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Agricultural Waste Valorization for Industrial Effluent Treatment: Simultaneous Adsorption of Cu(II), Fe(II), and MG Dye Using Coco Peat

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***Abstract*—This study investigated the removal of the heavy metals copper (Cu^{2+}) and iron (Fe^{2+}) from simulated textile wastewater using untreated coco peat adsorbent and Malachite Green (MG) dye. The effects of contact time and adsorbent dosage on adsorption capacity were examined in batch adsorption studies. Within 30 min, iron and copper reached their optimum adsorption capacities, and 10 g/L was determined to be the ideal dosage. MG showed a slower adsorption rate, reaching peak uptake at 180 min; however, Tukey HSD post-hoc analysis showed no significant difference in adsorption values between 30 and 180 min, allowing 30 min to be considered a practical contact time for all three pollutants. Physical forces and electrostatic interactions between the cationic species in solution and the functional groups on the coco peat were perceived to be contributing to the observed behavior. These results show that coco peat can be used as an economical, locally sourced material to treat wastewater. By promoting sustainable water treatment methods, the study helps achieve the UN Sustainable Development Goals, especially Goals 6, 12, and 13.**

***Keywords*—Coco peat adsorbent, Malachite Green removal, Heavy metal adsorption, Simulated textile wastewater, Batch adsorption experiment, Sustainable water treatment**

I. INTRODUCTION

The textile industry is a major consumer of freshwater and is known for discharging significant volumes of wastewater laden with hazardous contaminants. While the industry plays a key role in economic development, its processes, including desizing, scouring, bleaching, dyeing, and finishing, generate effluents with high biological oxygen demand (BOD), chemical oxygen demand (COD), colorants, suspended solids, surfactants, and heavy metals [1]. Among these, dyes and metals such as copper (Cu^{2+}) and iron (Fe^{2+}) are of particular concern due to their persistence, nonbiodegradability, and toxicity even at low concentrations, which significantly contribute to the complex composition of textile effluents that challenge conventional remediation processes. These pollutants threaten aquatic ecosystems, diminish photosynthetic activity, and pose serious health risks to humans, including organ damage and carcinogenic effects [2].

Basic Green 4, often known as Malachite Green (MG), is a synthetic cationic dye that is frequently utilized in textile processes. Its molecular structure contains quaternary ammonium and arylamine groups, which provide it with cationic qualities and solubility, as Chen *et al.* [3] claim. Fig. 1 illustrates this. Research has even connected MG to carcinogenic, teratogenic, and mutagenic effects in mammals and aquatic species. MG's molecular complexity, combined with its affinity to bind with organic matter and resist degradation, complicates its removal in typical treatment systems and warrants deeper investigation of alternative approaches.

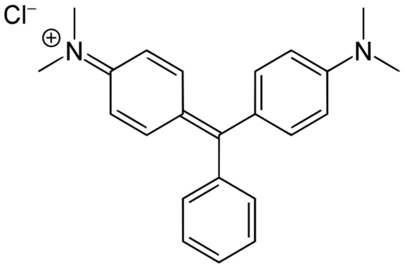

Fig. 1. Chemical structure of MG Dye.

Traditional wastewater treatment techniques, such as chemical precipitation, ion exchange, and membrane filtration, frequently encounter problems with costs of operation, sludge generation, and decreased efficacy when handling complex pollutant blends, according to a study by Ajiboye *et al.* [4]. In contrast, adsorption is a widely applied and practical option for removing dyes and heavy metals. It is valued for its operational simplicity, relatively high removal efficiency, low energy requirements, and potential for regeneration, particularly in resource-limited settings common in developing countries.

Agricultural wastes have garnered more attention as biosorbents among various adsorbents being studied. This interest is driven by their biodegradability, abundance, and cost-effectiveness, which not only support solid waste reduction but also provide a sustainable solution for wastewater management in industries facing economic and environmental constraints. One notable lignocellulosic byproduct from separating coconut husk fiber is Coco Peat (CP). Because cellulose, hemicellulose, and lignin contain reactive hydroxyl, carboxyl, and carbonyl groups, they have the ability to bind positively charged contaminants. Physical interactions, including capillary action and van der Waals forces, are supported by its fibrous and porous structure. Additionally, the chemical surface groups enable ion exchange and hydrogen bonding. Furthermore, coco peat's high moisture retention helps dissolve water-soluble pollutants, making them easier to adsorb [5].

While coco peat has been studied for the individual

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removal of dyes or heavy metals, its capacity for simultaneous adsorption of multiple contaminants—reflecting real-world textile wastewater conditions—remains underexplored; this study addresses that gap by evaluating the concurrent removal of MG dye, Fe^{2+}, and Cu^{2+} using untreated coco peat.

In a batch adsorption setup, this study examines the simultaneous removal of MG, Fe^{2+}, and Cu^{2+} from simulated textile wastewater using untreated CP at different adsorbent doses and contact times.

By valorizing agro-industrial waste for pollution control, this study contributes to the development of low-cost and environmentally benign adsorption approaches and conceptually aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

II. LITERATURE REVIEW

Many researchers have highlighted the potential of agricultural waste materials as biosorbents [6, 7] for removing contaminants from water system [8]. Coconut-based biosorbents, including coco peat and coconut husk, are frequently cited in the literature for their ability to achieve high removal efficiencies of heavy metal ions in batch adsorption systems. Coco peat has attracted interest as an effective adsorbent because of its lignocellulosic makeup and wide availability in tropical areas like the Philippines. Recent studies have provided deeper insights into the mechanisms and parameters influencing the adsorption behavior of coco peat and related coconut-derived materials. Numerous studies emphasize the potential of coconut-based materials for the adsorption of heavy metals and dyes from aqueous media. In particular, coco peat, also referred to as Coconut Coir Dust (CCD), has emerged as a low-cost and effective biosorbent due to its abundant functional groups and fibrous composition. Al Ashik *et al.* [9] demonstrated that CCD contains key functional groups such as hydroxyl, carboxylic, ester, and amine, which are responsible for binding cationic pollutants. The deprotonation of these groups raises the negative surface charge in alkaline conditions, which improves electrostatic interactions with cationic dye molecules like methylene blue, according to their Fourier Transform Infrared (FTIR) spectroscopic analysis. Similar findings were made by Bahar *et al.* [10], who discovered that coir pith ash (CPA), another substance derived from coconuts, efficiently eliminated arsenate ions from aqueous solutions because it included carbonyl and sulfhydryl groups, as demonstrated by surface morphology and functional group analysis.

The solution pH plays an essential role in the adsorption process. As the pH increases, the surface functional groups of the adsorbent become more negatively charged, improving the attraction between the adsorbent and positively charged metal or dye ions. Both Al Ashik *et al.* [9] and Bahar *et al.* [10] reported maximum removal of methylene blue and arsenate, respectively, at near-neutral to alkaline pH values, highlighting the importance of pH in optimizing biosorption performance.

Particle size has also been shown to influence the adsorption capacity of coco peat. Al Ashik *et al.* [9] reported that CCD particles less than 106 microns in diameter exhibited superior dye uptake compared to larger particle sizes, attributing this to the increased surface area and availability of active sites.

Adsorbent dosage is another important factor in the efficiency of contaminant removal. Bahar *et al.* [10] observed that increasing the dose of CPA enhanced arsenate removal up to a certain point, beyond which no further improvement was recorded. This behavior is attributed to the saturation of active sites and the overlapping of particles, which limits further adsorption. Such diminishing returns suggest the necessity of identifying an optimal dosage to balance efficiency and material use.

Al Ashik *et al.* [9] suggested that lignin and pectin residues in coco peat contribute to a heterogeneous but functionally active surface ideal for pollutant binding. Field Emission Scanning Electron Microscopy (FESEM) imaging from related investigations of coconut fiber and endocarp shows tight structures rich in functional groups, showing substantial molecular interaction potential, despite the apparent restricted visual porosity [11].

Research on the simultaneous removal of multiple pollutants using coco peat remains limited. Nonetheless, identical behavior is shown in a comparable study. According to Swarnalatha and Ayoob [12], coir pith absorbs heavy metals rapidly at first, with the majority of the adsorption taking place in the first few min of contact before declining gradually. Similarly, James *et al.* [13] found that coco peat derived from coconut shells achieved substantial metal removal in short contact times when treating heavy metal mixtures. These studies also noted that species-to-species competition among metal ions can slow down the adsorption rate once multiple contaminant types are present. In contrast, Corral-Bobadilla *et al.* [14] employed response surface methodology and kinetic modeling to optimize the removal of Cu(II) using activated carbon from grape stalk waste, focusing on fine-tuned operational parameters such as mixing speed and temperature. While such optimization studies offer high-efficiency designs, the present work focuses on evaluating baseline performance of untreated coco peat under simpler batch conditions—highlighting its potential as a low-cost biosorbent for multi-contaminant removal in resource-limited settings.

III. METHODOLOGY

A. Materials and Reagents

Coco peat was sourced from a local store. Copper(II) chloride dihydrate ($CuCl_2 \cdot 2H_2O$) and Basic Green 4 dye (Malachite Green, $C_{27}H_{34}N_2O_4S$) were purchased from Manila Chemical Center Incorporated, while ferrous sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$) was obtained from Puljed Trading Laboratory and Medical Supplies. All chemicals were of analytical grade and used without further purification.

B. Preparation of Coco Peat Adsorbent

To get rid of any soluble contaminants and debris, a 1 kg sample of raw CP was repeatedly cleaned with distilled water. Following a week of sun drying, it was oven-dried for six hours. The material was dried until it reached a constant weight, with periodic weighing every hour. After drying, the

CP was ground with an electric blender and passed through a 0.18 mm mesh screen, as suggested by Shakeri *et al.* [15]. The sieved adsorbent was stored in sealed glass containers to avoid moisture absorption and contamination before use.

C. Characterization of Coco Peat Adsorbent

The surface structure of the CP adsorbent was examined using FESEM at a 100x magnification. We identified functional groups with FTIR to check for active adsorption sites.

D. Preparation of Simulated Textile Wastewater

Aqueous solutions containing 50 mg/L of each of the target pollutants were made in order to imitate textile effluent. 0.212 g of $CuCl_2 \cdot 2H_2O$, 0.498 g of $FeSO_4 \cdot 7H_2O$, and 0.1 g of MG dye were individually dissolved in 50 mL of distilled water to generate individual stock solutions. These solutions were combined in a 2-L volumetric flask and diluted to the desired volume. The final simulated wastewater was stored in amber glass bottles, sealed, and kept away from light to prevent degradation. The pH of the mixed solution was measured between 4.4 and 4.7.

E. Characterization of Simulated Wastewater

The initial concentrations of the contaminants were confirmed by Nanotech Analytical Services and Training (NASAT) Labs using standard methods from Baird *et al.* [16]. MG was measured using UV-Vis spectrophotometry, while for Cu^{2+} and Fe^{2+} concentrations, Atomic Absorption Spectroscopy (AAS) was utilized.

F. Batch Adsorption Experiments

1) Effect of adsorbent dosage

Adsorption experiments took place in 500 mL Erlenmeyer flasks, each containing 350 mL of simulated textile wastewater. The adsorbent doses of 5, 10, 15, and 20 g/L were used to determine how dosage affects contaminant removal. The relatively high adsorbent dosage range selected in this study was a deliberate design choice to reflect practical treatment scenarios using untreated coco peat. As a raw biosorbent with lower surface area and adsorption efficiency compared to modified alternatives, larger doses are typically needed to ensure effective contaminant removal. This design decision also aligns with the study's aim to explore low-cost and readily deployable materials in resource-limited settings. The mixtures were stirred with a magnetic stirrer at 200 rpm for 30 min, following the method from Samaniego and Tanchuling [17]. All batch adsorption experiments were conducted at room temperature (approximately 25 ± 2 °C), and no external temperature control equipment was used. After stirring, the suspensions were filtered using Whatman No. 1 filter paper, and the filtrates were analyzed to determine the remaining concentrations of contaminants. All experiments were performed in duplicate and repeated twice to ensure reproducibility of results. The pH of the solution was monitored throughout the adsorption process using a calibrated digital pH meter.

2) Effect of contact time

The optimal adsorbent dosage from the earlier experiment was used to test how contact time affects the adsorption of contaminants. A set amount of CP was added to 350 mL of simulated wastewater in Erlenmeyer flasks and mixed at 200 rpm. Samples were taken at specific intervals of 10, 30, 60, 120, 180, and 240 min. The samples were then filtered and analyzed using UV-Vis spectroscopy and AAS, as previously described. Each experiment was repeated twice to make sure the data was reliable. A digital pH meter monitored the system's pH throughout the adsorption process.

3) Adsorption capacity and removal efficiency

The adsorption performance of the coco peat adsorbent was evaluated using the adsorption capacity and removal efficiency. The adsorption capacity at equilibrium, q_e(mg/g), was calculated using Eq. (1):

$$Q_e = \frac{(C_i - C_e)\, V}{m} \tag{1}$$

where C_i is the initial concentration of the contaminant, C_e is the equilibrium concentration after adsorption, V is the volume of the solution, and m is the mass of the adsorbent used.

The removal efficiency, $R(\%)$, was calculated using Eq. (2):

$$R\ (\%) = \frac{C_o - C_e}{C_o} \times 100 \tag{2}$$

These equations were applied consistently to determine the adsorption performance of Fe^{2+}, Cu^{2+}, and MG in all batch adsorption experiments.

IV. RESULT AND DISCUSSION

A. Characterization of the Coco Peat Adsorbent

A highly porous surface with heterogeneous features and randomly organized fiber textures was visible in the FESEM micrograph shown in Fig. 2. Its form suggests a large number of active sites, increasing surface area while promoting better adsorbate molecule interaction and diffusion. These physical features are beneficial for the adsorption of both dye and heavy metal ions, increasing accessibility and retention of pollutants.

Fig. 3 shows the FTIR spectrum of the CP, providing insight into the functional groups that potentially serve as binding sites for the adsorption of the contaminants examined. A broad peak at 3341 cm^{-1} indicates the presence of bonded hydroxyl groups derived from cellulose. The absorption peak at 2912 cm^{-1} corresponds to the stretching vibration of CH alkyl groups, which are characteristic of cellulose and hemicellulose. A sharp peak at 1255 cm^{-1} is attributed to CO stretching of carboxylic acid groups, while the narrow band at 1041 cm^{-1} is associated with primary alcohol CO bonds.

While not as strongly charged as carboxyl groups, the bonded hydroxyl groups can still participate in electrostatic interactions with the positively charged heavy metal cations and malachite green. However, literature shows that carboxyl groups in cellulose have pKa values around 3. At pH 4 and above, these groups begin to deprotonate, forming carboxylate anions that enhance binding with cationic pollutants. Hydroxyl groups in cellulose are much weaker acids compared to carboxyl groups and are generally only deprotonated under strongly alkaline conditions, so under typical aqueous pH, their contribution to electrostatic attraction is lower [18].

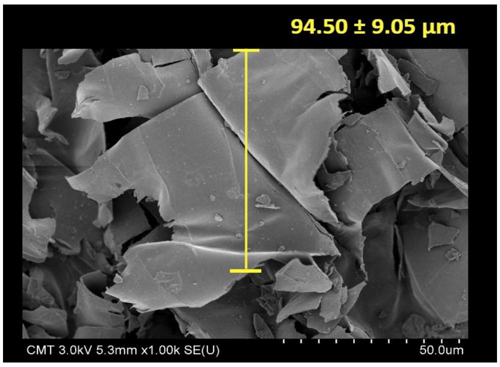

Fig. 2. FESEM Micrograph of Coco Peat Adsorbent.

The amount of lignin in the CP samples is apparent in a distinct peak at 1610 cm⁻¹, which shows the presence of conjugated carbon-carbon double bonds. Through processes like complexation with cationic species, ion exchange, and electrostatic interaction, the found functional groups confirm the lignocellulosic composition of CP and support its potential as an efficient biosorbent.

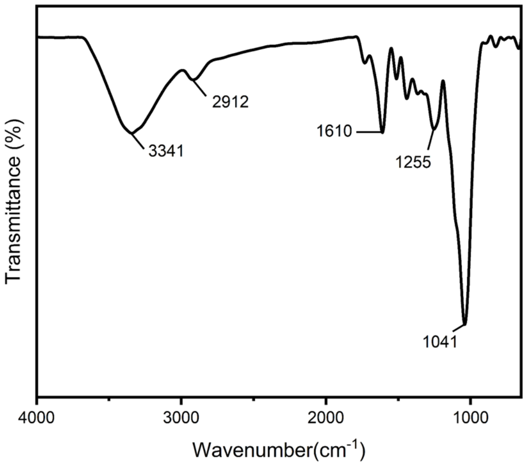

Fig. 3. FTIR spectrum of Coco Peat adsorbent.

B. *Batch Adsorption Experiments*

1) *Effect of adsorbent dosage*

The effects of varying the adsorbent dosage from 5 to 20 g/L on the absorption of all pollutants analyzed are shown in Fig. 4.

The adsorption capacity of CP improved from 0.41 to 2.44 mg/g for Fe^{2+} and from 1.76 to 2.58 mg/g for Cu^{2+} as the dosage was increased from 5 to 10 g/L. The increase in concentration can be explained by the higher level of adsorbent offering more active binding locations, which improves interactions between the target ions and the adsorbent surface. In contrast, the increase in adsorption capacity for MG dye over the same range was minimal, increasing only slightly from 1.87 to 1.90 mg/g.

A reverse trend was observed beyond 10 g/L. When the adsorbent dosage was increased to 15 g/L, the adsorption capacity declined to 2.09 mg/g for Fe^{2+}, 2.38 mg/g for Cu^{2+}, and 1.87 mg/g for MG. This decreasing trend continued at 20 g/L, suggesting a reduction in adsorption efficiency at higher dosages. The decline may be attributed to the greater number of unutilized binding sites at higher adsorbent concentrations, which results in overlapping and aggregation that reduces the effective surface area. Similar trends appeared in the findings of Salih *et al.* [19], who studied the removal of heavy metals and dyes at the same time using a composite chitosan adsorbent. Guechi and Hamdaoui [20] also reported similar results when they used potato peel to remove MG dye.

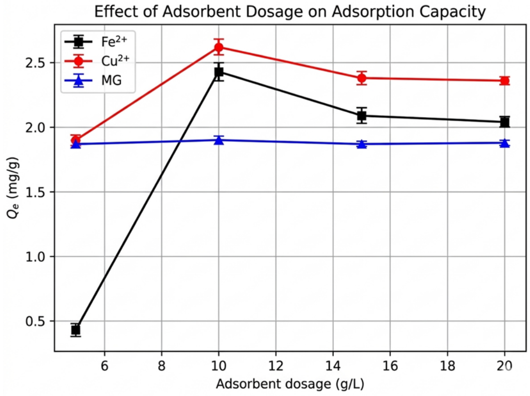

Fig. 4. Effect of adsorbent dosage on the adsorption capacity (mg/g) of CP for Fe^{2+}, Cu^{2+}, and MG from simulated textile wastewater.

The comparatively lower adsorption capacities observed in this study can be attributed to the use of untreated coco peat, which inherently provides fewer accessible adsorption sites than chemically modified biosorbents. Consequently, higher adsorbent dosages were required to achieve measurable uptake under batch conditions. In contrast, studies employing modified coco peat or column configurations, such as those by Kumari and Dey [21] and Sireesha and Sreedhar [22], report higher capacities. The present results, therefore, establish baseline adsorption behavior for raw coco peat in batch systems, providing a reference point for low-cost biosorbent applications.

It is also clear from Fig. 4 that changes in the adsorption capacity of MG dye across different dosages were relatively small compared to heavy metals. A similar pattern has been reported: Kumari & Dey [21] found that CP uptake of MG in a fixed-bed column increased with pH and dose, but plateaued beyond certain adsorbent dosages. Vijayaraghavan [23] observed that the biosorption of MG and crystal violet onto coco peat increased sharply within the critical pH range, indicating that pH strongly modulates the electrostatic interactions between dye molecules and the adsorbent surface.

The functional groups on CP become protonated at pH values lower than 4. This inhibits the adsorption of cationic dye molecules by producing a positively charged surface. When the pH is higher than 4, deprotonation takes place. As a result, the positively charged MG dye and the negatively charged adsorbent functional groups are more strongly attracted to one another electrostatically [18]. In this study, the pH of the solution during the adsorption tests remained in a narrow range between 4.7 and 5.2. Due to this consistency, the ability of CP to adsorb MG dye stayed stable at all dosages. The highest adsorption capacity for all three pollutants occurred at 10 g/L. The removal efficiencies were 95.46% for Fe^{2+}, 77.04% for Cu^{2+}, and 98.99% for MG dye. Consequently, this dosage was chosen as the ideal amount and applied in later studies examining how the duration of contact affects adsorption efficiency.

2) *Effect of contact time*

Fig. 5 shows the adsorption capacity of CP as a function of contact time. We evaluated contact times of 10, 30, 60, 120, 180, and 240 min.

The adsorption capacity of CP increased from 1.91 to 2.45 mg/g for Fe^{2+} and from 2.36 to 2.58 mg/g for Cu^{2+} as the contact period increased from 10 to 30 min. The availability of active binding sites and a sufficient period for metal ions to interact with the adsorbent surface can be seen in this spike. The equivalent removal efficiencies for Cu^{2+} and Fe^{2+} were 77.04% and 95.46%, respectively. Beyond 30 min, however, the adsorption capacity of CP for both heavy metals gradually declined, indicating a possible onset of desorption or re-equilibration within the system.

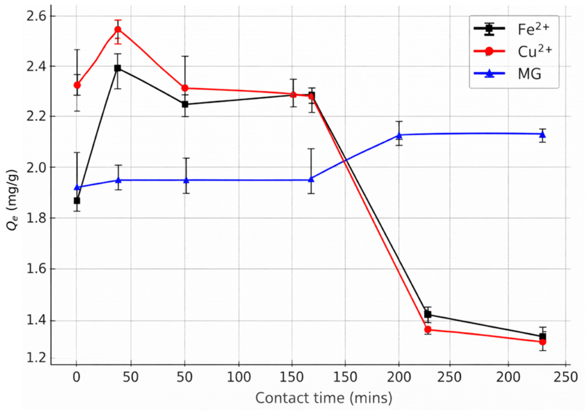

Fig. 5. Effect of contact time on the adsorption capacity (mg/g) of CP for Fe^{2+}, Cu^{2+}, and MG from simulated textile wastewater.

For MG, the adsorption capacity increased more slowly, rising steadily from 1.90 mg/g at 10 min to 2.13 mg/g at 180 min. At this point, the adsorption efficiency reached 99.41%, and no further uptake was observed beyond this duration, establishing 180 min as the equilibrium contact time for MG. However, statistical analysis using Tukey's Honestly Significant Difference (HSD) revealed no significant difference between adsorption values at 30 and 180 min for MG, suggesting that 30 min could be considered a statistically acceptable and operationally practical contact time despite the slower kinetic behavior observed.

The observed decrease in adsorption capacity for Fe^{2+} and Cu^{2+} after their respective peak values suggests that some of the adsorbed metal ions may have been released back into the solution. This is consistent with post-saturation dynamics observed in other competitive adsorption systems.

Competition for accessible sites is crucial in multiple contaminant adsorption. The experimental results showed that CP had a greater affinity for Fe^{2+} and Cu^{2+} than for MG. This behavior can be attributed to differences in ionic charge density, molecular size, and binding affinity. At pH 5, all contaminants under study exist in their cationic forms. However, Fe^{2+} and Cu^{2+} possess smaller hydrated radii and higher charge densities compared to MG, which enhance their electrostatic attraction and ion exchange interactions with the reactive functional groups on the surface of CP [18, 24].

C. *Statistical Analysis*

To determine if alterations to adsorbent dosage and contact time had a significant impact on the adsorption performance of CP for the pollutants under study in the simulated textile wastewater, a one-way analysis of variance (ANOVA) was performed. A 95% confidence level was used for the analysis. The removal of Fe^{2+} and Cu^{2+} was shown to be statistically significantly impacted by the dose of the adsorbent, suggesting that dosage variations affected the metals' adsorption capacity. The p-value for MG, on the other hand, was 0.055, indicating that dosage modification had no discernible impact on MG elimination within the investigated range of 5 to 20 g/L.

Tukey's HSD post hoc test further revealed that for Fe^{2+}, significant differences occurred between 5 g/L and all higher dosages, while no significant difference was found among the 10, 15, and 20 g/L groups. This supports the conclusion that 10 g/L is the optimal dosage for Fe^{2+} removal.

For Cu^{2+}, significant differences were observed across most pairwise comparisons, particularly between 5 g/L and the higher dosages. However, no significant difference was found between 15 and 20 g/L, suggesting that Cu^{2+} removal improved up to 15 g/L but plateaued thereafter.

Varying contact time significantly influenced the adsorption capacity of all three components, confirming its critical role in the removal of both heavy metals and dye.

For Fe^{2+}, Tukey HSD revealed that significant differences were present across most time intervals, except between closely spaced durations (e.g., 60 vs. 120 min and 180 vs. 240 min). The trend confirmed rapid initial adsorption followed by equilibrium and slight desorption at extended durations.

Similarly, Cu^{2+} showed significant changes in adsorption capacity across nearly all contact time intervals. Notably, the adsorption capacity declined between 120 and 180 min, aligning with observed desorption trends.

For MG, statistical differences were only observed between 10 min and longer contact times (specifically 180 and 240 min). Despite a gradual increase in adsorption with time, most pairwise comparisons beyond 30 min were statistically similar. These results suggest that the adsorption equilibrium for MG was reached around 180 min, consistent with experimental observations.

D. *Limitations and Outlook*

This study provides foundational insight into the application of untreated coco peat for the simultaneous adsorption of Fe^{2+}, Cu^{2+}, and Malachite Green dye under controlled batch conditions. However, the use of synthetic wastewater introduces limitations in matrix complexity, which future studies must address by incorporating real textile effluents containing a broader spectrum of competing ions, organic matter, and fluctuating pH. Key operational variables such as pH, ionic strength, and initial pollutant concentration were not independently varied in this study, and their specific effects on adsorption efficiency should be systematically investigated. The current setup also does not account for the dynamics of continuous treatment systems; hence, pilot-scale column studies and process modeling are necessary to determine practical viability. Furthermore, long-term usability must be assessed through adsorbent regeneration trials and desorption studies. Advanced surface characterization techniques, such as Brunauer–Emmett–Teller (BET) surface area analysis, zeta potential measurements, and X-ray Photoelectron Spectroscopy (XPS), should also be applied to elucidate adsorption mechanisms with greater precision. Finally, future work should include comprehensive life-cycle and cost-benefit analyses to establish the economic and environmental feasibility of scaling untreated coco peat as a decentralized treatment solution aligned with SDGs 6, 12, and 13.

V. CONCLUSION

This study evaluated the use of untreated coco peat (CP) as a biosorbent for the simultaneous removal of Malachite Green dye, copper (II), and iron (II) from simulated textile wastewater in a batch system. Adsorption performance was found to depend on both adsorbent dosage and contact time, with optimal removal observed at 10 g/L and within 30 min. While Fe^{2+} and Cu^{2+} achieved adsorption saturation early, MG exhibited gradual uptake, peaking at 180 min; however, statistical analysis confirmed no significant difference between the adsorption levels at 30 and 180 min.

The fibrous and porous morphology observed through FESEM imaging may have contributed to physical adsorption mechanisms such as van der Waals forces and capillary uptake. Additionally, the presence of functional groups capable of electrostatic interaction at the monitored pH range supports the removal of cationic species. These findings help establish baseline performance data for raw CP and reinforce its potential as a low-cost, locally available material for decentralized wastewater treatment. Further optimization and real-wastewater validation are recommended to support scale-up and long-term sustainability.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

E Manriquez, VM Quilo, and K Villena conducted the experiments, gathered initial data, performed preliminary analysis, and drafted the original manuscript. CK Andra supervised the research process, providing guidance throughout the experimental design and implementation. TR Panaligan and K. Villena refined the manuscript for publication by enhancing the structure, updating technical content, and aligning the paper with journal standards.

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