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Review

Metal Oxide-based Nanomaterial as Adsorbents for Methylene Blue Dye Adsorption

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ABSTRACT. Water pollution is caused by synthetic dyes, especially methylene blue (MB), and it has become a major environmental concern, so efficient and sustainable treatment technologies are needed. In this review, the recent advances in the application of metal oxide-based nanomaterials as adsorbents for MB removal from aqueous solutions are summarized. The characteristics of metal oxide nanomaterials, adsorption mechanisms, and effects of key operating parameters, including pH, contact time, initial dye concentration, temperature, and adsorbent dosage, are discussed. In addition, the regeneration and reusability of the adsorbents, as well as the challenges and future prospects for their practical application, are highlighted. Based on recent studies, a high adsorption performance is exhibited by metal oxide-based nanomaterials, such as ZnO, TiO_2, Fe_2O_3, CuO, Mn_3O_4, and their composites, because a large specific surface area, abundant active sites, and tunable physicochemical properties are possessed by them. However, some challenges are still faced, which are related to the synthesis cost, the long-term stability, the regeneration efficiency, and the environmental safety. In future research, green synthesis strategies, enhanced adsorbent stability, and pilot-scale evaluations should be focused on, so the practical implementation of metal oxide-based nanomaterials for sustainable wastewater treatment can be facilitated.

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INTRODUCTION

The textile industry is considered one of the main contributors to water pollution because liquid waste that contains synthetic dyes, heavy metals, salts, and various other chemicals is produced by it. Based on a World Bank report, about 17 – 20% of water pollution is caused by textile industry waste, mainly during the dyeing and finishing of fabrics (Rani *et al*., 2013; Saini, 2017). This pollution has become a growing concern because most synthetic dyes, especially azo dyes, are classified as persistent pollutants that are difficult to degrade naturally, since a complex aromatic structure, conjugated double bonds, and high chemical stability are possessed by them (An, 2007; Maddhinni et al., 2006). In addition to being resistant to biodegradation, several azo dyes are also toxic

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and can produce carcinogenic aromatic amines, thus polluting water bodies and endangering the health of humans and aquatic organisms (Sharma *et al*., 2021).

One of the synthetic dyes that is widely used in the textile industry is MB, which is a cationic thiazine-group dye with the molecular formula $C_{16}H_{18}ClN_3S$ and a molecular weight of 319.85 g/mol (Kuang *et al*., 2020). MB has a high solubility in water, so it is easily dispersed and difficult to separate from liquid waste, and a maximum absorption peak at a wavelength of about 664 nm is shown by it (Makeswari and Saraswathi, 2020; Sabar *et al*., 2020). Besides being widely used in the textile industry, MB is also used in the paper, pharmaceutical, and laboratory fields as a coloring agent. The complex aromatic structure and the system of conjugated double bonds cause MB to have a high chemical stability and to be difficult to degrade naturally (Khan *et al*., 2022). If it is discharged into water bodies without adequate treatment, light penetration can be reduced by MB, the photosynthesis of aquatic organisms can be inhibited, and the dissolved oxygen level can be lowered. Besides its environmental impact, exposure to MB at high concentrations can also cause various health problems, such as skin and eye irritation, digestive tract disorders, methemoglobinemia, respiratory disorders, and tissue damage that is caused by its toxic nature (Santoso *et al*., 2020; Sun *et al*., 2019; Zhou *et al*., 2019). Therefore, the development of an effective technology to remove MB from wastewater has become one of the main focuses in water treatment research.

Various methods have been developed to remove MB from waste or its liquid waste before it is released into the environment. In general, these technologies are grouped into physical, chemical, and biological methods (Dutta *et al*., 2011). Several methods that have been widely applied include coagulation or electrocoagulation, oxidation, photocatalytic degradation, biodegradation, phytoremediation, membrane processes, and liquid–liquid extraction (Churcley, 1998; Mondal, 2008; Stephenson and Duff, 1996). Although these methods have shown effectiveness in removing MB, each of them still has limitations, such as high operational cost, an efficiency that is affected by operating conditions, and the potential formation of by-products (Titchou *et al*., 2020). Therefore, the adsorption method has become one of the most widely developed alternatives because a high removal efficiency, a simple process, and easy regeneration of the adsorbent are offered by it.

Metal oxide-based nanoparticles are one type of nanomaterial that is widely developed as an adsorbent in wastewater treatment. This material has superior characteristics, such as a high specific surface area, good porosity, chemical stability, and abundant active sites (Althomali and Adeosun, 2023). This combination of characteristics increases the interaction between the adsorbent and the adsorbate, so a higher adsorption capacity and pollutant removal efficiency are produced compared with many conventional adsorbents, especially for the MB dye. Although the use of metal oxide-based nanoparticles for MB adsorption has been reported by various studies, these research results are still scattered across various publications with different material types and operating conditions. Therefore, a review that integrates the research development on material characteristics, adsorption mechanisms, factors that affect adsorption performance, and adsorbent reusability is needed. This review article is aimed at reviewing the development of metal oxide-based nanomaterials as adsorbents for methylene blue adsorption by discussing the material characteristics, adsorption mechanisms, factors that affect adsorption performance, reusability, and the challenges and prospects of its development in wastewater treatment.

MECHANISM OF METHYLENE BLUE ADSORPTION

The interaction between the adsorbate molecules and the adsorbent surface can occur through several mechanisms, such as hydrogen bonding, electrostatic interaction, π–π interaction, Van der Waals forces, hydrophobic interaction, and surface pore diffusion (Jefri *et al*., 2025; Rahmadan *et al*., 2021; Stark *et al*., 2025; Yu *et al*., 2020). The adsorption mechanism depends on the characteristics of the adsorbed contaminant. For ionic species, electrostatic interaction and ion exchange are the main mechanisms that play a role in the adsorption process (Jamel *et al*., 2025). Meanwhile, organic compounds tend to interact with the adsorbent through π–π interaction at their aromatic rings (Wasilewska *et al*., 2024). During the adsorption process, various intermolecular interactions can occur simultaneously, so the binding of the adsorbate onto the surface and inside the pore structure of the adsorbent is supported (Almahri *et al*., 2023; Ye *et al*., 2025).

The adsorption of MB using AC-CuO, AC-ZnO, and AC-TiO_2 composite materials that were synthesized from the pyrolysis residue of oily sludge containing CuO, ZnO, and TiO_2 showed that at pH 7, MB was migrated from the solution to the surface of the composite material. Then, at the solid–liquid interface, MB was bound to the active sites of the composite material through liquid-film diffusion and intraparticle diffusion, and it was removed mainly through chemical adsorption (Li *et al*., 2022). Meanwhile, the adsorption of MB using magnesium

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oxide (MgO) and lead oxide (PbO) nanoparticles that were synthesized through the co-precipitation method occurred through a combination of electrostatic interaction and chemisorption. The positively charged MB molecules were attracted toward the negatively charged metal oxide surface through electrostatic forces. Then, the oxygen-containing functional groups on the adsorbent surface acted as active sites that facilitated the formation of chemical bonds through Lewis acid–base interaction, so the MB adsorption capability was increased (Helali *et al*., 2024). A similar result was also shown by a study (Hkiri *et al*., 2024), in which the adsorption of MB onto WO_3 nanoflakes was controlled by the electrostatic interaction between the negatively charged WO_3 surface and the positively charged MB molecules. The negative charge of the WO_3 nanoflakes, which was confirmed through zeta potential analysis, increased its affinity toward MB, especially at low concentrations. As the MB concentration was increased, the adsorption mechanism was developed into a combination of electrostatic interaction and physical adsorption because the active sites on the adsorbent surface began to be saturated. This finding was supported by the results of FTIR analysis, adsorption isotherms, and molecular dynamics simulation, which showed that no new chemical species were formed during the adsorption process, so physical adsorption became a supporting mechanism that played a role at higher MB concentrations.

The adsorption mechanism of MB by iron oxide–hydrochar (FHC) and activated iron oxide–hydrochar (FAC) composites involves hydrogen bonding and π–π interaction. The shift of the absorption bands of the –OH, C=O, and quinone groups after adsorption showed the involvement of the surface functional groups in the formation of hydrogen bonds with the MB molecules. In addition, the change of the bands that are related to the aromatic ring indicated the presence of a π–π interaction between the aromatic structure of the adsorbent and the MB molecules, so the adsorption capability was increased (Hessien, 2023). The adsorption of MB onto the MnO_2@rGO nanocomposite involves several mechanisms that work synergistically, namely electrostatic interaction, π–π interaction, hydrogen bonding, chemisorption, and intraparticle diffusion. The electrostatic interaction is affected by the pH of the solution and the point of zero charge of the adsorbent. At the optimum pH condition, the MnO_2@rGO surface has a charge that supports the attraction with the positively charged MB molecules, so the adsorption affinity is increased. In addition, the graphitic structure of the reduced graphene oxide (rGO), which is rich in π electrons, allows a π–π interaction with the aromatic ring of the MB molecule to occur. The oxygen-containing functional groups, such as hydroxyl (–OH), carbon hydroxyl (C–OH), and epoxy (C–O), also act as active sites that form hydrogen bonds with the nitrogen atom of the MB molecule. The Mn–O group on the metal oxide also contributes through electrostatic interaction with the hydroxyl group of MB, so the binding of the adsorbate onto the adsorbent surface is strengthened. The dominant chemisorption mechanism is supported by the Dubinin–Radushkevich (D–R) isotherm result, which shows that adsorption is not only controlled by physical forces but also involves a chemical interaction between the MB molecules and the active sites of the adsorbent. Overall, the adsorption process is started with the transfer of the MB molecules from the solution toward the MnO_2@rGO surface, is continued with the binding onto the active functional groups through a combination of electrostatic interaction, π–π interaction, hydrogen bonding, and chemisorption, and is ended with the diffusion of the MB molecules into the mesoporous structure of the adsorbent until the adsorption equilibrium condition is reached (Munonde *et al*., 2023).

METAL OXIDE-BASED NANOMATERIALS AS METHYLENE BLUE ADSORBENTS

Metal oxide-based nanomaterials are one group of adsorbents that are widely developed to remove cationic dyes, such as MB, from water. This is caused by their characteristics, which include nanoparticle size, a high specific surface area, good chemical stability, and easy surface modification, so the interaction between the adsorbent and the adsorbate can be increased (Ramesh *et al*., 2018). Various studies, as shown in Table 1, have reported that metal oxides such as ZnO, TiO_2, CuO, ZrO_2, Al_2O_3, SiO_2, Fe_3O_4, MgO, MnO_2, and NiO are able to show a high adsorption efficiency toward MB, although their adsorption mechanisms and capacities differ depending on the properties of the material that is used (Ahangaran and Navarchian, 2020).

Metal oxide-based nanomaterials that are used as MB adsorbents can be grouped into three main types, namely single metal oxides, bimetallic oxides, and multi-metal oxides. Each group of materials has different physicochemical characteristics, which are affected by the chemical composition, the synthesis method, the particle size, and the surface properties. These differences in characteristics contribute to the variation of the MB adsorption capability, with a reported efficiency that ranges between 30% and 99.77%. This shows that the engineering of the composition and structure of the material is an effective strategy to increase the number of

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active sites, to improve the surface properties, and, in the end, to improve the performance of the adsorbent in removing MB from the solution.

Table 1. Metal oxide nanoparticles as methylene blue adsorbents.

Sample	Precursor	Synthesis Method	Particle Size (nm)	Adsorption Efficiency (%)	Reference
ZnO-NPs	$ZnCl_2.6H_2O$	*Green synthesis using Ocimum basilicum extract*	27.196	99.77	(Rorissa *et al*., 2025)
Fe–Mn (nFMBO)	$KMnO_4$, $FeSO_4.7H_2O$	Co-precipitation	496.7	96.5	(Lu *et al*., 2019)
AH-GO@MnO-NiO-ZnO	$Mn(NO_3)_2$, $Ni(NO_3)_2$, and $Zn(NO_3)_2$	Hydrothermal	-	93.05	(Barooah *et al*., 2024)
$NiFe_2O_4$	$Ni(NO_3)_2$, $Fe(NO_3)_3$, chitosan	*Sol–gel auto-combustion*	11,5	96.8	(Alshehri *et al*., 2025)
ZrO_2	$ZrOCl_2.8H_2O$	*Green synthesis using Sapindus mukorossi pericarp extract*	5	94	(Alagarsamy *et al*., 2022)
MgO	$Mg(NO_3)_2$	Co-precipitation	12,25	~40	(Helali *et al*., 2024)
PbO	$Pb(NO_3)_2$	Co-precipitation	69	~30	(Helali *et al*., 2024)
$NiO–SiO_2$	TEOS, CTAB, $Ni(NO_3)_2·6H_2O$	Modified Stöber method and impregnation	40-60	88.2	(Davoudi, 2022)
$CN–Fe_2O_3$	$FeSO_4·7H_2O$	*Green synthesis using Cola nitida leaf extract*	-	99	(Mbachu *et al*., 2023)
CuO@AC	$CuSO_4.4H_2O$ and dried pods of P. juliflora	Co-precipitation	28	>95	(Farooq *et al*., 2022)
AC-ZrO_2/CeO_2	AC, $ZrCl_4$, $CeCl_3·7H_2O$	Co-precipitation	231,83	72.96	(Zhang *et al*., 2024)
Mn_3O_4–Bi_2O_3	$Bi(NO_3)_3·5H_2O$) and ($Mn(NO_3)_2·4H_2O$)	Precipitation and wet impregnation	-	~95	(Al-saeedi *et al*., 2023)

Single metal oxides are binary oxides that are composed of one type of metal cation and an oxygen anion, such as ZnO, ZrO_2, MgO, and PbO. This material is widely used because it has a good stability, is easily obtained, is relatively cheap, and has redox activity that supports various applications, including adsorption. However, single metal oxides have limitations, such as a lower activity compared with noble metals and a limited number of active sites, especially in non-porous materials that only use the outer surface to interact with the adsorbate (Mabate *et al*., 2023). Among the single metal oxides, ZnO shows the best performance with an adsorption efficiency of 99.77%, followed by ZrO_2 at 94%. In contrast, MgO and PbO are only able to adsorb MB by about 40% and 30%, respectively. This difference shows that each metal oxide has a different affinity toward the MB molecule. Based on a study Rorissa et al. (2025), the high adsorption efficiency of ZnO is not only affected by its relatively small particle size but also by its surface characteristics. The FTIR characterization result showed the presence of hydroxyl (–OH), carbonyl (C=O), and C–O groups on the surface of the ZnO nanoparticles, which act as active sites in the adsorption process. The decrease in the intensity of the absorption bands of the –OH and C=O groups

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after adsorption, together with the appearance of new peaks that came from MB, indicated that an interaction between the dye molecules and the adsorbent surface occurred. In addition, the ZnO nanoparticles have a pH pzc value of about 4.35, so at a pH above this value the surface becomes negatively charged. This condition increases the electrostatic attraction toward the cationic MB molecules, so its adsorption efficiency becomes higher. In contrast, MgO and PbO show a lower adsorption efficiency because the number of available active sites is relatively limited. The adsorption process on both materials occurs quickly in the early stage because of the many empty active sites, and then it slows down as the adsorbent surface becomes saturated (Helali *et al*., 2024).

Several studies have developed bimetallic oxides, such as Fe–Mn (nFMBO), $NiFe_2O_4$, and Mn_3O_4–Bi_2O_3, to increase the number of active sites and to improve the surface properties. The combination of two types of metals can produce a synergistic effect in one adsorbent with a superior adsorption capability in removing contaminants compared with mono-metal oxides (Chen *et al*., 2018; Pan *et al*., 2014; Pazhoor *et al*., 2021). This synergistic effect is reflected by the high adsorption efficiency that is shown by the three bimetallic materials. This improvement in adsorption performance is related to the formation of more surface hydroxyl groups, an increase in the heterogeneity and distribution of active sites, and an improvement in the redox properties of the material. These characteristics strengthen the interaction between the adsorbent and the methylene blue molecules through the mechanisms of electrostatic attraction, surface complex formation, hydrogen bonding, and electron transfer, so the adsorption process occurs more effectively than on single metal oxides (Al-saeedi *et al*., 2023; Alshehri *et al*., 2025; Lu *et al*., 2019).

The development of nanoadsorbents is further directed toward the formation of multi-metal oxides and composite materials to overcome the limitations of single and bimetallic oxides. Multi-metal oxides combine more than two types of metals, so a more complex synergistic effect is produced, which not only increases the number of active sites, the surface charge distribution, and the redox properties of the material but also improves the physicochemical characteristics and reduces the tendency of nanoparticle agglomeration. This improvement in characteristics increases the interaction between the adsorbent and the MB molecules, so its adsorption performance becomes more optimal (Stankic *et al*., 2016). Meanwhile, composite materials are obtained through the combination of metal oxides with supporting materials, such as graphene oxide (GO), activated carbon (AC), and silica (SiO_2), which function to increase the specific surface area, to prevent nanoparticle agglomeration, to improve the structural stability, and to facilitate the diffusion of the adsorbate toward the active sites (Puttaningaiah, 2024). Examples of materials that have been developed include AH-GO@MnO–NiO–ZnO as a graphene oxide-based multi-metal oxide, and CuO@AC, NiO–SiO_2, and AC-ZrO_2/CeO_2 as metal oxide-based composites. In general, multi-metal and composite materials show a high adsorption efficiency because of the synergistic effect among the components, which increases the number of surface functional groups, the specific surface area, and the availability of active sites. However, the formation of a composite material does not always produce an improvement in adsorption performance, because its effectiveness is also affected by the proportion of each component, the homogeneity of the metal oxide dispersion, the strength of the interphase interaction, and the surface characteristics that are formed during the synthesis process.

Besides the type of material, the selection of the precursor also plays an important role in determining the characteristics of the adsorbent because the nucleation process, the crystal growth, the phase composition, the morphology, and the surface properties of the nanoparticles are affected by it (Khan *et al*., 2022). Metal salts such as nitrates, chlorides, and sulfates are widely used as precursors because they have a high solubility, so a homogeneous distribution of metal ions is produced and the formation of crystal nuclei during synthesis is made easier. The homogeneity of the precursor solution contributes to the formation of a material with a more uniform crystallinity, particle size, and morphology. In addition, the type of precursor also determines the chemical composition, the porosity, and the surface characteristics of the material that is produced (Kar *et al*., 2025; Seisenbaeva and Kessler, 2014). In the green synthesis method, the plant extract not only acts as a reducing agent but also as a capping agent that controls the nucleation process, the crystal growth, and the stabilization of the nanoparticles. Various secondary metabolite compounds, such as flavonoids, polyphenols, tannins, terpenoids, alkaloids, and saponins, act as electron donors to reduce the metal ions and at the same time form a protective layer on the surface of the nanoparticles. This mechanism is able to inhibit agglomeration, to control crystal growth, and to produce nanoparticles with a more uniform size and morphology. Besides increasing the stability of the nanoparticles, the presence of organic functional groups on the surface of the material can also enrich the number of active sites and increase the affinity of the adsorbent toward the methylene blue molecules through electrostatic interaction and hydrogen bonding (Alouani *et al*., 2026; Hameed *et al*., 2023; Jadoun *et al*., 2021).

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The synthesis method gives a direct effect on the formation of the crystal structure, the morphology, the particle size, and the surface characteristics of the adsorbent. Synthesis parameters, such as pH, temperature, reaction time, precursor concentration, and the calcination process, control the rate of nucleation and crystal growth, so the size and distribution of the produced particles are determined. Green synthesis produces nanoparticles through a biological reduction mechanism that occurs gradually, so the crystal growth is more controlled and agglomeration can be minimized (Mel *et al*., 2025). This is reflected in ZnO and CN–Fe_2O_3, which show a very high adsorption efficiency (Mbachu *et al*., 2023; Rorissa *et al*., 2025). The co-precipitation method produces the formation of crystal nuclei quickly through a precipitation process, so it is widely used because it is simple, economical, and easy to apply for the synthesis of metal oxides and multi-component materials. However, the quality of the produced material is strongly affected by the synthesis conditions, so a varied adsorption performance is produced (Li *et al*., 2023). The hydrothermal method uses high pressure and temperature to produce crystals with a more uniform morphology and a better crystallinity (Suhaimia *et al*., 2020; Wijanarko and Irfa'i, 2023), whereas the sol–gel auto-combustion method allows the mixing of metal ions at the molecular level, so nanoparticles with a small size and a homogeneous distribution are produced (Azevedo *et al*., 2026; Niu *et al*., 2017). Meanwhile, the Stöber method that is combined with impregnation produces a more even dispersion of the metal oxide on the silica matrix, so the structural stability and the availability of active sites are increased (Davoudi, 2022).

Particle size is one of the parameters that is most often related to adsorption performance because it is closely related to the ratio of surface area to volume (Pisceselia *et al*., 2026). Based on Table 1, the particle size of the nanoadsorbents ranges between 5 and 496.7 nm. In general, a smaller particle size increases the specific surface area, so the number of available active sites becomes larger and the diffusion distance of the adsorbate toward the adsorbent surface becomes shorter. This condition increases the frequency of collision between the MB molecules and the adsorbent surface, so the adsorption process occurs more effectively (Anisara *et al*., 2024; Khan *et al*., 2022; H. Li *et al*., 2022). This tendency is seen in ZnO, $NiFe_2O_4$, and ZrO_2, which have a relatively small particle size with a high adsorption efficiency (Alagarsamy *et al*., 2022; Alshehri *et al*., 2025; Rorissa *et al*., 2025). However, the relationship between particle size and adsorption efficiency is not always linear. Fe–Mn (nFMBO), for example, still shows a high adsorption efficiency although it has a much larger particle size compared with the other materials. This shows that particle size is not the only factor that determines the performance of the adsorbent (Lu *et al*., 2019). The specific surface area, the pore volume and diameter, the morphology, the crystallinity, the distribution of hydroxyl groups, and the surface chemical properties also give a significant contribution to the adsorption process, because these parameters determine the number of active sites that can interact with the methylene blue molecules and affect the diffusion mechanism and the bonding between the adsorbent and the adsorbate.

FACTORS AFFECTING METHYLENE BLUE ADSORPTION ON METAL OXIDES

The adsorption process is affected by several factors, such as pH, initial concentration, contact time, and adsorbent dosage. The optimization of these parameters will give a better description of the design of a large-scale wastewater treatment installation. Table 2 shows the important factors that affect the adsorption process.

Solution pH

One of the important factors that affects the adsorption process is the pH of the solution. The pH value can change the surface charge of the adsorbent, the degree of ionization of the functional groups, the speciation of the adsorbate, and the solubility of the adsorbate, so the interaction between the adsorbent and the adsorbate is affected (Egbosiuba and Abdulkareem, 2021; Qulub *et al*., 2024). A change in pH is generally carried out by adding an HCl or NaOH solution until the desired pH is reached, and then the mixture is stirred until the adsorption equilibrium is reached (Wardhani and Yahya, 2025). In the adsorption of MB, an increase in pH generally increases the adsorption capacity until an optimum condition is reached. At a low pH, the high concentration of H^+ ions causes the protonation of the adsorbent surface, so the adsorption of MB is inhibited because of the competition of the H^+ ions with the MB molecules for the active sites and the electrostatic repulsion. In contrast, at a higher pH, the adsorbent surface is deprotonated, so it becomes negatively charged and the electrostatic attraction toward the cationic MB is increased (Dwijayanti *et al*., 2020; Tubon-Usca *et al*., 2025).

This phenomenon is shown by Ngatijo *et al*. (2021) and Onu *et al*. (2023), which reported that the adsorption of MB onto Fe_3O_4-humic acid and PG-NiONPs adsorbents reached an optimum condition at pH 6. At a higher pH,

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the adsorption capacity began to decrease because of the increased competition of the OH^- ions with the MB molecules in occupying the active sites of the adsorbent. Meanwhile, the results of a study by Singh *et al*. (2017) showed that the removal efficiency of MB using Fe_3O_4@GTPs reached about 95% at pH 7. Under acidic conditions, the adsorption efficiency decreased because of the protonation of the polyphenolic hydroxyl groups on the adsorbent surface, whereas at a pH above 7 the efficiency only increased slightly, so a neutral pH was chosen as the optimum condition. A similar trend was also reported for CuO nanoparticles, which showed an increase in MB adsorption efficiency as the pH was increased until a maximum value of 82.05% was reached at pH 8 (Essa, 2024).

Table 2. Factors affecting adsorption.

Adsorption Factor	Effect on Adsorption	Main Characteristics
pH	A change in pH affects the surface charge of the adsorbent, the ionization degree of the dye, and the electrostatic interaction between the adsorbent and the adsorbate.	Controls the surface charge of the adsorbent and the speciation of the dye, so the adsorption efficiency is determined.
Contact time	An increase in contact time increases the amount of adsorbed adsorbate until the equilibrium condition is reached.	Describes the stages of adsorption, from fast adsorption to a slowdown of the adsorption rate until equilibrium.
Initial concentration	An increase in initial concentration increases the adsorption capacity, but the removal efficiency can decrease when the active sites begin to be saturated.	Determines the mass transfer driving force and utilization level of the active sites of the adsorbent.
Temperature	An increase in temperature can increase or decrease the adsorption capacity, depending on the thermodynamic nature of the process.	Adsorption can be exothermic or endothermic.
Adsorbent dosage	An increase in the adsorbent dosage increases the surface area and the number of active sites, so that the adsorption efficiency increases until the optimum dosage is reached.	Determines the number of available active sites and the optimum adsorbent dosage in the adsorption process.

Contact Time

Contact time is one of the important parameters that affects the efficiency of the adsorption process because it determines the length of the interaction between the adsorbate molecules and the adsorbent surface (Handayani et al., 2023). A variation of the contact time is carried out to find the optimum time that is needed so that the adsorption process reaches equilibrium (Lismawati and Nasra, 2024). The principle of the effect of contact time on the adsorption process is that the longer the contact time, the more adsorbate will be adsorbed because the adsorbent surface or the active sites have a greater chance to meet the adsorbate. However, after the equilibrium condition is reached, an increase in contact time no longer gives a significant increase in the adsorption capacity (Febriani *et al*., 2022; Jamel *et al*., 2025).

The result of a study by Alprol *et al*. (2024) on the adsorption of MB using green-synthesized ZnO nanoparticles showed that the removal efficiency increased as the contact time increased. The percentage of MB removal at a contact time of 5 – 30 minutes was still relatively low, namely 43.97 – 64.98%, whereas at a contact time of 60 – 180 minutes it increased to 76.84 – 79.80%. This increase showed that a longer contact time gave a greater chance for the MB molecules to interact with the ZnO surface, so the number of adsorbed molecules increased more. In the early stage, adsorption occurred quickly because the effective surface area and the number of available active sites were still quite large, so the MB molecules could easily be bound onto the adsorbent surface through a diffusion mechanism from the solution toward the adsorbent surface. However, after most of the active sites began to be filled, the adsorption rate became slower, so the increase in removal efficiency at a longer contact time was no longer as large as in the early stage.

A similar phenomenon was also reported by Jaramillo-Fierro and Cuenca (2024), who showed that an increase in contact time increased the adsorption capacity of MB on the GO/ZTO/TO composite. In the early stage (0 – 50 minutes), the adsorption capacity increased quickly because many active sites were still available and the mass transfer occurred more effectively. Then, the adsorption rate began to slow down as the number of empty active sites decreased. At a longer contact time (150 – 450 minutes), the adsorption curve approached the

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equilibrium condition, so an addition of contact time only gave an insignificant increase in adsorption capacity because most of the adsorption sites had been filled. Besides these two studies, several other metal oxide-based adsorbents also showed the same tendency. Although the reported optimum contact time varied, all of the studies showed that the adsorption of MB occurred very quickly in the early stage, and then the adsorption rate decreased until the equilibrium condition was reached. This pattern was reported for the adsorption of MB using CuO nanoparticles by Yadav *et al*. (2024), ZnO nanoparticles by Chemingui *et al*. (2023), TiO_2 and ZnO thin films by Vallejo *et al*. (2023), and the ZnO/TiO_2 composite by Praipipat *et al*. (2024). This difference in optimum time is affected by the characteristics of the adsorbent, such as the specific surface area, the pore volume and distribution, the particle size, the crystallinity, and the number of available active sites. Adsorbents with a larger surface area and a larger number of active sites generally provide more binding places for the MB molecules, so the mass transfer in the early stage is accelerated and the maximum adsorption capacity can be reached in a relatively shorter time.

Initial Concentration

The initial concentration of the dye is an important parameter in the adsorption process, because a certain mass of adsorbent can only interact with a certain amount of dye (Sahu and Singh, 2019). A UV-Vis spectrophotometer is used to calculate the amount of MB before and after adsorption. The amount of removed pollutant is strongly affected by the initial concentration of the contaminant and the active groups that are available on the adsorbent surface (Albroomi *et al*., 2017). Various studies have shown that an increase in the initial concentration of MB generally causes a decrease in removal efficiency, although the adsorption capacity increases. Zango *et al*. (2022) reported that an increase in the initial concentration of MB from 50 to 250 mg/L decreased the adsorption efficiency because of the limited number of active sites on the ZnO-chitosan nanocomposite. A similar result was also reported by Barooah *et al*. (2024), who obtained a decrease in removal efficiency from 93.79% at an initial concentration of 20 mg/L to 74.08% at 100 mg/L using the AH-GO@MnO-NiO-ZnO composite. The same decrease was also observed by Farooq *et al*. (2022), in which the removal efficiency of MB decreased from 96% to 81% when the initial concentration was increased from 5 to 25 mg/L. This phenomenon is caused by the increasing number of MB molecules that compete to occupy the limited number of active sites on the adsorbent surface. As the adsorption process proceeds, the number of available active sites decreases until finally a saturated condition is reached, so the removal efficiency decreases at a higher initial concentration.

In contrast, an increase in the initial concentration of MB generally increases the adsorption capacity because a larger mass transfer driving force is produced, so more MB molecules are diffused toward the adsorbent surface. This is shown by Farooq *et al*. (2022), who reported an increase in adsorption capacity from 2.5 mg/g to 12.5 mg/g as the initial concentration of MB was increased. Nevertheless, an adsorbent with good surface characteristics is still able to maintain a high removal efficiency at a large initial concentration. As an example, Yu *et al*. (2021) reported that the ZnO/Biochar-25% adsorbent was still able to remove MB with an efficiency of up to 95.19% at a high initial concentration, namely 160 mg/L, which showed that the surface area, the number of active sites, and the pore structure of the adsorbent play an important role in maintaining the adsorption performance under conditions of a high adsorbate concentration.

Temperature

Temperature can affect the performance of the adsorbent in the adsorption of gas or dissolved substances because it is related to the adsorption capacity. The effect of temperature can be studied by varying the temperature of the system while keeping the other parameters constant. In an exothermic adsorption, the adsorption capacity tends to decrease as the temperature increases, whereas in an endothermic adsorption, the adsorption capacity increases as the temperature increases (Akpasi and Isa, 2022). Various studies on adsorption using metal oxide-based adsorbents have shown that the adsorption process is generally endothermic. Mbachu *et al*. (2023) reported that an increase in temperature increased the adsorption capacity of MB until an optimum condition was reached, and then the adsorption capacity decreased at a higher temperature because the equilibrium of the system was reached. A similar result was also obtained by Onu *et al*. (2023), who reported an increase in the adsorption capacity of MB by PG-NiONPs nanoparticles from 320.13 mg/g to 483.50 mg/g when the temperature was increased from 25 to 50 °C. This increase was caused by the increased kinetic energy of the MB molecules, so the diffusion rate toward the adsorbent surface was increased and the mass transfer resistance was reduced. In line with this result, Li *et al*. (2025) showed that an increase in temperature increased the amount of adsorbed MB

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because the movement of the molecules was accelerated and the interaction between the adsorbate and the active sites of the adsorbent was made easier. The same finding was also reported by Zhang *et al*. (2020) on the adsorption of MB using a biochar/Fe_xO_y composite, in which the adsorption capacity increased as the temperature of the system was increased, which indicated that the adsorption process was endothermic. In general, these results show that an increase in temperature can increase the adsorption capacity of MB by accelerating the diffusion of the adsorbate molecules toward the adsorbent surface. However, if the temperature exceeds the optimum condition, the adsorption capacity can decrease because the adsorption equilibrium is disturbed or the stability of the interaction between the adsorbate and the adsorbent is reduced.

Adsorbent Dosage

The adsorbent dosage is an important parameter that determines the efficiency of the adsorption process because it is related to the number of active sites that are available to bind the adsorbate. Generally, an increase in the adsorbent dosage increases the removal efficiency until an optimum condition is reached, because more surface and active sites are available to interact with the adsorbate molecules. However, after almost all of the adsorbate molecules are adsorbed, an addition of adsorbent dosage no longer gives a significant increase in efficiency because the equilibrium of the system is reached (Dey *et al*., 2024). Tara *et al*. (2025) reported that an increase in the dosage of the rGO-BC@ZrO_2 nanocomposite from 0.5 to 2.0 g/L increased the removal efficiency of MB from about 25% to 96%, whereas an addition of dosage up to 3.0 g/L only gave a very small increase up to nearly 100%. This showed that the number of available active sites had been enough to adsorb almost all of the MB molecules in the solution. A similar result was also reported by Zhang *et al*. (2020), which showed that the amount of adsorbed MB increased as the adsorbent dosage was increased up to about 2 g/L because the number of available active sites was increased. However, at a higher dosage, the adsorption performance actually decreased. This decrease was related to the reduced amount of MB molecules per unit mass of adsorbent and the aggregation of the adsorbent particles, which caused some of the active sites to no longer be accessed effectively. A consistent finding was also reported by Gritli *et al*. (2024) on the adsorption of MB using Fe_3O_4 nanoparticles, in which an increase in adsorbent dosage increased the removal efficiency until an optimum dosage of 1.4 g/L was obtained. After the optimum dosage was reached, an addition of adsorbent no longer gave a meaningful increase because the amount of MB molecules became the limiting factor of the adsorption process. In addition, a study on ZnO from battery recycling by Hasan *et al*. (2024) showed that the optimum adsorbent dosage for MB adsorption was 0.5 g, whereas an addition of dosage above this value did not increase the efficiency significantly because most of the MB molecules had been adsorbed and the active sites became excessive compared with the amount of available adsorbate.

REUSABILITY OF ADSORBENTS

Reusability is an important parameter for evaluating the stability of an adsorbent after repeated use. A high reusability indicates that the adsorbent has structural durability and maintains its active sites, making it more economical and potentially applicable in wastewater treatment. Various studies have shown that metal oxide-based adsorbents have good stability, although a decrease in adsorption efficiency occurs after several cycles of use. Al-saeedi *et al*. (2023) reported that the 5% Mn_3O_4–Bi_2O_3 adsorbent was still able to remove MB by 95%, 90%, 83%, and 76% in the first until the fourth cycle, respectively, indicating good reusability. A similar result was reported by Tara *et al*. (2025), in which the rGO-BC@ZrO_2 nanocomposite that was regenerated using 0.2 M HCl still maintained a high adsorption efficiency after five adsorption–desorption cycles, with a decrease in efficiency of about 40% compared with the initial cycle. In addition, Zango *et al*. (2022) showed that the ZnO-chitosan nanocomposite was still effectively used up to six cycles, although the adsorption efficiency decreased from 93.39% to 54.04% on the 5 wt.% ZnO-chitosan composite and from 99.95% to 59.05% on the 10 wt.% ZnO-chitosan composite. This decrease in performance is generally caused by the reduced number of active sites because of the MB molecules that are still left on the adsorbent surface after the regeneration process. This finding is supported by Mbachu *et al*. (2023), who reported that CN–Fe_2O_3NPs still maintained an MB removal efficiency of 88% after six cycles of use. The FTIR and XRD characterization results showed a minimal change of the functional groups and the crystal structure, which indicated that the adsorbent remained stable during the regeneration process. In general, these various studies show that metal oxide-based adsorbents have a good reusability potential, although the adsorption efficiency tends to decrease gradually because of pore blockage, surface fouling, or a regeneration that does not fully release the adsorbate molecules from the adsorbent surface.

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CHALLENGES AND FUTURE PROSPECTS

Metal oxide-based nanomaterials have been developed as promising adsorbents for removing MB from wastewater because they have a high surface area, abundant active sites, and good adsorption capacity. Various studies have also shown that this material can reach a high removal efficiency and can be regenerated; therefore, it has the potential to be reused in several adsorption cycles. However, its implementation on an industrial scale still faces several challenges that need to be overcome. The synthesis process of nanomaterials generally requires complex preparation stages, relatively high energy consumption, and the use of certain chemicals that can increase the production cost and reduce sustainability. In addition, the stability of the adsorbent during repeated use is still a concern because the adsorption capacity can decrease because of surface fouling, pore blockage, particle aggregation, or a reduced number of active sites. Other challenges include the separation process of the nanoparticles from the water medium after adsorption and the limited information about the long-term toxicity, bioaccumulation, and impact of the nanomaterials on the environment; therefore, a more comprehensive risk study and regulation are needed before an application on a wide scale.

Research development in the last few years shows that metal oxide-based nanomaterials have very promising prospects as adsorbents for dye waste treatment. The development of green synthesis methods using biomass, plant extracts, or microorganisms has become one approach that has the potential to produce a more environmentally friendly, economical, and sustainable adsorbent. In addition, the development of metal oxide-based nanocomposites combined with carbon materials, biopolymers, or magnetic materials can increase the surface area, number of active sites, and stability, and can make the separation and regeneration process of the adsorbent easier. The integration of adsorption capability with photocatalytic, antimicrobial, or other advanced treatment properties also opens an opportunity to increase the efficiency of wastewater treatment in an integrated system. Future research needs to be focused on pilot-scale testing, the evaluation of performance on real wastewater, an economic analysis, and a life cycle assessment in order to bridge the gap between laboratory research and industrial implementation. With the support of material innovation, a more effective regeneration technology, and adequate regulation, metal oxide-based nanomaterials have the potential to become an efficient, safe, and sustainable adsorption technology in dye waste treatment in the future.

CONCLUSION

Metal oxide-based nanomaterials are a promising adsorbent to remove MB from wastewater because they have a high surface area, abundant active sites, and a good adsorption capacity. Their adsorption performance is affected by pH, contact time, initial concentration, temperature, and adsorbent dosage, so the optimization of these parameters is needed to reach the maximum efficiency. In addition, various metal oxide-based adsorbents show a good regeneration and reusability, although their efficiency tends to decrease after several cycles. The development of a more environmentally friendly synthesis method, an improvement in the stability of the adsorbent, and testing on a real scale are needed so that metal oxide-based nanomaterials can be applied sustainably in dye waste treatment.

CONFLICT OF INTEREST

There is no conflict of interest in this article.

AUTHOR CONTRIBUTIONS

FNF: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Visualization, Writing of the Manuscript Draft, and Manuscript Revision; AR: Validation, Methodology, Manuscript Review and Editing. DAWP: Data Analysis, Manuscript Review and Editing; SNH: Supervision, Project Administration, Validation, and Manuscript Review and Editing.

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DECLARATION OF GENERATIVE AI

During the preparation of this work, the authors used Elicit to review the literature, QuillBot to paraphrase, and ChatGPT for translation so that the text became clearer, more concise, and more accurate. After these tools or services were used, the content was reviewed and edited by the authors as needed, and full responsibility for the content of the published article is taken by the authors.

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