dyes in animals due to damage to seminiferous tubules and reduced spermatogenesis level [44, 45].

3. Magnetic Behavior of Ferrite-Based Magnetized Nanomaterials

The properties of magnetic nanomaterials are determined by the extrinsic magnetic field induced to materials. Descriptions of magnetic polarity in a nanomaterial help classify various types of magnetism found in nature. It is possible to define 5 main types of magnetism: antiferromagnetism, diamagnetism, ferrimagnetism, ferromagnetism, and paramagnetism [46]. Diamagnetism is a primary property of all atoms, and magnetization is quite low and opposite to the direction of the induced magnetic field. Lots of nanomaterials show paramagnetism property, whereas the orbit is raised from zero, a magnetization grows parallel to the induced magnetic field, but the magnetization efficiency is weak. Also, ferromagnetism is the property of such objects that are naturally magnetically arranged and which, even without using a field, develop spontaneous magnetization. Ferrimagnetism, where distinct atoms have various moment abilities, is different from ferromagnetism, but there is always an organized state under a specific critical temperature at that state. The magnetic substance, i.e., diamagnet, paramagnet, and ferromagnet, can be sorted according to its susceptibility. Many of the unique magnetic characteristics of nanomaterials are due to their strong surface-tovolume ratio [47, 48]. Saturation magnetism (Ms) changes through size before it reaches a threshold size above which magnetization is stable and near the bulk's value. In diverse disciplines, the linear dependency of Ms on size underneath this threshold was seen. Research on the shape effect affects magnetic nanocomposites' volume or associated size parameter properties. For spherical nanoparticles, the anisotropy value (magnetic anisotropy is the directional dependence of a material's magnetic properties) is greater than for cubic nanoparticles of a similar volume [49–52]. Composition is perhaps the most widely cited factor accountable for assessing a material's particular magnetic properties. These magnetic properties occur in the absence or presence of unpaired valence electrons deposited on metal ions or metal atoms present in magnetic nanomaterials [53, 54]. Magnetic behaviour is characterized by the direction of the magnetic moment (μ) connected with the electrons. We can measure the magnetic moment in magnetic nanomaterial [45, 55, 56] using the magnetic moment of only one electron, 1.73 Bohr magnetons (BM).

4. Diverse Approaches for the Fabrication of Magnetically Ferrite-Based Nanomaterials

There are multifarious approaches employed for the practical synthesis of using ferrite-based nanocomposite [57, 58], for instance, hydrothermal, sol-gel, sonochemical, solvothermal, precipitation, coprecipitation, solution combustion, probe sonication method, green synthesis, ultrasonication, and microwave-assisted methods [59–63]. Particle size distribution, crystal structure, particle size and shape control, and alignment are the crucial factors in the manufacturing of ferrite-based nanocomposite. Such approaches help produce magnetic ferrite-based composites, which are selectively stable at normal room temperature, regular shape, uniform size, nonaggregate, high monodispersity, etc. These methods are further categorised into three different approaches, physical, chemical, and biological, as shown in Figure 2.

The aforementioned synthetic approaches require comparatively higher experimental duration and high pressure and energy and involve noxious compounds or solvents, and stability depends on capping agents. However, nanomaterial synthesized via these methods shows higher photocatalytic degradation efficiency.

5. General Procedure for the Dye Degradation

Magnetic metal Fe_2O_4 /doped metal Fe_2O_4 composite is taken as a catalyst for the dye degradation of different dye (Figure 3) solution (any one among the following: MB, MO, MG, CV, CR, EY, RR 198, RR120, IC, DY, RB. etc.); dye under magnetic stirring/ultrasound irradiation/microwave irradiation with or without the addition of H_2O_2 in the presence of visible light/UV-C lamp/halogen lamp/Mercury-Xenon lamp/UV lamp with UV filter for visible light is used as the source (Table 1). At the start of the reaction, the catalyst is added to the dye solution and stirred the solution in the absence of light for 30 mins to attain the absorption equilibrium. Then, after 30 mins, the dye solution is exposed to the source. Then, the absorbances are measured, and from the reading, calculate the efficiency of the catalyst and the



FIGURE 2: Diverse approaches for the efficient fabrication of ferrite-based nanomaterial.



FIGURE 3: Various dye and their chemical structure.

time required for the dye degradation. Figure 4 represents the graphical representation of the dye degradation using magnetic ferrite NPs.

6. Dye Degradation Using Ferrite-Based Nanomaterials

Diverse dyes exist, which can be synthesized chemically in industry and occur in nature. The dyes we studied in this article are shown in Figure 3 with their name and structure for better understanding.

Farhadi et al. reported the ultrasound-assisted photocatalytic degradation of methylene blue (MB) dye (25 mg/L) within 70 min using CoFe₂O₄@ZnS composite and H₂O₂ (4 mM). The composite shows excellent reusability up to five cycles with significant property changes [59]. Siadatnasab et al. stated that the dye degradation efficiency of CuS/CoFe₂O₄ nanohybrid towards methylene blue (MB) dye (25 mg/L) and rhodamine B (RhB) dye (25 mg/L) along with H₂O₂ was accomplished within 30 minutes with 100% and 72% efficiency, respectively, via sonocatalytic process. However, the reusability study shows 5% drop in the catalytical activity after the 4th cycle [60]. Kalam et al. specified that photocatalytic degradation of methylene blue (MB) dye (1 mg/L) with H₂O₂ in visible light CoFe₂O₄ sample MST-2 shows 80% degradation of MB dye within 140 min than

TABLE 1: Various dye degradation using ferrite and metal-doped ferrite nanoparticles with some additives.

Name of the catalyst	Synthetic method	Size (nm)	Shape	Light source	Degradation %	Time (min)	Additive	Dye degraded	Ref.
CoFe ₂ O ₄ @ZnS	Hydrothermal	18	Spheres	Ultrasonic bath power of 100 W and frequency of 37 kHz	100	70	H_2O_2	Methylene blue dye	[59]
CuS/CoFe ₂ O ₄	Hydrothermal	17	Spherelike	Ultrasonic bath power of 100 W and frequency of 37 kHz	100	30	$\rm H_2O_2$	Methylene blue dye	[09]
CuS/CoFe ₂ O ₄	Hydrothermal	17	Spherelike	Ultrasonic bath power of 100 W and frequency of 37kHz	72	30	$\rm H_2O_2$	Rhodamine B (RhB)	[09]
CoFe ₂ O ₄ (MST-2)	Solvothermal	15	Spherical	Visible light	80	140	$\rm H_2O_2$	Methylene blue dye	[61]
${ m Ag_3PO_4} ext{-}{ m CoFe_2O_4}$	Precipitation	<30	Spherical	Tungsten halogen lamp with 500 W	100	60		Methyl orange (MO)	[62]
${ m Ag_3PO_4} ext{-CoFe}_2{ m O}_4$	Precipitation	<30	Spherical	Tungsten halogen lamp with 500 W	100	60	I	Rhodamine B (RhB)	[62]
${ m Co}_{0.25}{ m Zn}_{0.75}{ m Fe}_2{ m O}_4@{ m SiO}_2/{ m ZnO}$	Coprecipitation	10.6	Spherical	UV irradiation	100	120	I	Red amaranth dye	[63]
Cu Fe ₂ O ₄ /RGO	Solution combustion synthesis	I	Plate like	Two100 W Xenon lamps with an UV cut- off filter $(\lambda = 420 \text{ nm})$	92	180	I	Methylene blue (MB)	[64]
Cu Fe ₂ O ₄ @GO	I	Ι	I	I	93.3	30	PMS	Methylene blue (MB)	[65]
Cu Fe ₂ O ₄ /GO	Hydrothermal	30-40	I	Visible light by 450 W Xe arc lamp	I	I	H_2O_2	Rhodamine B (RhB) Acid orange II (AO7)	[99]
$Cu Fe_2O_4$	Coprecipitation	25.4		Ι	91.3	60	H_2O_2	Reactive red 2 (RR)	[67]
Cu Fe ₂ O ₄ -Fe ₂ O ₃	Pechini method	I	I	Solar radiation	100	180	$\rm H_2O_2$	Methylene blue (MB)	[68]
Fe_3O_4 -C-cu	Green synthesis	25	Spherical	I	100	$\stackrel{<}{\sim}$	NaBH_4	Methyl orange (MO)	[69]
Fe ₃ O ₄ -C-cu	Green synthesis	25	Spherical	I	100	3.20	NaBH_4	4-Nitrophenol	[69]
Fe ₃ O ₄ -C-cu	Green synthesis	25	Spherical	Ι	100	2.40	NaBH_4	2,4- Dinitrophenylhydrazine	[69]
Ag-Fe ₃ O ₄ /graphene	I	I	Spherical	Two 40 W UV-C lamps	94.78	120	H_2O_2	Methyl orange (MO)	[20]
Ag-Fe ₃ O ₄ /graphene	I		Spherical	Two 40 W UV-C lamps	66	120	H_2O_2	Methylene blue (MB)	[20]
Ag-Fe ₃ O ₄ /graphene	I		Spherical	Two 40 W UV-C lamps	81	120	$\mathrm{H_2O_2}$	Crystal violet (CV)	[20]
Ag-Fe ₃ O ₄ /graphene	I		Spherical	Two 40 W UV-C lamps	89	120	H_2O_2	Malachite green (MG)	[20]
Ag-Fe ₃ O ₄ /graphene			Spherical	Two 40 W UV-C lamps	75	120	H_2O_2	Congo red (CR)	[20]
Ag-Fe ₃ O ₄ /graphene	I		Spherical	Two 40 W UV-C lamps	70	120	H_2O_2	Eosin Y (EY)	[20]
S- Fe_3O_4	Hydrothermal	10-20	Spherical	I	100	30	$\mathrm{H_2O_2}$	Rhodamine B (RhB)	[71]
$(RGO)/Fe_3O_4$	Green synthesis	18	Spherical	I	95.18	12	NaBH_4	Methylene blue dye	[72]
${ m Ag_3PO4@MgFe_2O_4}$	Sol-gel	15-20	Irregular	300 W Xenon short arc lamps	98	30	H_2O_2	Rhodamine B (RhB)	[73]
$MgFe_2O_4$	Solid-state reaction	12.31	Spherical	Sunlight	100	$\stackrel{\scriptstyle \wedge}{_1}$	$\mathrm{H_2O_2}$	Malachite green (MG)	[74]
$MgFe_2O_4$	Autocombustion	7-16	Irregular	I		I	I	Methylene blue (MB)	[75]
MgFe ₂ O ₄ /TiO ₂	Sol-gel	20-30	I	500 W Xenon lamp				Rhodamine B (RhB)	[26]
$\mathrm{Ni}_{0.2}\mathrm{Cu}_{\mathrm{x}}\mathrm{Mn}_{0.2}\mathrm{Fe}_{2}\mathrm{O}_{4}$	Probe sonication	19	Irregular	UV light	98.1	120	1	Methylene blue (MB)	[77]

Journal of Nanomaterials

Name of the catalyst	Synthetic method	Size (nm)	Shape	Light source	Degradation %	Time (min)	Additive	Dye degraded	Ref.
$\mathrm{Ni}_{0.2}\mathrm{Cu}_{\mathrm{x}}\mathrm{Mn}_{0.2}\mathrm{Fe}_{2}\mathrm{O}_{4}$	Probe sonication	23	Irregular	UV light	43.3	120	I	Drimarene yellow (DY)	[77]
$MnFe_2O_4$	Ι	I	Ι	UV–C lamp (200–280 nm, 9 W, Philips)	>90	06	H_2O_2	Reactive red 120 (RR120)	[78]
$MnFe_2O_4$	I		Ι	UV–C lamp (200–280 nm, 9 W, Philips)	06<	60	H_2O_2	Reactive red 198 (RR198)	[78]
MnFe ₂ O ₄ /TA/ZnO	Hydrothermal		Spherical	Visible light	84.2	90		Congo red (CR)	[20]
MnFe ₂ O ₄ /rGO	Coprecipitation	I	Spherical	UV irradiation	97	60	Ι	Methylene blue (MB)	[80]
$MnFe_2O_4$	Solvothermal	90- 100	Spherical	Sunlight	98	180	H_2O_2	Methyl orange (MO)	[81]
$NiFe_2O_4$	Chemical precipitation	Ι	Ι	Microwave irradiation	97	5	I	Brilliant green (BG)	[82]
NiFe ₂ O ₄ /T/GOx	Solvothermal	I	Cluster	UV	98.6	06	I	Indigo carmine (IC)	[83]
NiFe ₂ O ₄ @TiO ₂	Sol-gel	18.85	Spherical	UV lamp 300 W Xenon lamp	90.06	06	I	Methyl orange (MO)	[84]
BCN/NiFe2O4	Sol-gel	100	Sheet-like	Mercury-Xenon lamp (350 W)	98	80	I	Methylene blue (MB)	[85]
$NiFe_2O_4$	Sonochemical	9-17	Cube-like	UV light 400 W hg lamp	89.4	<80	Ι	Methylene blue (MB)	[98]
$NiFe_2O_4$	Sonochemical	9-17	Cube-like	UV light 400 W hg lamp	43	120	I	Drimarene yellow (DY)	[86]
ZnO/CF/NG	Hydrothermal	I	Ι	10 W LED lamp	98	140	I	Malachite green (MG)	[87]
ZnO/ZF/NG	Hydrothermal	I	Ι	10 W LED lamp	92	140	Ι	Malachite green (MG)	[87]
ZnO/CF/NG	Hydrothermal	I	Ι	10 W LED lamp	66	140	I	Methyl orange (MO)	[87]
ZnO/ZF/NG	Hydrothermal	I	Ι	10 W LED lamp	94	140	Ι	Methyl orange (MO)	[87]
$ZnFe,O_4$	I	I	I	UV-C lamp 200–280 nm 9 W	I	I	Н,О,	Reactive red 198 (RR198)	[88]
- 1				4			1	keactive red 120 (RR120)	
$ZnFe_2O_4@ZnO$	Microwave	17	Ι	Visible light 125 W hg lamp	100	540	I	Methyl orange (MO)	[68]
MIL-101(Cr)/RGO/ ZnFe,O ₄	Hydrothermal	24	Spherelike	Ultrasonic frequency of 37 kHz	95	50	H_2O_2	Methylene blue (MB)	[06]
MIL-101(Cr)/RGO/ ZnFe ₂ O ₄	Hydrothermal	24	Spherelike	Ultrasonic frequency of 37 kHz	100	5	$\rm H_2O_2$	Congo red (CR)	[06]
MIL-101(Cr)/RGO/ ZnFe ₂ O ₄	Hydrothermal	24	Spherelike	Ultrasonic frequency of 37 kHz	94	50	H_2O_2	Rhodamine B (RhB)	[06]
$\mathrm{ZnFe_2O_4}$	Combustion reaction	I	Spherical	Ι	I	I	I	Rhodamine B (RhB)	[91]
$\rm Ni_{0.4}Zn_{0.6}Fe_{1.8}Al_{0.1}Gd_{0.1}O_4$	Sol-gel			I	96	180	I	Reactive blue (RB-21)	[92]
$MnCe_{0.3}Fe_{1.7}O_4$	Microwave combustion	22-26	Sphere- shaped	Visible light (Xenon lamp 300 W; $\lambda > 400$ nm)	91.53	120		Methylene blue (MB)	[93]
CuO/HAP/ferrite	Precipitation	<25		Visible irradiation	>90	60	Ι	Rhodamine B (RhB)	[94]

TABLE 1: Continued.

Ref.	[95]	[96]	[67]	[86]	[66]	[100]	[101]
Dye degraded	Indigo carmine (IC)	Methylene blue (MB)	Congo red (CR)	Methyl orange (MO)	Methylene blue (MB)	Synozol blue CA	Malachite green (MG)
Additive	I	H_2O_2			Fenton's agent	$\mathrm{H_2O_2}$	H_2O_2
Time (min)	120	8	150	160	180	15	35
Degradation %	<55	71.6	84	93.46	96	98	95
Light source	Hg lamp at 365 nm a UV-A lamp (15 W)	50 W tungsten halogenated lamp	I	I	Ι	I	Visible light
Shape	Spherelike	Spherical	Spherical	Spherical	Cubical and irregular	Spherical	Ι
Size (nm)	13	8-38	20-60		19-32	3-47	40-50
Synthetic method	Sol-gel	Solid-state	Sol-gel	Coprecipitation	Coprecipitation	Coprecipitation	Solid state
Name of the catalyst	$CoFe_2O_4/SnO_2$	MnFe ₂ O ₄ /B. cla	$Co_{0.4}Mg_{0.4}Cu_{0.2}Fe_{1.9}Cr_{0.1}O_4$	CoFe ₂ O ₄ -SiO ₂ -TiO ₂	$Ca_{0.2}Cu_{0.8}Fe_2O_4$	$\mathrm{Mn}_{0.6}\mathrm{Zn}_{0.4}\mathrm{Fe}_{2}\mathrm{O}_{4}$	NiFe ₂ O ₄

TABLE 1: Continued.



FIGURE 4: Dye degradation using magnetic ferrite and metal-doped ferrite nanocatalyst.

the MST-3 and MST-1 [61]. Gan et al. quantified the photocatalytic performance of Ag_3PO_4 -CoFe₂O₄ nanocomposite in a tungsten halogen lamp with light 500 W output power towards methylene blue (MB) dye (10 mg/L) and rhodamine B (RhB) dye (10 mg/L) which completely degraded within 30 min. Increasing the dye concentration to 40 mg/L was degraded completely within 60 min. Ag_3PO_4 -CoFe₂O₄ (7.5%) shows high degradation capacity that Ag_3PO_4 -CoFe₂O₄ (10%) sample [62]. López et al. reported that the multifunctional Co_{0.25}Zn_{0.75}Fe₂O₄@SiO₂ with and without ZnO coated nanomaterial was used for the dye degradation of red amaranth dye (25 mg/L). The Co_{0.25}Zn_{0.75}Fe₂O₄@SiO₂/ZnO degrades red amaranth dye by about 90% after 90 min under UV irradiation [63].

Moreover, Astaraki et al. specified the synthesis of CuFe₂O₄/RGO nanocomposite for dye degradation of methylene blue (MB) (15 mg/L) with a light source as two 100 W Xenon lamps with a UV cut-off filter. The catalyst shows a 3% decrease in catalytic activity after the 4th cycle [64]. Lei et al. show the synthesis and catalytic activity of $CuFe_2O_4@GO$ hybrid for methylene blue (MB) dye degradation. The 200 mg/L catalysts and PMS dosage of 0.8 mmol/L are sufficient for 93.3% photocatalytic degradation of methylene blue (MB) dye (20 mg/L) in 30 min. Furthermore, an increase in the catalyst amount to 400 mg/L does not show a boost in the catalytic degradation rate of MB dye. In contrast, the rise in the PMS dosage to 1 mmol/L shows a small decline in MB degradation rate [65]. Chen et al. demonstrated the hydrothermal synthesis of magnetic CuFe₂O₄/ GO and their dye degradation potential towards acid orange II (AO7) and rhodamine B (RhB) without H_2O_2 in the presence visible light. The photocatalytic application of $CuFe_2O_4/$ GO (800 mg/L) for acid orange II (AO7) dye (0.05 mM) degradation at pH = 7 shows 77% efficiency [66]. Yu et al. testified dye degradation C.I. Reactive red 2 (RR) (100 mg/L), with 10 mg of the nanoscale-confined precursor of CuFe2O4

and 4 mL of H₂O₂, displays 91.3% degradation in 60 min. Furthermore, the efficiency of the CuFe₂O₄ enhances to 94.3% by calcination at higher temperatures [67]. da Nóbrega Silva et al. revealed that the visible-light-driven photocatalytic performance of CuFe2O4-Fe2O3 (1g/L) nanocatalyst for the methylene blue (MB) dye (50 mg/L) degradation in the presence of H_2O_2 (300 Mg/L) at neutral pH shows 64% efficiency with 0.6-FC-2. Furthermore, the recyclability study of the catalyst shows a 2.33% decrease in April and a 10.15% increase in May in the second cycle [68]. Kalantari et al. disclosed catalytic activity of Fe_3O_4 -C-Cu nanocatalyst (30 mg) and aqua solution of methyl orange (MO) $(3.0 \times 10^{-5} \text{ M},$ 25 mL) with aqueous NaBH₄ (5.3×10^{-3} M, 25 mL), and MO degradation takes place within 50 seconds. Moreover, there is no significant loss in the catalytical activity after 4th cycle [69].

In addition, Saleh and Taufik explained the ultravioletlight-assisted degradation of the MO and MB (20 mg/L). Ag-Fe3O4/graphene (0.4 gm) composites act as a catalyst with 4 mL 30% H₂O₂. Furthermore, Ag-Fe3O4/graphene composite (25 wt% Ag-Fe3O4/graphene and 10 wt% of graphene) shows efficient catalyst reusability [70]. Tang et al. exhibited that sulfidation-modified Fe₃O₄ nanoparticle (S- Fe_3O_4NP) (50 mg/L) catalyst for the photocatalytic degradation of rhodamine B (10 mg/L) in the presence of H₂O₂ (13 mg/L) shows 99% degradation within 10 min. Recyclability study shows the catalyst 84.3% efficiency for rhodamine B dye after 3rd cycle [71]. Vinothkannan et al. showed that the synthesis of RGO/Fe₃O₄ nanocomposites (10 mg) for methylene blue (MB) $(9.37 \times 10^{-5} \text{ M})$ dye degradation with the addition of using 5.8×10^{-2} M of NaBH₄ under ultrasonicated shows 95.18% efficiency within 12 min. Moreover, the catalyst displays 89.4% efficiency after the 7th cycle [72]. Zhou et al. synthesised Ag₃PO₄@MgF_e2O₄ composites for the dye degradation of rhodamine B using visible irradiation. The dye degradation experiment of aqueous RhB

(10 mg/L) was performed in the presence of 300 W Xenon short-arc lamps with a UV filter (\geq 400 nm), and the amount of Ag3PO4@MgFe2O4 (10%) catalyst (20 mg/100 mL) degrades 98% of dye in 20 min [73]. Das and Dhar publicized the photocatalytic degradation of malachite green (MG) by using MgFe₂O₄ nanocatalyst in the presence of H₂O₂. The 40 mg of catalyst in 70 mL of MG (10 mg/L) and 0.1 mL 10% H₂O₂ in absence of light gives 100% degradation in 50 seconds [74].

Cabrera et al. manufacture nanostructured MgFe₂O₄ ferrites and check their methylene blue dye degradation efficiency. In 35 min, 60 and 75% of methylene blue (MB) dye degraded under light and dark conditions, respectively [75]. Zhang et al. testified the fabrication of MgFe₂O₄/TiO₂ and checked the degradation efficiency of rhodamine B (RB) dye in the presence of UV and visible light 500 W Xenon lamps as a source. The 2 wt% MgFe₂O₄/TiO₂ catalyst shows 100% efficiency in 40 min using UV light whereas 3 wt% MgFe₂O₄/TiO₂ catalysts evince excellent efficiency in visible light [76]. Amulya et al. manufacture Cu-doped NiMnFe₂O₄ (60 mg) nanoparticles using the probe sonication method and study their photocatalytic dye degradation activity under UV light towards Drimarene yellow (DY) and methylene blue (MB) dyes. The degradation efficiency of DY is 43.3% when dopant 0.1, whereas MB is 98.1% when 0.4 is dopant [77]. Mahmoodi reported the synthesis of MnFe₂O₄ and dye degradation ability for reactive red 120 (RR120) and reactive red 198 (RR198), concentration (100 mg/L), in the presence of H₂O₂ (1.2 mM) [78]. Boutra et al. described the synthesis of MnFe₂O₄/TA/ZnO nanocomposites and studied their dye degradation performance for the Congo red (CR) using visible light radiations. Congo red (CR) (16 mg/L) dye degraded using 50 mg of the catalyst shows 84.2% efficiency in 90 min. Reusability study confirmations and degradation efficiency at the end of 5th cycle were 77.5% [79]. Mandal et al. investigated the methylene blue dye (MB) (10 mg/L) degradation utilizing MnFe₂O₄/rGO. The catalyst (0.03 g) shows 97% efficiency in 60 min in the presence of a UV lamp of 40 W [80]. Sahoo et al. described the synthesis of mesoporous silica encapsulated with magnetic MnFe₂O₄ nanoparticles for the dye degradation study. The methyl orange (MO) dye (0.6 mg mL/L) is degraded utilizing mesoporous silica encapsulated $MnFe_2O_4$ (20 mg) along with 2 mL H₂O₂, resulting in 98% degradation in the presence of sunlight in 180 min. Furthermore, the catalyst shows a negligible change in the efficiency after 5th cycle [81]. Zhang et al. showed NiFe2O4 powders as a nanocatalyst for the photocatalytic degradation of brilliant green (BG) dye (20 mg mL/L) under microwave irradiation (output power 500 W) for 2 min to degrade 97% dye [82]. Atacan et al. explained the decolorization of indigo carmine (IC) dye (10 mg/L) using NiFe₂O₄/T/GOx in 90 min. Decolorize 98.6% and 37.6% under a UV lamp and Fenton process, respectively [83]. Baig et al. explained that the synthesis of NiFe₂O₄@TiO₂ for dye degradation of methyl orange (MO) dye using a UV lamp (300 W Xenon) with a cut-off filter shows 90.06% activity. Furthermore, increasing the percentage of TiO₂ from 10% to 40% in the catalyst NiFe2O4 increases the photocatalytic activity from 72% to 90.06%, respectively [84].

Furthermore, Kamal et al. stated that boron-doped C₃N₄/NiFe₂O₄ nanocomposite was fabricated and investigated their use for methylene blue (MB) dye degradation. The catalyst BCN/NiFe2O4 (100 mg) is mixed with methylene blue (MB) dye (5 ppm) in a Mercury-Xenon lamp (350 W) as a source of visible light and shows 98% degradation efficiency in 80 min. However, the reusability study shows a 1.69% decrease in the catalyst after 3rd cycle [85]. Amulya et al. reported the sonochemical fabrication of NiFe₂O₄ nanocatalyst and studied their dye degradation activity for the Drimarene yellow (DY) and methylene blue (MB) dyes. The 60 mg NiFe₂O₄ is added to MB and DY dyes separately; each with 20 ppm concentration and irradiated with a 400 W Hg lamp shows 89.4% for MB and 43.3% for DY degradation. In addition, the catalyst shows a 10% decrease in efficiency after 5th consecutive cycle [86]. Chandel et al. elucidate the fabrication of ZnO/ZnFe₂O₄/NG and ZnO/CoFe₂O₄/NG nanocatalyst for the efficient degradation of malachite green (MG) and methyl orange (MO) dyes in the presence of halogen lamp. The ZnO/ZnFe₂O₄/NG shows 92% and 98%, and with ZnO/CoFe₂O₄/NG shows 98% and 99% for MG and MO dyes, respectively. A recyclability study shows an insignificant change in the catalytic activity after the 10th cycle [87]. Mahmoodi explained the synthesis of $ZnFe_2O_4$ and dye degradation capacity for reactive red 120 (RR120) and reactive red 198 (RR198) concentrations (100 mg/L) and the amount of nanocatalyst (0.20 g) and H_2O_2 (1.2 mM) at 25°C in the presence of UV-C lamp (200-280 nm, 9 W, Philips) [88]. Kulkarni et al. enlighten that the synthesis of core-shell ZnFe₂O₄@ZnO nanocatalyst for degradation of methyl orange (MO) dye in visible light using 125 W Hg lamp 100% degradation takes place in 9 h. Reusability study shows a 5% decrease in the efficiency after 2nd reuse [89]. Nirumand et al. convey that the synthesis of MIL-101(Cr)/RGO/ZnFe₂O₄ nanocatalyst (0.5 g/L) for the degradation of rhodamine B (RB) (25 mg/L) dye using ultrasound irradiation in the appearance of H₂O₂ is 95% in 50 min. The methylene blue (MB) and Congo red (CR) dyes degraded 100% and 95%, and the time required were 2 min and 50 min, respectively, under similar conditions. The catalyst study shows excellent recyclability after the 4th cycle [90]. Oliveira et al. explain the fabrication of $ZnFe_2O_4$ and examine the dye degradation performance using visible light degradation of rhodamine B (RB) and malachite green (MG) dye degradation using visible irradiation of 3 lamps from Taschibra[®] full spiral of 25 W as source [91].

7. Mechanistic Study of Dye Degradation Using Ferrite-Based Nanomaterials

The mechanistic study, which shows how the magnetic ferrite is responsible for the dye degradation and the graphical representation, was discussed in this section.

Nirumand et al. [90] reported the sonocatalytic dye degradation, which involves a sonoluminescence phenomenon capable of generating a relatively wide wavelength range that is used to excite the electron in both $ZnFe_2O_4$ and MIL-101(Cr), leading to the formation of holes. The transfer of an electron from CB of $ZnFe_2O_4$ to CB of MIL-101(Cr)



FIGURE 5: (a) A plausible mechanism for sonocatalytic degradation of dyes over MIL- $101(Cr)/RGO/ZnFe_2O_4$ nanocomposite using ultrasound irradiation. (b) Schematic representation of mechanism takes place during dye degradation (reproduce from [81]).



FIGURE 6: (a) A proposed mechanism for degradation of dyes using Cu-doped NiMnFe₂O₄ nano-photocatalyst under UV light. (b) Schematic representation of mechanism takes place during dye degradation (reproduce from [68]).

and the holes from VB of MIL-101(Cr) to VB of $ZnFe_2O_4$ and how it is utilized for the degradation is shown in Figure 5(a) graphically, and Figure 5(b) shows how the step-wise reaction takes place in the dye degradation.

Amulya et al. [77] specified the catalytic role of Cudoped NiMnFe₂O₄ in dye degradation. The catalyst is subjected to light irradiation that excites the electron in CB, which leads to holes in the VB. Furthermore, the created holes react with water to generate OH[•] radicals which disintegrate dye molecules, and super oxide is generated using oxygen and excited electron in CB. The detailed reaction progress and schematic representation of dye degradation are shown in Figures 6(a) and 6(b), respectively.

Furthermore, Chandel et al. [87] elucidated how the $ZnO/CoFe_2O_4/NG$ and $ZnO/ZnFe_2O_4/NG$ magnetic nanocomposites degrade dye solution. When exposed to a visible-light source, the catalyst creates electrons and holes in CB and VB, respectively. The redox scale shows strong interfacial contact, and the positioning of CB facilitates the movement of an electron from CB of ZF to ZnO and avoids the hole-electron recombination by forming heterojunctiontype II. The detailed schematic representations of dye degradation using $ZnO/ZnFe_2O_4/NG$ and $ZnO/CoFe_2O_4/NG$ catalyst are shown in Figures 7(a) and 7(b), respectively.

Similarly, various reports on catalytic dye degradation using ferrites and metal ferrites are tabulated in Table 1.

8. Future Scope

This article compiled and reviewed the degradation of different dyes using ferrite-based nanomaterials. According to the literature, dye degradation using ferrite-based nanomaterials is supposed to have improved efficiency. However, the distinction between both the magnetic and ferrite-based composites is just a guideline. From this reconsideration, we also like to point out that it is necessary to choose a minimum manufacturing cost with strong dye degradation performance and also a multipurpose catalyst viable for various types of contaminants because the selection of the catalyst is an important event in the decision to introduce



FIGURE 7: (a, b) Schematic representation of dye degradation using $ZnO/ZnFe_2O_4/NG$ and $ZnO/CoFe_2O_4/NG$ catalysts, respectively (reproduce from [78]).

a suitable large-scale magnetic catalyst. This article shows that the ferrite-based nanomaterial used for dye degradation contains a simple preparation method and cheap chemical reagents. However, by analyzing the efficacy of magnetic nanocomposite regeneration, economic viability should be improved, as regeneration studies can assess the reusability of magnetic nanocomposites. On the other hand, a lot of new, powerful software is built to resolve mathematical models and complex data that are supposed to be represented more adequately and help understand the mechanism's insight. In addition, the use of energy-dispersive X-ray spectroscopy (EDX), scanning electron microscope (SEM), Fourier transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC), electron spin resonance (ESR), scanning tunneling microscopy (STM), dynamic light scattering (DLS), X-ray diffraction (XRD) analysis, X-ray photoelectron spectroscopy (XPS), Brunauer-Emmett-Teller (BET), superconducting quantum interference device (SQUID), vibrating sample magnetometer (VSM), magnetic force microscopy (MFM), atomic force microscopy (AFM), X-ray absorption spectroscopy (XAS), zeta potential, and thermogravimetric analysis (TGA) is strongly recommended for characterization assessments.

Moreover, from an environmental point of view, developing a safer and more effective approach to dye degradation is necessary. Keeping this in mind, the study was carried out to find magnetic nanoparticles for dye degradation.

9. Conclusion

The article highlights the implications of the successful production of nanomaterials based on magnetic ferrite and its applications for the treatment of dye effluents. Special note should be made of the important mechanisms of action of magnetic nanomaterials in the treatment of dye effluents, like photocatalytic degradation and adsorption, concerning just the mitigation of dyes typically used throughout the textile sector. The use of renewable or environmentally friendly reductants to fabricate ferrite-based nanomaterials has been shown to demonstrate the effective elimination of different dyes from wastewater. However, with recent research data, the possibility of ferrite-based nanomaterials discharged into the ecosystem and their exposure to terrestrial and marine biological systems at trace concentrations is known. In addition, the application of ferrite-based nanomaterials to dye effluent treatment procedures involves extensive obstacle evaluations, as well as there are also restricted environmental protection assessment studies. Furthermore, no legislation relating to the maximum allowable concentrations of ferrite-based nanomaterials in wastewater is in place to ensure the environment's safety and human health. Therefore, it is essential to evaluate ferrite-based nanomaterial harmful effects and hazards associated with the implementation of ferrite-based nanomaterials in the treatment of dye effluent. The sulphidation process has recently become one of the natural solutions for mitigating the toxicity of ferrite-based nanomaterials and their effects on sewage processing plants. The study on in vivo immunotoxicity, the effect of ferrite-based nanomaterials form on toxic effect, and the thorough advancement of ferrite-based nanomaterial adsorption kinetics on various biological macromolecules occur during infancy. The overall understanding of ferrite-based nanomaterial absorption, distribution, and effective dye degradation is demonstrated in this study.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] H. S. Rai, M. S. Bhattacharyya, J. Singh, T. K. Bansal, P. Vats, and U. C. Banerjee, "Removal of dyes from the effluent of textile and dyestuff manufacturing industry: a review of emerging techniques with reference to biological treatment," *Critical Reviews in Environmental Science and Technology*, vol. 35, no. 3, pp. 219–238, 2005.

- [2] S. Madhav, A. Ahamad, P. Singh, and P. K. Mishra, "A review of textile industry: wet processing, environmental impacts, and effluent treatment methods," *Environmental Quality Management*, vol. 27, no. 3, pp. 31–41, 2018.
- [3] X.-C. Jin, G. Q. Liu, Z. H. Xu, and W. Y. Tao, "Decolorization of a dye industry effluent by Aspergillus fumigatus XC6," *Applied Microbiology and Biotechnology*, vol. 74, no. 1, pp. 239–243, 2007.
- [4] Z. Badani, H. Ait-Amar, A. Si-Salah, M. Brik, and W. Fuchs, "Treatment of textile waste water by membrane bioreactor and reuse," *Desalination*, vol. 185, no. 1-3, pp. 411–417, 2005.
- [5] R. Jain, M. Mathur, S. Sikarwar, and A. Mittal, "Removal of the hazardous dye rhodamine B through photocatalytic and adsorption treatments," *Journal of Environmental Management*, vol. 85, no. 4, pp. 956–964, 2007.
- [6] D. Van Thuan, T. L. Nguyen, H. H. Thi et al., "Development of indium vanadate and silver deposited on graphitic carbon nitride ternary heterojunction for advanced photocatalytic degradation of residual antibiotics in aqueous environment," *Optical Materials*, vol. 123, article 111885, 2022.
- [7] S. Ghotekar, S. Pansambal, K. Y. A. Lin, D. Pore, and R. Oza, "Recent advances in synthesis of CeVO4 nanoparticles and their potential scaffold for photocatalytic applications," *Topics in Catalysis*, pp. 1–15, 2022.
- [8] H. N. Cuong, S. Pansambal, S. Ghotekar et al., "New frontiers in the plant extract mediated biosynthesis of copper oxide (CuO) nanoparticles and their potential applications: a review," *Environmental Research*, vol. 203, article 111858, 2022.
- [9] U. G. Akpan and B. H. Hameed, "Parameters affecting the photocatalytic degradation of dyes using TiO₂-based photocatalysts: a review," *Journal of Hazardous Materials*, vol. 170, no. 2-3, pp. 520–529, 2009.
- [10] E. Forgacs, T. Cserháti, and G. Oros, "Removal of synthetic dyes from wastewaters: a review," *Environment International*, vol. 30, no. 7, pp. 953–971, 2004.
- [11] C. Lops, A. Ancona, K. di Cesare et al., "Sonophotocatalytic degradation mechanisms of rhodamine B dye via radicals generation by micro- and nano-particles of ZnO," *Applied Catalysis B: Environmental*, vol. 243, pp. 629–640, 2019.
- [12] S. Pansambal, S. Ghotekar, S. Shewale, K. Deshmukh, N. Barde, and P. Bardapurkar, "Efficient synthesis of magnetically separable CoFe2O4@ SiO2 nanoparticles and its potent catalytic applications for the synthesis of 5-aryl-1, 2, 4-triazolidine-3-thione derivatives," *Journal of Water and Environmental Nanotechnology*, vol. 4, no. 3, pp. 174–186, 2019.
- [13] R. Hudson, Y. Feng, R. S. Varma, and A. Moores, "Bare magnetic nanoparticles: sustainable synthesis and applications in catalytic organic transformations," *Green Chemistry*, vol. 16, no. 10, pp. 4493–4505, 2014.
- [14] R. Kalia, A. Chauhan, R. Verma et al., "Photocatalytic degradation properties of Li-Cr ions substituted CoFe2O4Nanoparticles for wastewater treatment application," *Physica Status Solidi*, vol. 219, no. 8, article 2100539, 2022.
- [15] S. Chikazumi, S. Taketomi, M. Ukita et al., "Physics of magnetic fluids," *Journal of Magnetism and Magnetic Materials*, vol. 65, no. 2-3, pp. 245–251, 1987.
- [16] A. K. Gupta and M. Gupta, "Cytotoxicity suppression and cellular uptake enhancement of surface modified magnetic nanoparticles," *Biomaterials*, vol. 26, no. 13, pp. 1565–1573, 2005.

- [17] T. Hyeon, "Chemical synthesis of magnetic nanoparticles," *Chemical Communications*, vol. 8, no. 8, pp. 927–934, 2003.
- [18] Q. Li, V. Kumar, Y. Li, H. Zhang, T. J. Marks, and R. P. H. Chang, "Fabrication of ZnO nanorods and nanotubes in aqueous solutions," *Chemistry of Materials*, vol. 17, no. 5, pp. 1001–1006, 2005.
- [19] S. Mornet, S. Vasseur, F. Grasset et al., "Magnetic nanoparticle design for medical applications," *Progress in Solid State Chemistry*, vol. 34, no. 2-4, pp. 237–247, 2006.
- [20] J. B. Haun, T. J. Yoon, H. Lee, and R. Weissleder, "Magnetic nanoparticle biosensors," *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology*, vol. 2, no. 3, pp. 291–304, 2010.
- [21] M. Takafuji, S. Ide, H. Ihara, and Z. Xu, "Preparation of poly (1-vinylimidazole)-grafted magnetic nanoparticles and their application for removal of metal ions," *Chemistry of Materials*, vol. 16, no. 10, pp. 1977–1983, 2004.
- [22] D. W. Elliott and W.-X. Zhang, "Field assessment of nanoscale bimetallic particles for groundwater treatment," *Environmental Science & Technology*, vol. 35, no. 24, pp. 4922– 4926, 2001.
- [23] S. Ghotekar, H. C. A. Murthy, A. Roy, M. Bilal, and R. Oza, "Magnetic nanomaterials-based biosorbents," in *Nano-Bio-sorbents for Decontamination of Water, Air, and Soil Pollution*, pp. 605–614, Elsevier, 2022.
- [24] H. Dabhane, S. Chatur, S. Ghotekar et al., "Methods for the synthesis of nano-biosorbents for the contaminant removal," in *Nano-Biosorbents for Decontamination of Water, Air, and Soil Pollution*, pp. 61–73, Elsevier, 2022.
- [25] V. Dutta, J. Devasia, A. Chauhan et al., "Photocatalytic nanomaterials: applications for remediation of toxic polycyclic aromatic hydrocarbons and green management," *Advances*, vol. 11, article 100353, 2022.
- [26] A. H. Lu, E. E. Salabas, and F. Schüth, "Magnetic nanoparticles: synthesis, protection, functionalization, and application," *Angewandte Chemie International Edition*, vol. 46, no. 8, pp. 1222–1244, 2007.
- [27] V. Dutta, S. Sharma, P. Raizada et al., "Recent progress on bismuth-based Z-scheme semiconductor photocatalysts for energy and environmental applications," *Journal of Environmental Chemical Engineering*, vol. 8, no. 6, article 104505, 2020.
- [28] K. G. Kelele, A. Tadesse, T. Desalegn, S. Ghotekar, R. Balachandran, and H. C. A. Murthy, "Synthesis and characterizations of metal ions doped barium strontium titanate (BST) nanomaterials for photocatalytic and electrical applications: a mini review," *International Journal of Materials Research*, vol. 112, no. 8, pp. 665–677, 2021.
- [29] A. Khan, S. Malik, S. Shah et al., "Nanoadsorbents for environmental remediation," *Nanotechnology for Environmental Remediation*, pp. 103–120, 2022.
- [30] S. Pansambal, R. Oza, S. Borgave et al., "Bioengineered cerium oxide (CeO₂) nanoparticles and their diverse applications: a review," *Applied Nanoscience*, pp. 1–26, 2022.
- [31] H. Dabhane, S. Ghotekar, P. Tambade et al., "A review on environmentally benevolent synthesis of CdS nanoparticle and their applications," *Environmental Chemistry and Ecotoxicology*, vol. 3, pp. 209–219, 2021.
- [32] P.-H. Mao, N. N. Huy, S. Ghotekar et al., "Single-step synthesized functionalized copper carboxylate framework meshes as hierarchical catalysts for enhanced reduction of nitrogen-

containing phenolic contaminants," *Catalysts*, vol. 12, no. 7, p. 765, 2022.

- [33] R. Kumar, P. Raizada, A. A. P. Khan et al., "Recent progress in emerging BiPO₄-based photocatalysts: synthesis, properties, modification strategies, and photocatalytic applications," *Journal of Materials Science & Technology*, vol. 108, pp. 208–225, 2022.
- [34] A. Kumar, V. Hasija, A. Sudhaik et al., "Artificial leaf for light-driven CO₂ reduction: basic concepts, advanced structures and selective solar-to-chemical products," *Chemical Engineering Journal*, vol. 430, article 133031, 2022.
- [35] S. Sharma, V. Dutta, P. Raizada et al., "An overview of heterojunctioned ZnFe₂O₄ photocatalyst for enhanced oxidative water purification," *Journal of Environmental Chemical Engineering*, vol. 9, no. 5, article 105812, 2021.
- [36] I. M. Banat, P. Nigam, D. Singh, and R. Marchant, "Microbial decolorization of textile-dyecontaining effluents: a review," *Bioresource Technology*, vol. 58, no. 3, pp. 217–227, 1996.
- [37] V. Vadivelan and K. V. Kumar, "Equilibrium, kinetics, mechanism, and process design for the sorption of methylene blue onto rice husk," *Journal of Colloid and Interface Science*, vol. 286, no. 1, pp. 90–100, 2005.
- [38] S. Ramchandani, M. das, A. Joshi, and S. K. Khanna, "Effect of oral and parenteral administration of metanil yellow on some hepatic and intestinal biochemical parameters," *Journal* of Applied Toxicology, vol. 17, no. 1, pp. 85–91, 1997.
- [39] M. Das, S. Ramchandani, R. K. Upreti, and S. K. Khanna, "Metanil yellow: a bifunctional inducer of hepatic phase I and phase II xenobiotic-metabolizing enzymes," *Food and Chemical Toxicology*, vol. 35, no. 8, pp. 835–838, 1997.
- [40] S. Gupta, M. Sundarrajan, and K. Rao, "Tumor promotion by metanil yellow and malachite green during rat hepatocarcinogenesis is associated with dysregulated expression of cell cycle regulatory proteins," *Teratogenesis, Carcinogenesis, and Mutagenesis*, vol. 23, no. S1, pp. 301–312, 2003.
- [41] S. Sachdeva, K. V. Mani, S. K. Adaval, Y. P. Jalpota, K. C. Rasela, and D. S. Chadha, "Acquired toxic methaemoglobinaemia," *The Journal of the Association of Physicians of India*, vol. 40, no. 4, pp. 239-240, 1992.
- [42] S. Chandro and T. Nagaraja, "A food poisoning outbreak with chemical dye-an investigation report," *Medical Journal* of Armed Forces India, vol. 43, no. 4, pp. 291–293, 1987.
- [43] B. Hausen, "A case of allergic contact dermatitis due to metanil yellow," *Contact Dermatitis*, vol. 31, no. 2, pp. 117-118, 1994.
- [44] H. Tiwari, "Assessment of teratogenecity and embryo toxicity of dye waste-water untreated sludge from Sanganer on Swiss albino mice when administered during growth period of gestation," *Water Resources Development*, vol. 2, pp. 48–53, 2012.
- [45] R. Sivashankar, A. B. Sathya, K. Vasantharaj, and V. Sivasubramanian, "Magnetic composite an environmental super adsorbent for dye sequestration - a review," *Environmental Nanotechnology, Monitoring & Management*, vol. 1-2, pp. 36–49, 2014.
- [46] A. Akbarzadeh, M. Samiei, and S. Davaran, "Magnetic nanoparticles: preparation, physical properties, and applications in biomedicine," *Nanoscale Research Letters*, vol. 7, no. 1, pp. 1–13, 2012.
- [47] N. A. Frey, S. Peng, K. Cheng, and S. Sun, "Magnetic nanoparticles: synthesis, functionalization, and applications in

bioimaging and magnetic energy storage," *Chemical Society Reviews*, vol. 38, no. 9, pp. 2532–2542, 2009.

- [48] S. Singamaneni, V. N. Bliznyuk, C. Binek, and E. Y. Tsymbal, "Magnetic nanoparticles: recent advances in synthesis, selfassembly and applications," *Journal of Materials Chemistry*, vol. 21, no. 42, pp. 16819–16845, 2011.
- [49] S. H. Noh, W. Na, J. T. Jang et al., "Nanoscale magnetism control via surface and exchange anisotropy for optimized ferrimagnetic hysteresis," *Nano Letters*, vol. 12, no. 7, pp. 3716–3721, 2012.
- [50] Q. Song and Z. J. Zhang, "Shape control and associated magnetic properties of spinel cobalt ferrite nanocrystals," *Journal* of the American Chemical Society, vol. 126, no. 19, pp. 6164– 6168, 2004.
- [51] A. M. Salgueiro, A. L. Daniel-da-Silva, A. V. Girão, P. C. Pinheiro, and T. Trindade, "Unusual dye adsorption behavior of κ-carrageenan coated superparamagnetic nanoparticles," *Chemical Engineering Journal*, vol. 229, pp. 276– 284, 2013.
- [52] G. Salazar-Alvarez, J. Qin, V. Šepelák et al., "Cubic versus spherical magnetic nanoparticles: the role of surface anisotropy," *Journal of the American Chemical Society*, vol. 130, no. 40, pp. 13234–13239, 2008.
- [53] G. Zhen, B. W. Muir, B. A. Moffat et al., "Comparative study of the magnetic behavior of spherical and cubic superparamagnetic iron oxide nanoparticles," *The Journal of Physical Chemistry C*, vol. 115, no. 2, pp. 327–334, 2011.
- [54] A. Williams, V. L. Moruzzi, C. D. Gelatt Jr., J. Kübler, and K. Schwarz, "Aspects of transition-metal magnetism," *Journal of Applied Physics*, vol. 53, no. 3, pp. 2019–2023, 1982.
- [55] A. R. West, Basic solid state chemistry, John Wiley & Sons Incorporated, 1999.
- [56] A. G. Kolhatkar, A. Jamison, D. Litvinov, R. Willson, and T. Lee, "Tuning the magnetic properties of nanoparticles," *International Journal of Molecular Sciences*, vol. 14, no. 8, pp. 15977–16009, 2013.
- [57] R. Suresh, S. Rajendran, P. S. Kumar, D. V. N. Vo, and L. Cornejo-Ponce, "Recent advancements of spinel ferrite based binary nanocomposite photocatalysts in wastewater treatment," *Chemosphere*, vol. 274, article 129734, 2021.
- [58] K. K. Kefeni, B. B. Mamba, and T. A. Msagati, "Application of spinel ferrite nanoparticles in water and wastewater treatment: a review," *Separation and Purification Technology*, vol. 188, pp. 399–422, 2017.
- [59] S. Farhadi, F. Siadatnasab, and A. Khataee, "Ultrasoundassisted degradation of organic dyes over magnetic CoFe₂O₄@ZnS core-shell nanocomposite," *Ultrasonics Sonochemistry*, vol. 37, pp. 298–309, 2017.
- [60] F. Siadatnasab, S. Farhadi, and A. Khataee, "Sonocatalytic performance of magnetically separable CuS/CoFe₂O₄ nanohybrid for efficient degradation of organic dyes," *Ultrasonics Sonochemistry*, vol. 44, pp. 359–367, 2018.
- [61] A. Kalam, A. G. al-Sehemi, M. Assiri et al., "Modified solvothermal synthesis of cobalt ferrite (CoFe₂O₄) magnetic nanoparticles photocatalysts for degradation of methylene blue with H₂O₂/visible light," *Results in Physics*, vol. 8, pp. 1046–1053, 2018.
- [62] L. Gan, L. Xu, and K. Qian, "Preparation of core-shell structured CoFe₂O₄ incorporated Ag₃PO₄ nanocomposites for photocatalytic degradation of organic dyes," *Materials & Design*, vol. 109, pp. 354–360, 2016.

- [63] J. López, A. A. Ortíz, F. Muñoz-Muñoz et al., "Magnetic nanostructured based on cobalt-zinc ferrites designed for photocatalytic dye degradation," *Journal of Physics and Chemistry of Solids*, vol. 150, article 109869, 2021.
- [64] H. Astaraki, S. Masoudpanah, and S. Alamolhoda, "Effects of fuel contents on physicochemical properties and photocatalytic activity of CuFe₂O₄/reduced graphene oxide (RGO) nanocomposites synthesized by solution combustion method," *Journal of Materials Research and Technology*, vol. 9, no. 6, pp. 13402–13410, 2020.
- [65] X. Lei, M. You, F. Pan et al., "CuFe₂O₄@GO nanocomposite as an effective and recoverable catalyst of peroxymonosulfate activation for degradation of aqueous dye pollutants," *Chinese Chemical Letters*, vol. 30, no. 12, pp. 2216–2220, 2019.
- [66] P. Chen, X. Xing, H. Xie, Q. Sheng, and H. Qu, "High catalytic activity of magnetic CuFe₂O₄/graphene oxide composite for the degradation of organic dyes under visible light irradiation," *Chemical Physics Letters*, vol. 660, pp. 176–181, 2016.
- [67] D. Yu, H. Ni, L. Wang, M. Wu, and X. Yang, "Nanoscale-confined precursor of CuFe₂O₄ mediated by hyperbranched polyamide as an unusual heterogeneous Fenton catalyst for efficient dye degradation," *Journal of Cleaner Production*, vol. 186, pp. 146–154, 2018.
- [68] E. da Nóbrega Silva, I. L. Brasileiro, V. S. Madeira et al., "Reusable CuFe₂O₄-Fe₂O₃ catalyst synthesis and application for the heterogeneous photo-Fenton degradation of methylene blue in visible light," *Journal of Environmental Chemical Engineering*, vol. 8, no. 5, article 104132, 2020.
- [69] E. Kalantari, M. A. Khalilzadeh, D. Zareyee, and M. Shokouhimehr, "Catalytic degradation of organic dyes using green synthesized Fe₃O₄-cellulose-copper nanocomposites," *Journal of Molecular Structure*, vol. 1218, article 128488, 2020.
- [70] R. Saleh and A. Taufik, "Ultraviolet-light-assisted heterogeneous Fenton reaction of Ag- Fe₃O₄/graphene composites for the degradation of organic dyes," *Journal of Environmental Chemical Engineering*, vol. 7, no. 1, article 102895, 2019.
- [71] X. Tang, Z. Li, K. Liu et al., "Sulfidation modified Fe₃O₄ nanoparticles as an efficient Fenton-like catalyst for azo dyes degradation at wide pH range," *Powder Technology*, vol. 376, pp. 42–51, 2020.
- [72] M. Vinothkannan, C. Karthikeyan, G. Gnana kumar, A. R. Kim, and D. J. Yoo, "One-pot green synthesis of reduced graphene oxide (RGO)/Fe₃O₄ nanocomposites and its catalytic activity toward methylene blue dye degradation," *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, vol. 136, pp. 256–264, 2015.
- [73] T. Zhou, G. Zhang, P. Ma et al., "Efficient degradation of rhodamine B with magnetically separable Ag₃PO₄@MgFe₂O₄ composites under visible irradiation," *Journal of Alloys and Compounds*, vol. 735, pp. 1277–1290, 2018.
- [74] K. C. Das and S. S. Dhar, "Rapid catalytic degradation of malachite green by MgFe₂O₄ nanoparticles in presence of H₂O₂," *Journal of Alloys and Compounds*, vol. 828, article 154462, 2020.
- [75] A. Cabrera, C. E. Rodríguez Torres, S. G. Marchetti, and S. J. Stewart, "Degradation of methylene blue dye under dark and visible light conditions in presence of hybrid composites of nanostructured MgFe₂O₄ ferrites and oxygenated organic compounds," *Journal of Environmental Chemical Engineering*, vol. 8, no. 5, article 104274, 2020.

- [76] L. Zhang, Y. He, Y. Wu, and T. Wu, "Photocatalytic degradation of RhB over MgFe₂O₄/TiO₂ composite materials," *Materials Science and Engineering: B*, vol. 176, no. 18, pp. 1497– 1504, 2011.
- [77] M. S. Amulya, H. P. Nagaswarupa, M. R. A. Kumar, C. R. Ravikumar, and K. B. Kusuma, "Enhanced photocatalytic and electrochemical properties of Cu doped NiMnFe₂O₄ nanoparticles synthesized via probe sonication method," *Applied Surface Science Advances*, vol. 2, article 100038, 2020.
- [78] N. M. Mahmoodi, "Manganese ferrite nanoparticle: synthesis, characterization, and photocatalytic dye degradation ability," *Desalination and Water Treatment*, vol. 53, no. 1, pp. 84–90, 2015.
- [79] B. Boutra, N. Güy, M. Özacar, and M. Trari, "Magnetically separable MnFe₂O₄/TA/ZnO nanocomposites for photocatalytic degradation of Congo red under visible light," *Journal of Magnetism and Magnetic Materials*, vol. 497, article 165994, 2020.
- [80] B. Mandal, J. Panda, P. K. Paul, R. Sarkar, and B. Tudu, "MnFe₂O₄ decorated reduced graphene oxide heterostructures: nanophotocatalyst for methylene blue dye degradation," *Vacuum*, vol. 173, article 109150, 2020.
- [81] B. Sahoo, S. K. Sahu, S. Nayak, D. Dhara, and P. Pramanik, "Fabrication of magnetic mesoporous manganese ferrite nanocomposites as efficient catalyst for degradation of dye pollutants," *Catalysis Science & Technology*, vol. 2, no. 7, pp. 1367–1374, 2012.
- [82] L. Zhang, X. Liu, X. Guo, M. Su, T. Xu, and X. Song, "Investigation on the degradation of brilliant green induced oxidation by NiFe₂O₄ under microwave irradiation," *Chemical Engineering Journal*, vol. 173, no. 3, pp. 737–742, 2011.
- [83] K. Atacan, N. Güy, S. Çakar, and M. Özacar, "Efficiency of glucose oxidase immobilized on tannin modified NiFe₂O₄ nanoparticles on decolorization of dye in the Fenton and photo-biocatalytic processes," *Journal of Photochemistry* and Photobiology A: Chemistry, vol. 382, article 111935, 2019.
- [84] M. M. Baig, E. Pervaiz, and M. J. Afzal, "Catalytic activity and kinetic studies of core@ shell nanostructure NiFe₂O₄@ TiO₂ for photocatalytic degradation of methyl orange dye," *Journal* of the Chemical Society of Pakistan, vol. 42, no. 4, p. 531, 2020.
- [85] S. Kamal, S. Balu, S. Palanisamy, K. Uma, V. Velusamy, and T. C. K. Yang, "Synthesis of boron doped $C_3N_4/NiFe_2O_4$ nanocomposite: an enhanced visible light photocatalyst for the degradation of methylene blue," *Results in Physics*, vol. 12, pp. 1238–1244, 2019.
- [86] M. S. Amulya, H. P. Nagaswarupa, M. R. A. Kumar, C. R. Ravikumar, S. C. Prashantha, and K. B. Kusuma, "Sonochemical synthesis of NiFe₂O₄ nanoparticles: characterization and their photocatalytic and electrochemical applications," *Applied Surface Science Advances*, vol. 1, article 100023, 2020.
- [87] N. Chandel, K. Sharma, A. Sudhaik et al., "Magnetically separable ZnO/ZnFe₂O₄ and ZnO/CoFe₂O₄ photocatalysts supported onto nitrogen doped graphene for photocatalytic degradation of toxic dyes," *Arabian Journal of Chemistry*, vol. 13, no. 2, pp. 4324–4340, 2020.
- [88] N. M. Mahmoodi, "Zinc ferrite nanoparticle as a magnetic catalyst: synthesis and dye degradation," *Materials Research Bulletin*, vol. 48, no. 10, pp. 4255–4260, 2013.
- [89] S. D. Kulkarni, S. Kumbar, S. G. Menon, K. S. Choudhari, and C. Santhosh, "Magnetically separable core-shell ZnFe₂O₄@ZnO nanoparticles for visible light photodegradation of methyl orange," *Materials Research Bulletin*, vol. 77, pp. 70–77, 2016.

- [90] L. Nirumand, S. Farhadi, A. Zabardasti, and A. Khataee, "Synthesis and sonocatalytic performance of a ternary magnetic MIL-101(Cr)/RGO/ZnFe₂O₄ nanocomposite for degradation of dye pollutants," *Ultrasonics Sonochemistry*, vol. 42, pp. 647–658, 2018.
- [91] T. P. Oliveira, G. N. Marques, M. A. Macedo Castro et al., "Synthesis and photocatalytic investigation of $ZnFe_2O_4$ in the degradation of organic dyes under visible light," *Journal* of Materials Research and Technology, vol. 9, no. 6, pp. 15001–15015, 2020.
- [92] S. Ahmed, M. Oumezzine, and E.-K. Hlil, "Sol-gel synthesis of ferrites nanoparticles and investigation of their magnetic and photocatalytic activity for degradation of reactive blue 21 dye," *Journal of Molecular Structure*, vol. 1235, article 130262, 2021.
- [93] S. A. Al-Zahrani, A. Manikandan, K. Thanrasu et al., "Influence of Ce3+ on the structural, morphological, magnetic, photocatalytic and antibacterial properties of spinel MnFe₂O₄ nanocrystallites prepared by the combustion route," *Crystals*, vol. 12, no. 2, p. 268, 2022.
- [94] E. C. Paris, J. O. D. Malafatti, A. J. Moreira et al., "CuO nanoparticles decorated on hydroxyapatite/ferrite magnetic support: photocatalysis, cytotoxicity, and antimicrobial response," *Environmental Science and Pollution Research*, vol. 29, no. 27, pp. 41505–41519, 2022.
- [95] N. AbouSeada, M. Ahmed, and M. G. Elmahgary, "Synthesis and characterization of novel magnetic nanoparticles for photocatalytic degradation of indigo carmine dye," *Materials Science for Energy Technologies*, vol. 5, pp. 116–124, 2022.
- [96] A. Almahri, "The solid-state synthetic performance of bentonite stacked manganese ferrite nanoparticles: adsorption and photo-Fenton degradation of MB dye and antibacterial applications," *Journal of Materials Research and Technology*, vol. 17, pp. 2935–2949, 2022.
- [97] A. Selmi, H. Teymourinia, A. Zarei, M. Timoumi, and A. Ramazani, "CMCFO-Cr0. 1 Nanoferrites: sol-gel synthesis, structural, and magnetic studies: applications for photodegradation of Congo red dye," *Iranian Journal of Catalysis*, vol. 12, no. 1, pp. 97–106, 2022.
- [98] P. L. Hariani, M. Said, S. Salni, N. Aprianti, and Y. Naibaho, "High efficient photocatalytic degradation of methyl orange dye in an aqueous solution by CoFe₂O₄-SiO₂-TiO₂ magnetic catalyst," *Journal of Ecological Engineering*, vol. 23, no. 1, pp. 118–128, 2022.
- [99] T. Ajeesha, A. Manikandan, A. Anantharaman et al., "Structural investigation of Cu doped calcium ferrite (Ca_{1-x}Cu_{x-} Fe₂O₄; x=0, 0.2, 0.4, 0.6, 0.8, 1) nanomaterials prepared by co-precipitation method," *Journal of Materials Research and Technology*, vol. 18, pp. 705–719, 2022.
- [100] M. A. Tony and M. Eltabey, "End-of-life waste criteria: synthesis and utilization of Mn–Zn ferrite nanoparticles as a superparamagnetic photocatalyst for synergistic wastewater remediation," *Applied Water Science*, vol. 12, no. 2, pp. 1– 17, 2022.
- [101] A. Hakimyfard and S. Khademinia, "Hirshfeld surface analysis of solid-state synthesized NiFe₂O₄ nanocomposite and application of it for photocatalytic degradation of water pollutant dye," *International Journal of Nano Dimension*, vol. 13, no. 2, pp. 155–167, 2022.