

บทความวิจัย (Research Article)

Decolorization of Methylene Blue and Malachite Green Using *Hydrilla* (*Hydrilla verticillata*)

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ABSTRACT

This study evaluated the decolorization performance of *Hydrilla verticillata* in water contaminated with methylene blue (MB) and malachite green (MG) at an initial dye concentration of 100 mg/L under continuous fluorescent illumination (24 h). MB exhibited a gradual decrease in absorbance, achieving 87% decolorization after 24 h and 93% after 96 h. MG was decolorized more rapidly, reaching 43% after 1 h and complete (100%) decolorization after 72 h. After 96 h, total Kjeldahl nitrogen (TKN) increased significantly ($p < 0.05$), whereas dissolved oxygen (DO) decreased significantly ($p < 0.05$) in both treatments, while pH remained stable (6–7). FT-IR spectra of MB and MG before and after treatment showed similar characteristic absorption bands, with no detectable changes in the major peaks, indicating that no detectable structural changes occurred in the dye molecules during the experimental period.

1. Introduction

Nowadays, synthetic dyes such as methylene blue (MB) and malachite green (MG) are widely used in the textile, leather, paper, aquaculture, and laboratory industries. They are inexpensive, readily available, and highly effective, making them popular for a wide range of industrial and laboratory applications. However, these same properties contribute to their persistence in aquatic environments and their widespread occurrence in contaminated water bodies. Their intense color and resistance to natural degradation make their removal from wastewater a major environmental challenge. When released into natural water bodies, these dyes can exert severe toxic effects on aquatic ecosystems. They reduce light penetration and dissolved oxygen levels, thereby inhibiting photosynthesis in submerged aquatic plants. As a result, aquatic vegetation gradually declines, leading to reduced food availability and oxygen supply for aquatic organisms. Furthermore, because of their chemical stability, synthetic dyes can persist in the environment for extended periods. They may also bioaccumulate in aquatic organisms, enter the food chain, and ultimately pose toxic risks to higher organisms, including humans. Even at low concentrations, these dyes have been reported to exhibit mutagenic, teratogenic, and carcinogenic effects, raising serious environmental and public health concerns. The oral median lethal dose (LD₅₀) of methylene blue and malachite green in rats has been reported to be 1,180 and 275 mg/kg, respectively (Clemmensen et al., 1984; Seif et al., 2004; Abdullah et al., 2016). Conventional wastewater treatment methods, such as chemical oxidation, membrane filtration, and activated carbon adsorption, are often expensive, require sophisticated infrastructure, and may generate secondary pollutants. As an alternative, phytoremediation, which uses plants to remove, degrade, or stabilize contaminants, has attracted increasing attention as a simple, cost-effective, and environmentally friendly approach. This technique is particularly suitable for developing countries and small-scale wastewater treatment systems because of its low operating cost, minimal energy requirements, and sustainable nature. Successful phytoremediation depends on selecting plant species that can tolerate and grow well in contaminated water while effectively removing pollutants.

The use of aquatic plants has been recognized as an effective alternative for wastewater treatment. *Hydrilla verticillata*, a submerged macrophyte, has shown considerable potential for phytoremediation because of its rapid growth, high biomass production, and large surface area, which enhance its capacity to adsorb and accumulate pollutants, including synthetic dyes. As a submerged aquatic plant, *H. verticillata* absorbs water, nutrients, and dissolved substances directly from the surrounding water through its leaves and stems. Its tissues contain extensive aerenchyma that facilitate gas exchange and buoyancy in aquatic environments (Sriphen, 1987). In addition, hydrilla propagates easily and is widely distributed in freshwater ecosystems, making it a readily available and sustainable plant for wastewater treatment. It is also commonly cultivated in aquaria and aquaculture ponds, where it provides shelter for aquatic organisms, improves water quality, and contributes to oxygen production. Because of these characteristics, *H. verticillata* has considerable potential for the remediation of dye-contaminated wastewater. Therefore, the aim of this study was to evaluate the decolorization of methylene blue (MB) and malachite green (MG) in contaminated water using *H. verticillata*.

2. Materials and methods

2.1 Collection and preparation of plant

H. verticillata was collected from the greenhouse of the Department of Botany. The plant was washed thoroughly with tap water and distilled water to remove dirt. The acclimatization was done in laboratory conditions with tap water only for 7 days under contact of natural sunlight.

Table 1 Characteristics of methylene blue and malachite green

Parameters	Methylene Blue	Malachite Green
Molecular formula	C ₁₆ H ₁₈ N ₃ SCl	C ₂₃ H ₂₅ ClN ₂
Molecular weight (g/mol)	319.851	364.911
Color index number	52015	42000
Density (g/ml)	1.0	1.0448
Melting point (°C)	190	158-160
λ _{max} (nm)	664	618

2.2 Synthetic water of methylene blue and malachite green

Methylene blue (MB) was obtained from the Department of Biology, whereas malachite green (MG) was obtained from the Department of Microbiology. Synthetic dye solutions of MB and MG were prepared at an initial concentration of 100 mg/L following the method described by Karaghool et al. (2022). This concentration was selected because it is widely used in laboratory-scale dye removal studies, provides reliable spectrophotometric measurements, and represents a relatively high contaminant loading for evaluating treatment performance. Each dye solution was prepared to a final volume of 1,000 mL and used as synthetic wastewater in the subsequent experiments. Approximately 20 g (fresh weight) of *H. verticillata* was placed in a 2,000-mL glass beaker containing the dye solution. The decolorization of MB and MG by *H. verticillata* was monitored using a UV-visible spectrophotometer (Model V-5100, Serial No. AD2203026, METASH Instruments, Shanghai, China) at wavelengths of 664 nm and 618 nm for MB and MG, respectively.

2.3 Water quality analysis

The following parameters: TKN (Total Kjeldahl Nitrogen), dissolved oxygen (DO), pH and temperature (T) were measured for the dye-contaminated water before and after the experiment using standard laboratory procedures.

2.4 Experimental setup for removal of methylene blue and malachite green

Twelve glass beakers were prepared, consisting of six control groups without *H. verticillata* (three containing methylene blue and three containing malachite green) and six treatment groups with *H. verticillata* (three containing methylene blue and three containing malachite green). Each group was prepared in triplicate, and each beaker contained 1,000 mL of synthetic dye solution with either methylene blue or malachite green at an initial concentration of 100 mg/L. The treatment groups were supplemented with 20 g (fresh weight) of *H. verticillata* and maintained at room temperature under continuous fluorescent illumination at approximately 4,000 lux. This light intensity was selected to provide stable and reproducible lighting conditions throughout the experiment while supporting the photosynthetic activity of *H. verticillata*. Water samples were collected after 1, 2, 3, 4, 5, 24, 48, 72, and 96 h of treatment and filtered through Whatman No. 40 filter paper prior to analysis. The absorbance of each sample was measured at 664 nm for methylene blue and 618 nm for malachite green using a UV-visible spectrophotometer until the absorbance reached zero or a near-zero value.

2.5 Characterization of methylene blue and malachite green by FT-IR spectroscopy (Model: Spectrum Two, PerkinElmer, U.S.A)

Water samples from the experimental group containing MB and MG were subjected to FT-IR analysis both prior to and following the experiment. This comparative assessment aimed to determine whether any structural

alterations of MB and MG occurred during the course of the experiment. FT-IR analysis was performed using dye solutions collected at the end of the 96 h treatment period.

2.6 Analysis of dye decolorization

The decolorization of methylene blue and malachite green was evaluated using spectrophotometric analysis. Water samples were collected at 1, 2, 3, 4, 5, 24, 48, 72, and 96 h during the decolorization process, and their absorbance was measured using a UV-Vis spectrophotometer at the characteristic wavelengths of each dye (approximately 664 nm for methylene blue and 618 nm for malachite green). The percentage of dye removal was calculated from the initial and subsequent absorbance values, providing a quantitative assessment of decolorization efficiency under the experimental conditions. The percentage decolorization was calculated using the following equation:

$$\text{Decolorization (\%)} = \frac{\text{Initial absorbance} - \text{Observed absorbance}}{\text{Initial absorbance}} \times 100 \quad (\text{Parshetti, 2006})$$

If slightly negative absorbance values were obtained after blank correction, they were treated as zero because negative absorbance has no physical meaning and may occur when the measured absorbance approaches the practical detection limit of the instrument.

2.7 Data analysis

The experimental results were presented as mean $\pm$ standard deviation (SD) based on three independent replicates ($n = 3$). Water quality parameters (TKN, DO, pH, and temperature) were summarized descriptively to characterize the dye-contaminated wastewater before and after the experiment. Decolorization efficiency was analyzed using SPSS version 16.0. Differences between the control and treatments were evaluated by one-way analysis of variance (ANOVA). Differences were considered statistically significant at $p < 0.05$.

3. Results and Discussion

3.1 Water quality analysis

The characteristics of methylene blue and malachite green are presented in Table 1. The physicochemical parameters, including dissolved oxygen (DO), pH, temperature (T), and total Kjeldahl nitrogen (TKN), were measured in MB- and MG-contaminated water before and after the experiment (Tables 2). In the control group, before the experiment, the mean temperature, pH, DO, and TKN values of the MB-contaminated water were 29.10 ± 0.10 °C, 7.33 ± 0.15 , 7.35 ± 0.02 mg/L, and 2.05 ± 0.14 mg/L, respectively. For the MG-contaminated water, the corresponding mean values were 29.10 ± 0.10 °C, 6.67 ± 0.15 , 7.35 ± 0.02 mg/L, and 2.05 ± 0.14 mg/L, respectively. In the control group, after the experiment, the mean temperature, pH, DO, and TKN values of the MB-contaminated water were 29.97 ± 0.32 °C, 8.43 ± 0.15 , 6.89 ± 0.17 mg/L, and 4.89 ± 0.80 mg/L, respectively. For the MG-contaminated water, the corresponding mean values were 30.17 ± 0.06 °C, 7.80 ± 0.10 , 6.84 ± 0.08 mg/L, and 2.30 ± 0.05 mg/L, respectively. Overall, the physicochemical parameters of the MB and MG control groups showed no substantial changes before and after the experiment.

In the treatment group, before the experiment, the mean temperature, pH, DO, and TKN values of the MB-contaminated water were 29.10 ± 0.10 °C, 6.67 ± 0.15 , 7.35 ± 0.15 mg/L, and 2.05 ± 0.14 mg/L, respectively. For the MG-contaminated water, the corresponding mean values were 28.93 ± 0.06 °C, 6.47 ± 0.31 , 5.15 ± 0.47 mg/L, and 16.16 ± 2.53 mg/L, respectively. After the experiment, the mean temperature, pH, DO, and TKN values of the MB-contaminated water in the treatment group were 30.17 ± 0.11 °C, 7.17 ± 0.25 , 2.14 ± 0.44 mg/L, and 159.70 ± 14.14 mg/L, respectively. For the MG-contaminated water, the corresponding mean values were 30.17 ± 0.06 °C, 6.93 ± 0.21 , 1.45 ± 0.04 mg/L, and 159.80 ± 2.72 mg/L, respectively.

During the decolorization process, the solution temperature increased in both the MB and MG treatments, indicating that the interaction between hydrilla and the dyes involved thermal changes. After treatment, the pH remained within the neutral range in both the MB and MG treatments. Hydrilla absorbed substantial amounts of nutrients, including nitrogen, from the water and sediment for growth, which can reduce the total Kjeldahl nitrogen (TKN) concentration in the water. However, when the plant died and decomposed, the accumulated organic nitrogen may be released back into the water, potentially increasing TKN levels. In addition, MB and MG can reduce light penetration into the water, thereby inhibiting photosynthesis and decreasing dissolved oxygen (DO) production. This effect was consistent with the observed decline in DO and the death of hydrilla after 96 h in the MG treatment.

Table 2. Parameters of MB and MG contaminated wastewater before and after the experiment (mean $\pm$ standard deviation; n=3)

	TKN (mg/L)				DO (mg/L)				pH				Temperature (°C)			
	Controls		Treatments		Controls		Treatments		Controls		Treatments		Controls		Treatments	
Before	MB 2.05 $\pm$ 0.14	MG 2.05 $\pm$ 0.14	MB 2.05 $\pm$ 0.14	MG 16.16 $\pm$ 2.53	MB 7.35 $\pm$ 0.02	MG 7.35 $\pm$ 0.02	MB 7.35 $\pm$ 0.15	MG 5.15 $\pm$ 0.47	MB 7.33 $\pm$ 0.15	MG 6.67 $\pm$ 0.15	MB 6.67 $\pm$ 0.15	MG 6.47 $\pm$ 0.31	MB 29.10 $\pm$ 0.10	MG 29.10 $\pm$ 0.10	MB 29.10 $\pm$ 0.10	MG 28.93 $\pm$ 0.06
After	4.89 $\pm$ 0.80	2.3 $\pm$ 0.05	159.7 $\pm$ 14.14	159.8 $\pm$ 2.72	6.89 $\pm$ 0.17	6.84 $\pm$ 0.08	2.14 $\pm$ 0.44	1.45 $\pm$ 0.04	8.43 $\pm$ 0.15	7.8 $\pm$ 0.10	7.17 $\pm$ 0.25	6.93 $\pm$ 0.21	29.97 $\pm$ 0.32	30.17 $\pm$ 0.06	30.17 $\pm$ 0.11	30.17 $\pm$ 0.06

Water quality analysis after the experiment showed that the MB and MG treatments exhibited elevated TKN concentrations, decreased dissolved oxygen (DO) levels, and pH values that remained within the acceptable range. The increase in TKN may be associated with the decomposition of hydrilla biomass and the subsequent release of organic nitrogen into the water. In addition, plant respiration and microbial decomposition may have contributed to the observed decrease in DO. According to the standards for wastewater discharge from Type A buildings, the acceptable pH range is 5–9, and the total Kjeldahl nitrogen (TKN) concentration must not exceed 35 mg/L (Tiyapairat, 2005). In the present study, the pH values of both treatments remained within the regulatory limits.

Hydrilla absorbed nutrients, including nitrogen, from the water and sediment during growth, which may contribute to a reduction in TKN concentration. However, as the plants senesce and decompose, the accumulated organic nitrogen may be released back into the water, potentially increasing TKN levels. Furthermore, MB and MG reduce light penetration into the water, thereby inhibiting photosynthesis and decreasing oxygen production, which may lead to lower DO concentrations. This explanation is consistent with the experimental observations, in which hydrilla in the MG treatment died after 72 h, while most hydrilla in the MB treatment died after 96 h. Light is an essential factor for photosynthesis. In this experiment, fluorescent lighting was provided as a controlled light source. Under these conditions, MB decolorization increased rapidly during the first hour and then continued to increase gradually until 96 h. Imron et al. (2019) investigated the phytoremediation of methylene blue using *Lemna minor* and demonstrated strong phytoremediation potential, achieving $80.56 \pm 0.44\%$ methylene blue removal within 24 h while maintaining plant growth. In the present study, MG decolorization increased during the first hour, decreased between 2 and 4 h, and then gradually increased. After 48 h, the decolorization efficiency increased markedly. These results suggest that continuous illumination enhanced the decolorization performance of hydrilla. The findings are consistent with the hypothesis that hydrilla is capable of removing dye from contaminated water. Chahar et al. (2024) investigated the removal of the toxic dye malachite green using the aquatic plants *Hydrilla verticillata* and *Najas minor*. Using 750 mg of plant biomass and an initial dye concentration of 25 mg/L, the authors reported that *H. verticillata* exhibited a higher removal efficiency than *N. minor*, with maximum removal efficiencies of 98% and 80%, respectively, after 5 days. In addition, *H. verticillata* removed approximately 67% of malachite green within 4 h, and the removal efficiency increased to 85% after 10 h.

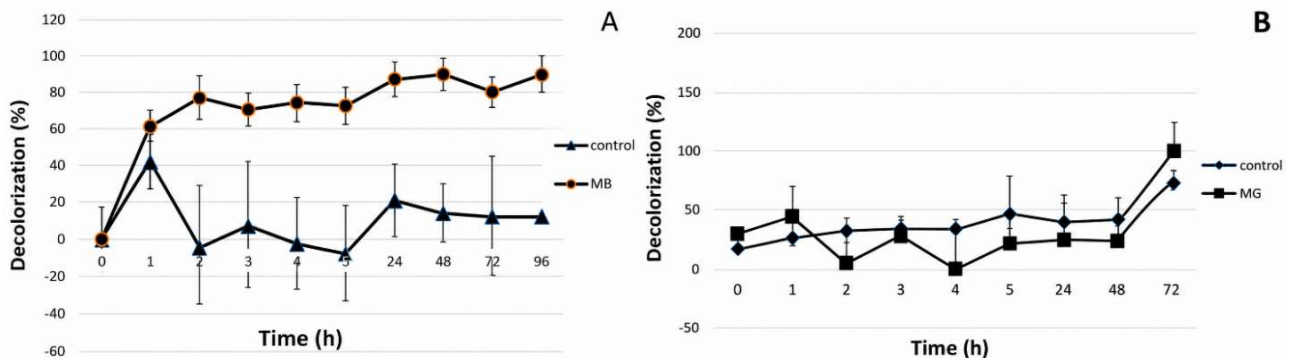
**Figure 1.** Decolorization values (%) A) MB and B) MG

Figure 1A shows that MB decolorization in the treatment group increased over time, from $61.54 \pm 8.25\%$ at 1 h to a maximum of $93.37 \pm 8.21\%$ at 96 h, indicating effective uptake of MB by hydrilla. In contrast, the MB control group exhibited low and inconsistent decolorization ($-7.53 \pm 24.84\%$ to $42.23 \pm 17.65\%$) over the same period, confirming that the observed dye removal was primarily attributable to the presence of hydrilla.

Figure 1B shows that MG decolorization in the treatment group was variable during the early stages of the experiment but increased markedly after 24 h ($24.42 \pm 36.53\%$), reaching a maximum of $100.00 \pm 55.67\%$ at 72 h. During the final stage of decolorization, a few samples exhibited slightly negative absorbance values after blank correction because the residual dye concentration approached the practical detection limit of the UV–Vis spectrophotometer. Under

these conditions, measurement uncertainty and normal instrumental fluctuations may result in small negative absorbance values, which do not represent physically meaningful negative light absorption. Therefore, negative absorbance values were assigned a value of zero, and the corresponding maximum decolorization efficiency was reported as 100%. The decolorization efficiency in the MG control group gradually increased over time, ranging from $17.14 \pm 8.88\%$ to $72.92 \pm 16.94\%$, indicating that some color loss occurred even in the absence of *H. verticillata*. However, the reduction in malachite green concentration observed in the control group suggests that factors other than hydrilla also contributed to color removal. Possible abiotic mechanisms include photodegradation under continuous fluorescent light exposure, the intrinsic instability of malachite green in aqueous solution, precipitation of dye molecules during the experimental period, and limited adsorption onto the glass beaker surface. Although these mechanisms were not directly investigated in this study, they may have contributed to the partial decrease in dye concentration observed in the control treatment. Therefore, the greater decolorization observed in the presence of *H. verticillata* is likely attributable to the combined effects of plant-mediated processes and these background abiotic factors. The sharp increase in MG decolorization in the presence of hydrilla indicated effective dye uptake. However, the mortality of hydrilla by 96 h suggests that MG is more toxic to the plant than MB. Ahila (2021) evaluated the phytoremediation potential of *Pistia stratiotes*, *Salvinia adnata*, and *Hydrilla verticillata* for the treatment of dye-containing wastewater and reported dye accumulation in the roots and leaves of *P. stratiotes* and *S. adnata*. Anjana and Thanga (2011) reported that *Eichhornia* sp. achieved the highest decolorization efficiency in textile effluent. Thilakar et al. (2012) identified *P. stratiotes* as an effective hyperaccumulator that removes contaminants and nutrients through rhizofiltration, thereby promoting high biomass production.

In the present study, wastewater color decreased after 48 h of incubation with hydrilla, whereas plant decay became evident after 72 h of exposure, likely due to the toxic effects of prolonged dye exposure and contaminant accumulation. Decolorization of MG-contaminated wastewater showed only minor fluctuations during the early stages of the experiment, followed by a marked increase after 48 h and reaching a maximum at 72 h. This pattern suggests that hydrilla is capable of removing MG from contaminated water, although the process was slower than that observed for MB. The relatively high initial concentration of MG may have exerted toxic effects on the plants, thereby limiting their uptake capacity during the early stages of the experiment. This observation is consistent with the findings of Parshetti et al. (2006), who reported that the bacterium *Kocuria rosea* achieved low decolorization efficiencies of only 13% and 6% at malachite green (MG) concentrations of 70 and 100 mg/L, respectively. Their results indicated that the toxicity of MG increased with increasing dye concentration, thereby inhibiting microbial activity and reducing dye removal efficiency. Similarly, in the present study, at an MG concentration of 100 mg/L, *H. verticillata* was unable to rapidly remove the dye during the initial stage of exposure, as evidenced by only minor changes in decolorization during the first hour. This delayed response further supports the conclusion that high MG concentrations can suppress biological uptake mechanisms, resulting in slow and less efficient decolorization during the early stages of treatment. Overall, *H. verticillata* demonstrated effective decolorization potential in water contaminated with MB and MG. The plant achieved up to 93% decolorization of MB within 96 h, whereas MG decolorization reached 100% after 72 h.

The results demonstrate that *H. verticillata* has strong potential for the phytoremediation of dye-contaminated water, particularly for the cationic dyes methylene blue (MB) and malachite green (MG). The high decolorization efficiency of MB (up to 93% within 96 h) indicates effective dye removal, likely through adsorption onto plant surfaces and subsequent uptake by the plant. This finding is consistent with previous phytoremediation studies, in which aquatic plants achieved 80–95% MB removal under suitable conditions, highlighting the importance of contact time and plant biomass (Imron et al., 2019). The faster and more consistent removal of MB compared with MG suggests that dye structure may play an important role in the decolorization process. As a relatively simple cationic dye, MB may be more readily removed by *H. verticillata*, whereas MG exhibited greater variability, possibly because of its higher molecular complexity and greater toxicity to plant tissues. The fluctuating decolorization pattern of MG, followed by a marked increase to 100% after 72 h, may be attributed to delayed uptake by the plant, adsorption–desorption dynamics, or experimental variability. Similar behavior has been reported in other biosorption systems treating cationic dyes (Bayram et al., 2022). Furthermore, the gradual increase in decolorization over time indicates that dye removal by *H. verticillata* is a time-dependent process. The observed decolorization is likely the result of multiple processes acting simultaneously, including adsorption onto plant surfaces, rhizofiltration, and biological uptake. Similar trends have been reported for other aquatic plants, in which decolorization efficiency increased with exposure time as the interaction between the dye molecules and plant biomass became more extensive (Abdullah et al., 2018).

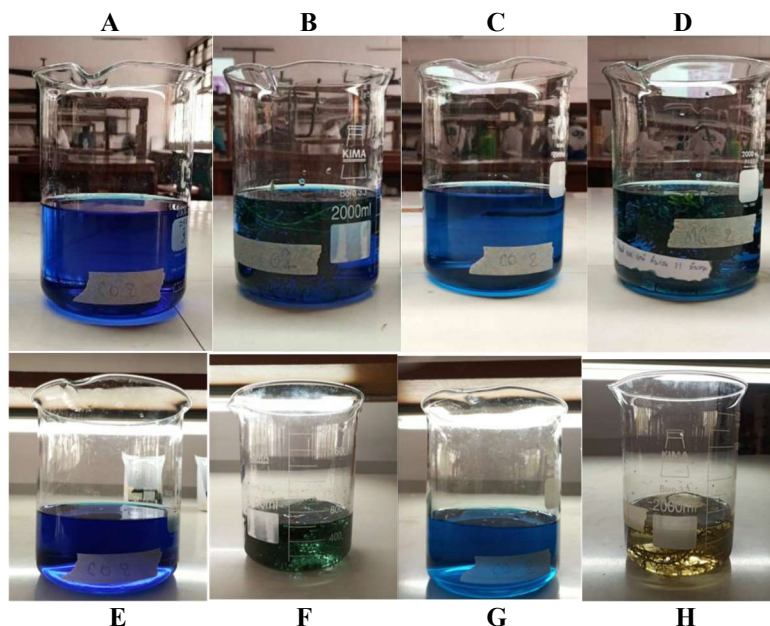


Figure 2. MB and MG dye-contaminated water A) MB control 0 h. B) MB treatment 0 h. C) MG control 0 h. D) MG treatment 0 h. E) MB control 96 h. F) MB treatment 96 h. G) MG control 72 h. H) MG treatment 72 h.

Figure 2F and H show that the treatment group exhibited a continuous increase in the decolorization of both MB- and MG-contaminated wastewater over the experimental period. These findings are consistent with previous phytoremediation studies, which have demonstrated that, in both floating and submerged aquatic plant systems, the plant rhizosphere plays a crucial role in the removal of contaminants, decolorization, and the improvement of water quality. The rhizosphere, which is in direct contact with the surrounding water, facilitates several phytoremediation mechanisms, including rhizofiltration (removal of contaminants by plant roots), phytostabilization (immobilization of contaminants within the root zone), and rhizodegradation (degradation of contaminants by plant roots and associated microorganisms) (Chandra et al., 2017; Tangahu et al., 2011). The removal of MB increased with increasing exposure time (Pathania et al., 2017; Vieira et al., 2009). Increasing the contact time between the dye solution and the plants enhances the likelihood of interactions between dye molecules and the plant surface (Khataee et al., 2012). A longer contact time allows more dye molecules to interact with the available sorption sites on the plant surface, thereby improving dye removal efficiency. This finding is consistent with those reported by Nasrullah et al. (2015) and Tangahu et al. (2011), who observed that increasing the incubation time resulted in higher decolorization efficiency.

3.2 Characterization of MB and MG by FT-IR spectroscopy

The FT-IR spectra of MB before treatment and MBAF after treatment exhibited similar spectral patterns (Figure 3A). The broad absorption band at 3354 cm^{-1} was assigned to the O–H stretching vibration of hydroxyl groups. The weak peak at 1635 cm^{-1} corresponded to the aromatic C=C stretching vibration, while the absorption band at 1228 cm^{-1} was attributed to the C–N stretching vibration of tertiary amine groups (Coates, 2000; Silverstein et al., 2014). The similarity of these characteristic absorption bands indicates that MB and MBAF possessed the same chemical structure. Similarly, the FT-IR spectra of MG before treatment and MGAF after treatment showed comparable spectral patterns (Figure 3B). The broad absorption band at 3366 cm^{-1} was assigned to the O–H stretching vibration of hydroxyl groups. The peak at 1630 cm^{-1} corresponded to the aromatic C=C stretching vibration, whereas the absorption bands at 1363 cm^{-1} and 1216 cm^{-1} were attributed to the C–N stretching vibration of tertiary aromatic amine groups (Socrates, 2001). The similarity of the characteristic absorption bands before and after treatment indicates that the chemical structure of malachite green remained unchanged during the experiment. Overall, the FT-IR spectra of MB and MBAF, as well as MG and MGAF, exhibited similar characteristic absorption bands, with no new peaks or significant shifts following treatment (Figure 3). These findings indicated that no detectable structural changes occurred in either dye during the decolorization process. Therefore, the observed color removal was not associated with detectable chemical degradation of the dye molecules under the experimental conditions.

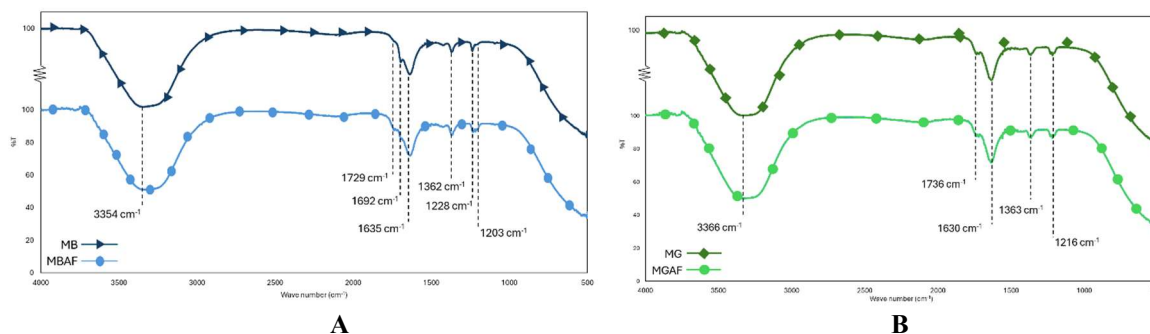


Figure 3. Fourier transform infrared spectroscopy (FT-IR) spectra of A) MB and MBAF B) MG and MGAF.

4. Conclusions

Hydrilla verticillata demonstrated effective decolorization of water contaminated with methylene blue (MB) and malachite green (MG), achieving up to 93% decolorization of MB within 96 h and complete (100%) decolorization of MG within 72 h. FT-IR analysis revealed similar characteristic absorption bands before and after treatment, with no noticeable changes in the positions of the major peaks, indicating that no detectable structural changes occurred in the dye molecules under the experimental conditions. These findings suggest that *H. verticillata* has considerable potential as a cost-effective and environmentally friendly alternative to conventional physicochemical treatment methods, which are often expensive and may generate secondary pollution. Furthermore, its submerged growth habit provides a large surface area for interaction with pollutants, making it a promising candidate for the remediation of dye-contaminated water.

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