

Original Research Article

Synthesis of Mg-doped CuO Nanoparticles for Efficient Removal of Congo Red Dye from Wastewater: Adsorption study

ABSTRACT

Water contamination from a variety of sources has made it increasingly difficult to access clean drinking water. The release of effluents into water bodies is a serious environmental problem. This study presents the synthesis of magnesium-doped copper oxide (Mg-CuO) nanoparticles as a promising adsorbent for the efficient removal of Congo Red dye from aqueous solutions. Mg-CuO nanoparticles were synthesized via a facile and cost-effective co-precipitation method and characterized using various techniques. The adsorption capacity of Mg-CuO nanoparticles for Congo Red dye was systematically investigated, revealing outstanding adsorption efficiency. Equilibrium adsorption data were well-fitted to the Langmuir isotherm model, suggesting monolayer adsorption behavior, while the pseudo-second-order kinetic model described the adsorption kinetics accurately. The influence of various experimental parameters, including initial dye concentration, pH, adsorbent dosage, and contact time, on the adsorption process was studied in detail. Optimal conditions for maximal adsorption efficiency were determined. Additionally, the thermodynamic analysis indicated that the adsorption of Congo Red onto Mg-CuO nanoparticles was spontaneous and endothermic. The exceptional adsorption performance of Mg-CuO nanoparticles, attributed to the synergistic effect of magnesium doping and high surface area, highlights their potential as an eco-friendly and efficient adsorbent for the removal of Congo Red dye from wastewater. This research contributes to the advancement of sustainable materials for environmental remediation and underscores the importance of exploring nanomaterials for water purification applications.

Keywords: Nanotechnology, CuO nanoparticles, Adsorption, Coprecipitation method, Doping, equilibrium modeling.

1. INTRODUCTION

Water is essential for life, and access to clean water is a fundamental human right. It is also a vital resource for many industries, including those that produce food, drugs, and electronics [1]. However, the world is facing a growing crisis [2], as freshwater resources are declining due to climate change [3], population growth, and pollution [4]. One of the biggest challenges is that only 3% of the Earth's water is freshwater, and most of this is locked up in glaciers and ice caps [5]. The most readily available source of freshwater is seawater [6], but it is too salty to drink or use for most industrial purposes. Wastewater effluents are discharged from homes, businesses, and industries [7]. They can contain a variety of pollutants, including organic matter, nutrients, heavy metals, and pathogens [8]. Water effluents can have a negative impact on the environment and human health if they are not properly treated [7]. There are a number of ways to treat water effluents, including physical, chemical, and biological methods [9]. Physical methods, such as sedimentation and filtration, can remove suspended solids and other large particles from the water [10]. Chemical

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i.e. various, numerous...

20 methods, such as coagulation and disinfection, can remove dissolved pollutants and kill harmful bacteria. Biological
21 methods, such as activated sludge and trickling filters, can remove organic matter and nutrients from the water [11].

22 The type of treatment that is used for water effluents depends on the specific pollutants that are present in the wastewater
23 [12]. For example, if the wastewater contains a lot of organic matter, then a biological treatment method would be most
24 effective. If the wastewater contains a lot of heavy metals, then a chemical treatment method would be most effective.
25 Biological treatment methods, such as activated sludge and trickling filters, are very effective at removing organic matter
26 from water effluents. Organic matter is **broken down** by bacteria in these systems, which produces carbon dioxide and
27 water [13]. Nutrients, such as nitrogen and phosphorus, can be removed from water effluents using a variety of methods,
28 including chemical precipitation, biological nutrient removal, and ion exchange. Heavy metals can be removed from water
29 effluents using chemical precipitation, ion exchange, and adsorption. Pathogens [14], such as bacteria and viruses, can
30 be removed from water effluents using disinfection [15]. Disinfection can be achieved using a variety of methods, including
31 chlorination, ozonation, and ultraviolet radiation. The specific treatment methods that are used for water effluents will
32 depend on the specific pollutants that are present in the wastewater, the desired removal efficiency, and the cost of the
33 treatment process [16].

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34 Nanotechnology is the manipulation of matter at the atomic and molecular level to create new materials and devices with
35 unique properties [17]. It has the potential to revolutionize **many industries**, including water treatment [18]. Nanomaterials
36 have a number of advantages over conventional materials for water treatment. They are **very small**, with a large **surface**
37 **area to volume ratio**[19]. This makes them very effective at adsorbing and removing contaminants from water.
38 Nanomaterials can also be functionalized to target specific contaminants [20]. Nanotechnology is already being used in a
39 variety of ways to treat wastewater. For example, nanoparticles can be used to remove heavy metals, organic pollutants,
40 and bacteria from water. Nanotechnology can also be used to develop new water filters and membranes that are more
41 efficient and durable than conventional filters and membranes. Nanotechnology is a promising new technology for water
42 treatment. It has the potential to help us solve the global water crisis by providing us with new and innovative ways to
43 clean and reuse wastewater [21].

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44 Dye-based color repels have several advantages over pigment-based color repels [22]. Due to their high solubility in
45 solvents, dye-based **repels typically** do not require additional dispersion steps [23]. Additionally, they have superior
46 transmittance, purer color, and sharper absorption bands than pigments due to their lower particle masses. The textile
47 dyeing industry produces a significant amount of colored wastewater, which is a major source of water pollution [24]. More
48 than 15% of dyes are lost during the textile manufacturing process, contributing to the colorful wastewater streams. Textile
49 wastewater is one of the most severely polluted fluids that **needs** to be treated due to its unique properties. It contains a
50 variety of chemicals, including dyes and inorganic compounds. These chemicals can pose major risks to the environment
51 and human health if not properly handled. Organic dyes **are particularly harmful because** they are often toxic and
52 carcinogenic [25]. They can endanger marine life, microorganisms, and human health. Textile wastewater treatment is a
53 complex and challenging process. There are a variety of methods that can be used, but they are all expensive and require
54 specialized expertise [26].

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55 Adsorption is a process that occurs when a substance (adsorbate) accumulates on the surface of another substance
56 (adsorbent) [27]. This process is driven by surface forces, such as van der Waals forces or chemical bonding. Adsorption
57 is a versatile and effective process for removing contaminants from wastewater [28]. It is relatively inexpensive, easy to
58 use, and environmentally friendly. Adsorption methods can be classified into two types: physical adsorption and chemical
59 adsorption. In physical adsorption, the adsorbate is held to the adsorbent by weak van der Waals forces. This type of
60 adsorption is reversible, meaning that the adsorbate can be released from the adsorbent by changing the conditions, such
61 as temperature or pressure. In chemical adsorption, the adsorbate is held to the adsorbent by strong chemical bonds.
62 This type of adsorption is irreversible, meaning that the adsorbate cannot be released from the adsorbent without
63 breaking the chemical bonds [29]. Adsorption is a promising technology for wastewater treatment. It has the potential to
64 remove a wide range of contaminants from wastewater, including heavy metals, organic pollutants, and bacteria [30].

65 Dye adsorption is a process of **removing** dye molecules from wastewater using a solid adsorbent [31]. This process is
66 popular because it is simple, flexible, and easy to operate. It is also relatively inexpensive, insensitive to harmful
67 contaminants, and does not produce any hazardous compounds. Ideal adsorbents for dye removal are able to function
68 under a variety of wastewater parameters, **cost-effective**, able to remove a variety of contaminants, high adsorption
69 capacity, **highly** selective for different concentrations, large surface area, durable and reusable. A variety of adsorbents
70 can be used to treat wastewater containing dyes, including bio-sorbents, carbon-based nano-adsorbents [32], and
71 polymer-based adsorbents. Activated carbon-based adsorbents [33] are widely studied in this field due to their excellent

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72 chemical strength, low density, structural flexibility, and suitability for field-scale applications. Natural and synthetic clays
73 are also frequently used as adsorbents for dye removal from aqueous solutions due to their widespread availability, low
74 cost, high effectivity [34].

75 Congo red is a water-soluble azo dye that has been used for a variety of industrial and commercial purposes [35],
76 including textile dyeing, papermaking, and leather tanning. However, Congo red is also a known carcinogen and toxic
77 pollutant [36] and its release into the environment can have serious adverse consequences. Congo red can enter the
78 environment through a variety of pathways, including wastewater discharges from industrial and commercial facilities,
79 runoff from agricultural fields fertilized with sewage sludge, and leaching from landfills. Once in the environment, Congo
80 red is highly persistent and can bioaccumulate in aquatic organisms [37]. Exposure to Congo red can cause a variety of
81 health problems in humans and animals, including cancer, liver damage, kidney damage, and neurological disorders.
82 Congo red is also a known endocrine disruptor, and exposure can interfere with hormone function and reproduction.

83 The co-precipitation method is a simple, inexpensive technique for producing metal-doped nanoparticles [38]. It involves
84 mixing atomic particles to create compounds with perfect stoichiometry at low temperatures. This method can be used to
85 create drug delivery systems by encapsulating drugs in nanoparticles, or to remove contaminants from water or air by
86 precipitating them out of solution. Co-precipitation is commonly used in industrial applications due to its simplicity and
87 effectiveness in controlling the morphology of the nanoparticles [39].

88 CuO NPs have a variety of unique properties [40], including high surface area, high reactivity, and excellent electrical and
89 thermal conductivity. These properties make CuO NPs promising candidates for a wide range of applications, including
90 water purification, energy storage, and catalysis. In water purification, CuO NPs **can be used to remove** a variety of
91 contaminants from water, including heavy metals, dyes, and organic pollutants [41]. CuO NPs **can also be used**
92 to disinfect water by killing bacteria and other microorganisms. In energy storage, CuO NPs **can be used to** develop lithium-
93 ion batteries and supercapacitors [42] with high energy density and power density. CuO NPs **can also be used to** develop
94 solar cells and other photovoltaic devices with high efficiency. In catalysis, CuO NPs **can be used to catalyze** a variety of
95 chemical reactions, including the hydrogenation of unsaturated hydrocarbons, the oxidation of carbon monoxide, and the
96 reduction of nitrogen oxides. CuO NPs can be synthesized using a variety of methods, including chemical precipitation,
97 sol-gel synthesis, and hydrothermal synthesis. The synthesis method used will affect the size, shape, and crystallinity of
98 the CuO NPs [43].

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99 Doping is a method of improving the properties of materials by introducing impurities into their crystal lattice [44]. Doping
100 is widely used in a variety of industries, including catalysis, electronics, and biomedicine. Metal-doped nanoparticles are
101 particularly useful for these applications because their properties can be tailored to meet specific needs. Copper-doped
102 iron oxide nanoparticles have been shown to be effective at removing organic dyes from wastewater [45].

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104 2. EXPERIMENTAL DETAILS

105 2.1 Material Synthesis

106 In the co-precipitation method, aqueous solutions of copper and magnesium salts are mixed together in the presence of a
107 base, such as sodium hydroxide. This results in the formation of a precipitate of Mg-CuO nanoparticles. The precipitate is
108 then filtered, washed, and dried to obtain the desired Mg-CuO nanoparticles. In **present** research, copper nitrate trihydrate
109 ($\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$) and magnesium nitrate hexahydrate ($\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) was dissolved in deionized water to **obtain** two
110 separate solutions. Then magnesium nitrate solution was added to the copper nitrate solution under vigorous stirring.
111 Sodium hydroxide (NaOH) solution was added to the mixed solution until the pH reaches 10. Stirring was continued for 30
112 minutes to ensure complete precipitation. The precipitate was filtered and washed thoroughly with deionized water. The
113 precipitates were dried in an oven at 100°C for 2 hours [46].

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114 2.2 BATCH ADSORPTION

115 To prepare a stock solution of Congo Red dye, 1g of the dye was dissolved in distilled water and the volume was made up
116 to 1000ml in a measuring flask. Different ppm solutions, including 10ppm, 20ppm, 30ppm, 40ppm, and 50ppm, were
117 prepared from the stock solution using the dilution formula ($C_1V_1=C_2V_2$). For Mg-doped CuO nanoparticles, the pH was
118 adjusted using 0.1 M NaOH and 0.1 M HCl. Adsorption tests were carried out to determine the removal efficiency of Mg-

119 doped Copper oxide nanoparticles. Different parameters of dose rate, concentration, pH, and contact time were
120 investigated with all adsorbent doses of 0.05g.

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121 Adsorption tests were performed by taking 50ml of working solution with specific pH in 250ml conical flasks. All the conical
122 flasks with samples were placed in an orbital shaker for 90 min at the speed of 110rpm. The dose rate effect was
123 investigated with all adsorbent doses of 0.05g, 0.07g, 0.1g, 0.2g, 0.3g, and 0.5g. For Mg-doped CuO nanoparticles
124 adsorption, the pH effect was observed at pH 2. The effect of the initial dye concentration was investigated at 10ppm,
125 25ppm, 50ppm, 75ppm, 100ppm, and 150ppm. Contact time was varied at the interval of 5, 10, 15, 20, 30, 45, 60, and 90
126 minutes. Temperature was varied at 30, 35, 40, 45, 50, and 60 °C

127 3. RESULTS AND DISCUSSION

128 3.1 CHARACTERIZATION OF TiO₂ NANOPARTICLES

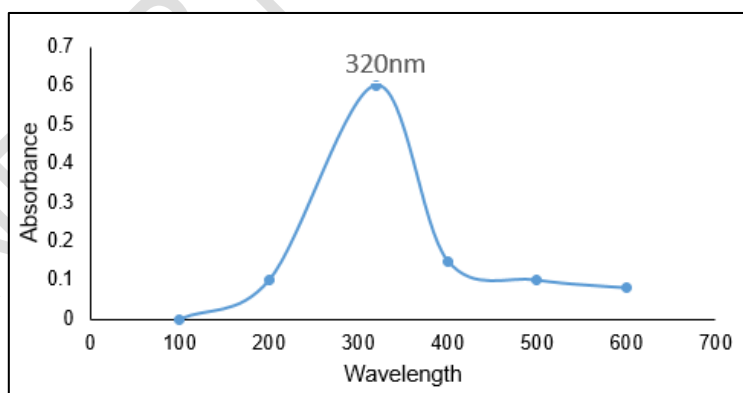
129 3.1.1 Uv- Visible spectroscopy

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133 Ultraviolet-visible (UV-vis) spectroscopy is a versatile technique that can be used to characterize the optical properties of
134 materials, including Mg-doped CuO nanoparticles. UV-vis spectroscopy measures the absorption of light by a material at
135 different wavelengths. The absorption spectrum of a material can be used to identify the different electronic transitions
136 that occur within the material. Mg-doped CuO nanoparticles have a characteristic absorption peak in the UV-vis spectrum
137 at around 320 nm [47]. This peak is attributed to the electronic transition from the valence band to the conduction band of
138 CuO. The position and intensity of this peak can be affected by the doping concentration of Mg. For example, studies
139 have shown that the absorption peak shifts to a higher wavelength and the intensity of the peak decreases as the Mg
140 doping concentration increases. UV-vis spectroscopy can also be used to determine the band gap energy of Mg-doped
141 CuO nanoparticles. The band gap energy is the energy difference between the valence band and the conduction band of
142 a material. It is an important parameter for determining the electrical conductivity and optical properties of a material. To
143 determine the band gap energy of Mg-doped CuO nanoparticles, the Tauc plot of the absorption spectrum can be used.
144 The Tauc plot is a plot of the square root of the absorption coefficient versus the photon energy. The band gap energy can
145 be determined by extrapolating the linear portion of the Tauc plot to the x-axis. Studies have shown that the band gap
146 energy of Mg-doped CuO nanoparticles decreases as the Mg doping concentration increases. This is because the Mg
147 dopant introduces new energy levels into the band gap of CuO. Overall, UV-vis spectroscopy is a powerful tool for
148 characterizing the optical properties of Mg-doped CuO nanoparticles. The information obtained from UV-vis spectroscopy
149 can be used to optimize the synthesis and processing of Mg-doped CuO nanoparticles for specific applications.

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150 Fig. 1 UV- Vis Spectrum of Mg doped CuO NPs

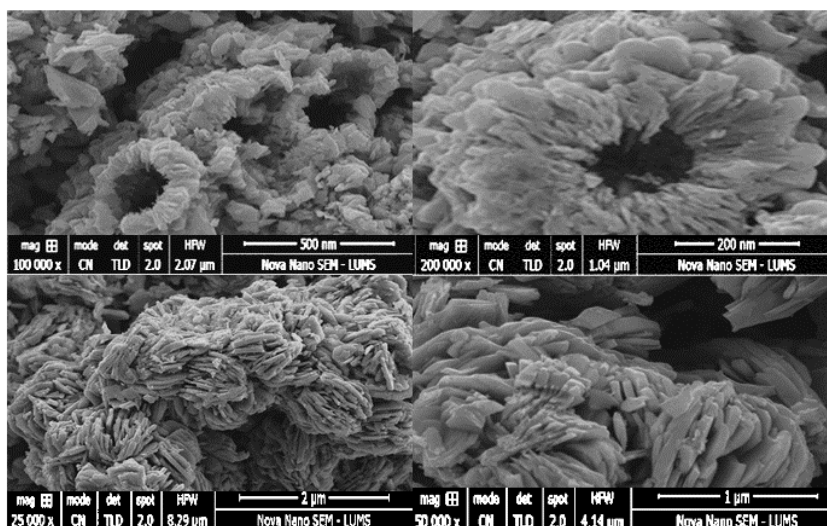
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152 Comment [Ibsa Neme19]: SEM anlysis or morphological analysis?

153 3.1.2 SEM Analysis

154 Scanning electron microscopy (SEM) images of Mg-doped CuO nanoparticles can reveal a variety of morphological
155 features, depending on the synthesis method and doping concentration. For example, SEM images of Mg-doped CuO

155 nanoparticles prepared by the hydrothermal method have shown that the nanoparticles can have a variety of shapes,
 156 including spherical, rod-shaped, and flower-like. The size of the nanoparticles can also vary depending on the synthesis
 157 conditions, but is typically in the range of 10-100 nanometers. SEM images can also be used to assess the dispersion of
 158 Mg-doped CuO nanoparticles in a matrix. For example, SEM images of Mg-doped CuO nanoparticles dispersed in a
 159 polymer matrix have shown that the nanoparticles can be evenly dispersed throughout the matrix. This is important for
 160 ensuring that the nanoparticles can effectively perform their desired function, such as enhancing the electrical conductivity
 161 of the polymer. Overall, SEM images can be a valuable tool for characterizing the morphology and dispersion of Mg-
 162 doped CuO nanoparticles. This information can be used to optimize the synthesis and processing of these nanoparticles
 163 for specific applications [46].



164
 165 **Fig. 2 SEM images of Mg-doped CuO Nanoparticles**

166 3.2 Effect of pH

167 The pH of the solution has a significant effect on the adsorption of dye onto Mg-doped CuO nanoparticles. This is
 168 because the pH of the solution affects the surface charge of the Mg-doped CuO nanoparticles and the ionization state of
 169 the dye molecules. At low pH, the surface of the Mg-doped CuO nanoparticles is positively charged, while the dye
 170 molecules are neutral or negatively charged. This electrostatic attraction between the positively charged Mg-doped CuO
 171 nanoparticles and the negatively charged dye molecules enhances the adsorption process. At high pH, the surface of the
 172 Mg-doped CuO nanoparticles becomes negatively charged, while the dye molecules become negatively charged or
 173 neutral. This electrostatic repulsion between the negatively charged Mg-doped CuO nanoparticles and the negatively
 174 charged dye molecules inhibits the adsorption process. Therefore, the optimal pH for the adsorption of dye onto Mg-doped
 175 CuO nanoparticles is generally in the acidic range. However, the optimal pH may vary depending on the specific dye
 176 molecule being adsorbed. A study on the adsorption of Congo red dye onto Mg-doped CuO nanoparticles found that the
 177 maximum adsorption capacity was achieved at a pH of 6. Overall, the pH of the solution has a significant effect on the
 178 adsorption of dye onto Mg-doped CuO nanoparticles. It is important to optimize the pH of the solution to achieve
 179 maximum adsorption efficiency.
 180
 181

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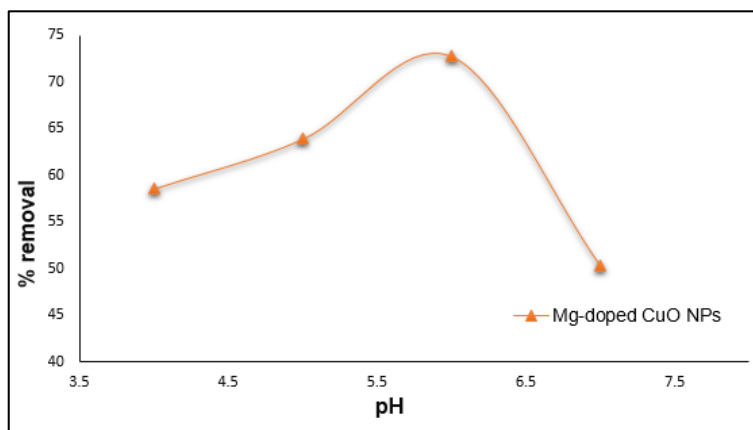


Fig. 3 Effect of pH

Conditions of experiment

Adsorbents = Mg-doped CuO nanoparticles

pH for Dye = 6

concentration = 50ppm

Adsorbent quantity = 0.05g, 0.1g, 0.15g, 0.2g, and 0.25g.

time = 0 second to 1440 minutes

3.3 Effect of Contact Time

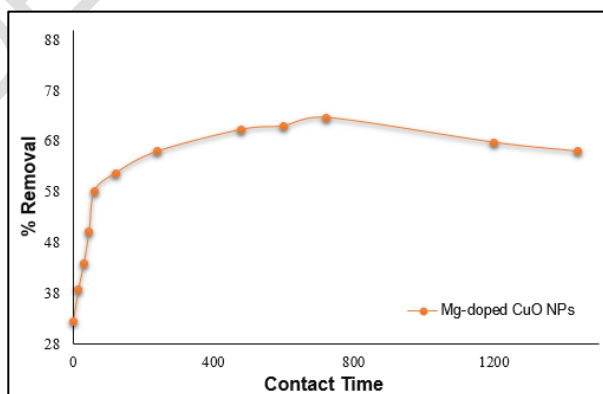
The contact time between the Mg-doped CuO nanoparticles and the dye solution has a significant effect on the adsorption of dye. This is because the contact time determines how long the dye molecules have to interact with the Mg-doped CuO nanoparticles and diffuse to the adsorption sites. At short contact time, there is less time for the dye molecules to interact with the Mg-doped CuO nanoparticles and diffuse to the adsorption sites. As a result, the adsorption efficiency is low. At long contact time, there is more time for the dye molecules to interact with the Mg-doped CuO nanoparticles and diffuse to the adsorption sites. As a result, the adsorption efficiency increases. However, there is a limit to the increase in adsorption efficiency with increasing contact time. This is because all of the active adsorption sites on the surface of the Mg-doped CuO nanoparticles will be saturated at a certain contact time. Any additional contact time will not result in any further adsorption of dye molecules. Therefore, the optimal contact time for the adsorption of dye onto Mg-doped CuO nanoparticles is generally at a moderate level. However, the optimal contact time may vary depending on the specific dye molecule being adsorbed. A study on the adsorption of Congo red dye onto Mg-doped CuO nanoparticles found that the adsorption efficiency increased with increasing contact time, up to a point of saturation.

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204 **Fig. 4 Effect of Contact Time**

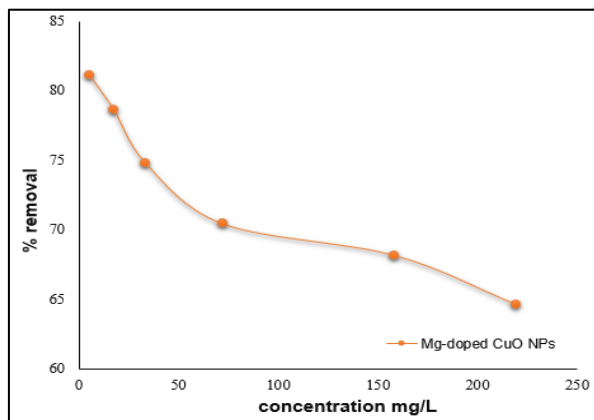
205 **3.4 Effect of Concentration**

206 The initial concentration of the dye solution has a significant effect on the adsorption of dye onto Mg-doped CuO
207 nanoparticles. This is because the initial concentration of the dye solution affects the number of dye molecules available
208 for adsorption. At low initial dye concentration, there are fewer dye molecules available for adsorption. **As a result, the**
209 **adsorption capacity of the Mg-doped CuO nanoparticles is high.** At high initial dye concentration, there are more dye
210 **molecules** available for adsorption. However, the adsorption capacity of the Mg-doped CuO nanoparticles is limited. **As a**
211 **result, the adsorption efficiency decreases.** This is because **all of the** active adsorption sites on the surface of the Mg-
212 doped CuO nanoparticles will be saturated at a high initial dye concentration. Any additional dye molecules will not be
213 able to adsorb onto the Mg-doped CuO nanoparticles. Therefore, the optimal initial dye concentration for the adsorption of
214 dye onto Mg-doped CuO nanoparticles is generally at a low level. However, the optimal initial dye concentration may vary
215 depending on the specific dye molecule being adsorbed. A study on the adsorption of Congo red dye onto Mg-doped CuO
216 nanoparticles found that the adsorption capacity decreased with increasing initial dye concentration.

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217 **Fig. 5 Effect of Concentration**

218 **4EQUILLIBRIUM MODELS**

219 **4.1 Langmuir Adsorption Isotherm**

222 The Langmuir isotherm model assumes that optimum adsorption is achieved when a single layer of solute molecules
223 completely covers the adsorbent surface, and that there is no migration of adsorbate molecules across the surface plane.
224 This model is based on the assumptions that the adsorbent surface is uniform and homogeneous. Each adsorption site
225 can only accommodate one adsorbate molecule. Adsorption is reversible, meaning that both adsorption and desorption
226 can occur simultaneously. There is no interaction between adsorbed molecules[48].

227 The Langmuir isotherm equation relates the concentration of adsorbate in the aqueous solution to the amount of
228 adsorbate adsorbed on the adsorbent surface at equilibrium:

229
$$C_e/q_e = 1/KLq_m + C_e/q_m$$

230 Where C_e is the equilibrium concentration of adsorbate in the aqueous solution (mg/L), q_e is the amount of adsorbate
231 adsorbed on the adsorbent surface at equilibrium (mg/g), q_m is the maximum adsorption capacity of the adsorbent (mg/g),
232 KL is the Langmuir adsorption constant (L/mg)

233 The Langmuir isotherm model is a useful tool for describing the adsorption of a wide variety of substances, including
234 heavy metals, dyes, and organic pollutants. It is particularly useful for systems where monolayer adsorption is the
235 dominant adsorption mechanism. Overall, the Langmuir isotherm model is a valuable tool for understanding and predicting
236 adsorption behavior. However, it is important to note that the model is based on a number of assumptions, and it may not
237 be applicable to all systems.

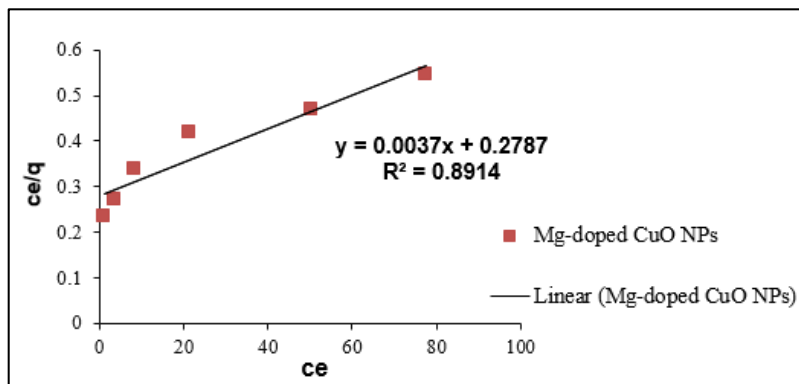


Fig. 6 Langmuir Isotherm

4.2 Freundlich Adsorption Isotherm

The Freundlich isotherm model is an empirical equation that describes the adsorption of solutes on the surface of sorbents. The model is based on the assumptions that the adsorbent surface is heterogeneous, with different adsorption sites having different affinities for the adsorbate. Multilayer adsorption can occur. There is no interaction between adsorbed molecules[49].

The Freundlich isotherm equation is as follows:

$$\log(q_e) = 1/n \log(C_e) + \log(K_f)$$

where: q_e is the amount of adsorbate adsorbed per unit mass of adsorbent at equilibrium (mg/g), C_e is the equilibrium concentration of adsorbate in the aqueous solution (mg/L), K_f is the Freundlich adsorption constant (L/mg), $1/n$ is the Freundlich heterogeneity factor. The Freundlich adsorption constant (K_f) is a measure of the adsorption capacity of the adsorbent. The Freundlich heterogeneity factor ($1/n$) provides information about the nature of the adsorption process. If $1/n$ is less than 1, then the adsorption process is favorable. If $1/n$ is greater than 1, then the adsorption process is unfavorable. Mg-doped CuO NPs have been shown to be effective adsorbents for the removal of heavy metals from aqueous solutions. The Freundlich isotherm model has been used to describe the adsorption of heavy metals onto Mg-doped CuO NPs. Studies have shown that the Freundlich isotherm model fits the experimental data well, indicating that multilayer adsorption is the dominant adsorption mechanism. Overall, the Freundlich isotherm model is a useful tool for describing the adsorption of heavy metals onto Mg-doped CuO NPs. The model suggests that multilayer adsorption is the dominant adsorption mechanism.

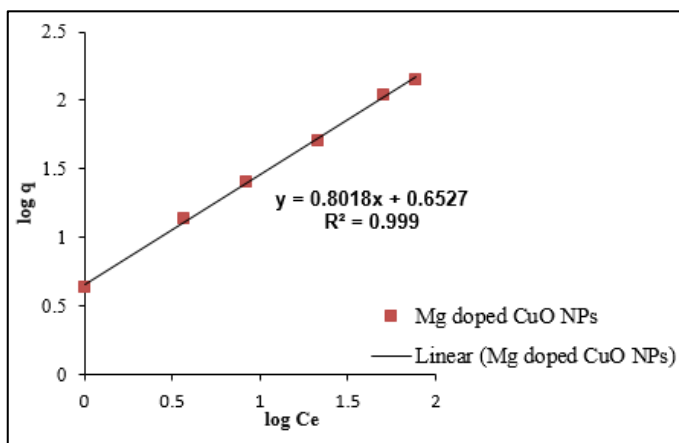


Fig. 7 Freundlich Isotherm

Table 1: Comparison of Models

Langmuir model				Freundlich model			
q_e (exp) (mg/g)	X_m (mg/g)	K_L (L/mg)	R^2	$1/n$	q_e (cal) (mg/g)	K_2 (g mg ⁻¹ min ⁻¹)	R^2
142	75.3	0.0132	0.891	0.801	147	0.426	0.999

4. CONCLUSION

Mg-CuO nanoparticles were synthesized via a facile and cost-effective co-precipitation method and demonstrated outstanding adsorption efficiency for Congo Red dye removal from aqueous solutions. The Langmuir isotherm model and pseudo-second-order kinetic model well-fitted the equilibrium adsorption data and adsorption kinetics, respectively.

Optimal conditions for maximal adsorption efficiency were determined. The thermodynamic analysis indicated that the adsorption of Congo Red onto Mg-CuO nanoparticles was spontaneous and endothermic. The exceptional adsorption performance of Mg-CuO nanoparticles, attributed to the synergistic effect of magnesium doping and high surface area, highlights their potential as an eco-friendly and efficient adsorbent for the removal of Congo Red dye from wastewater.

6. Declarations

Ethical Approval: Not applicable (NA)

Availability of data and materials: Not applicable (NA)

Ethics approval/declarations: Not applicable (NA)

Consent to participate. NA

Consent for publication. NA

Availability of data and material/ Data availability. NA

Code availability (software application or custom code). NA

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