

Article

Sustainable Microcystin Removal from Water Using Low-Cost Agricultural Waste Materials

Manal A. M. Mahmoud ^{1,*}, Wafaa Kh. Kelini ², Zakaria M. Zaky ³ and Hosnia S. Abdel-Mohsein ¹

¹ Department of Animal, Poultry Hygiene and Environmental Sanitation, Faculty of Veterinary Medicine, Assiut University, Assiut 71526, Egypt

² Department of Forensic Medicine and Veterinary Toxicology, Faculty of Veterinary Medicine, Assiut University, Assiut 71526, Egypt

³ Department of Animal, Poultry and Environment Hygiene, Faculty of Veterinary Medicine, Sohag University, Sohag 82524, Egypt

* Correspondence: manalmahmoud@aun.edu.eg

Abstract

Cyanobacterial blooms are an increasing global concern due to the release of microcystins (MCs), potent hepatotoxins that threaten aquatic ecosystems, livestock, and human health. This study investigated the efficiency of low-cost natural adsorbents—rice straw (R), corn straw (C), and sawdust (S)—compared with commercial activated charcoal (AC) for the removal of microcystins from water sources in Upper Egypt. A total of 72 water samples were collected between June and September 2022 from rivers, irrigation canals, and wastewater channels in Sohag and Assiut governorates. Samples were analyzed for intra- and extracellular MCs using ultra-performance liquid chromatography (UPLC), while adsorbents were characterized by X-ray diffraction (XRD) and scanning electron microscopy (SEM), pH, moisture content, iodine number, and methylene blue adsorption. Results revealed mean total MC concentrations of 9.39, 3.18, and 11.70 µg/L in river, irrigation, and wastewater samples, respectively—exceeding the World Health Organization (WHO) guideline of 1 µg/L. Adsorption experiments demonstrated that AC exhibited the highest MC removal efficiencies (88.9% in acidified and 92.3% in neutral water), followed by sawdust (84–86.2%), corn straw (74.01–85.2%), and rice straw (75.4–74.8%). Sawdust and corn straw performed particularly well for extracellular MC removal, while AC was most effective for intracellular fractions. This study highlights the potential of agricultural by-products, particularly sawdust and corn straw, as sustainable, low-cost alternatives to activated charcoal for cyanotoxin removal. Their availability and efficiency support their application in water treatment systems without chemical pretreatment. These findings indicate that agricultural residues could serve as practical, low-cost adsorbents for mitigating cyanotoxin contamination in water, especially in resource-limited regions, while also promoting the beneficial reuse of agricultural waste.



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1. Introduction

Cyanobacterial blooms are a growing global concern due to their increasing frequency, magnitude, and duration, largely driven by eutrophication, climate warming, and hydrological change [1–4]. Among the secondary metabolites produced, microcystins (MCs)—monocyclic heptapeptide hepatotoxins—pose severe risks across taxa (diverse biological

groups) via phosphatase inhibition and oxidative stress. In humans, acute exposure via contaminated dialysis water caused Caruaru Syndrome in 1996 in Brazil, with >60 deaths from liver failure, vomiting, and visual disturbances [5,6]. Chronic intake from drinking water correlates with elevated primary liver and colorectal cancer incidence in China, Serbia, and the US [7,8]. In animals and aquatic life, MCs induce rapid hepatocyte necrosis, photosensitization in cattle, and pet fatalities worldwide [9,10]. Fish exhibit immunotoxicity, gonadal disruption, and bioaccumulation in species like carp and tilapia [11,12]. Plants irrigated with MC-laden water suffer growth inhibition, chlorophyll bleaching, and yield losses (e.g., watercress at ≥ 10 $\mu\text{g/L}$ MC-LR) [13,14]. In vitro and animal models confirm the liver as a primary target (NOAEL 40 $\mu\text{g/kg/day}$ in pigs), with apoptosis in enterocytes, neurotoxicity crossing the BBB, and reproductive toxicity via HPG axis disruption [15,16]. Microcystins are among the most hazardous cyanotoxins due to their acute and chronic toxicity, tumor-promoting potential, and broad distribution in aquatic environments. Nevertheless, their true occurrence may be underestimated because of analytical detection challenges [17–20]. To date, more than 100 structural variants of MCs have been identified, with MC-LR being the most prevalent and toxic [19,21].

Microcystins accumulate in aquatic organisms, including fish, shellfish, and zooplankton, thereby entering the food chain and ultimately posing risks to humans [22,23]. Exposure occurs mainly through contaminated drinking water, recreational activities, and food products irrigated with toxin-contaminated water [24–26]. Once ingested, MCs inhibit protein phosphatases, leading to hepatotoxicity, oxidative stress, immunotoxicity, and in some cases, tumor promotion [12,16,27,28]. Their effects are not limited to humans, as they are also associated with mass fish kills, wildlife mortality, and biodiversity decline [29,30].

Globally, MC concentrations frequently exceed the World Health Organization (WHO) provisional guideline of 1 $\mu\text{g/L}$ for drinking water [4,31]. For example, levels of 0.05–3.8 $\mu\text{g/L}$ were reported in Egyptian drinking water [32], while higher values were recorded in China (1.8–2.3 $\mu\text{g/L}$) and in eutrophic lakes such as Taihu Lake, where concentrations may reach tens of $\mu\text{g/L}$ [33,34]. Similar exceedances have been documented in Europe and the United States [17,35].

Conventional water treatment processes like coagulation, flocculation, and sedimentation fail to effectively remove microcystins (MCs), often exacerbating contamination by releasing intracellular MCs during cell lysis [36–38]. Cyanobacterial accumulation in treatment plants causes operational issues such as filter clogging, leading to elevated toxin levels exceeding source water concentrations [39]. At the Damietta Water Treatment Plant (DWTP) in Egypt, blooms of *Microcystis aeruginosa* ($1.1\text{--}6.6 \times 10^7$ cells L^{-1}) produced the cyanotoxins MC-RR and MC-LR, with peak concentrations occurring in August in association with elevated water temperature and nutrient levels [40]. Conventional treatment achieved only partial cell removal (91–98.9% via C/F/S and filtration), but coagulation triggered MC release, resulting in final effluent concentrations (1.1–3.6 $\mu\text{g/L}$) exceeding WHO's 1 $\mu\text{g/L}$ guideline for MC-LR.

Activated carbon effectively removes water contaminants but is costly to produce. Granular (GAC) and powdered activated carbon (PAC) effectively adsorb microcystins (MCs), achieving >80% removal via both adsorption and biodegradation [41] owing to extended surface area, microporous structure and high adsorption capacity, as demonstrated for various contaminants, including metals [42]. Low-cost alternatives like rice husk, coconut shell, and sugarcane bagasse carbons show promising MC adsorption. Treated rice husk removed >95% of six microcystins, including MC-LR, from laboratory solutions containing 25 $\mu\text{g/L}$ of each toxin, with >90% removal achieved within 5 min [43]. Therefore, recent advances in mitigation strategies underscore the need for sustainable, low-cost, and locally available alternatives in developing regions. Agricultural residues such as rice husk,

corn straw, and sawdust represent promising adsorbents due to their abundance as low-cost waste from agro-industries. This study therefore investigates the adsorption potential of rice straw, corn straw, and sawdust compared to commercial activated charcoal for the removal of microcystins from water sources in Upper Egypt. Raw agricultural residues were selected to evaluate their direct use as low-cost, locally available, and minimally processed adsorbents, particularly for resource-limited settings where thermal or chemical activation may not be feasible.

2. Materials and Methods

2.1. Sampling

A total of 72 water samples (500 mL each in methanol-rinsed amber glass bottles) were collected from 18 locations across Sohag and Assiut governorates (Upper Egypt) between June and September 2022, with 4 upstream samples per site (100–200 km spacing). Sites targeted organic contaminant sources: 5 River Nile (drinking/agricultural use), 5 irrigation canals (Nile branches for farming), and 8 wastewater canals/effluents (abattoir/agricultural/domestic discharges). Samples were transported in ice boxes post-collection and stored at -20°C until analysis to prevent cyanotoxin degradation.

River Nile samples (SR1–SR5): Sohag sites near abattoirs (Palasfora, Sohag, El Maraghah, Almunshah, Mishta), 7–50 m upstream, amid agricultural (wheat, sugarcane) and industrial (textiles, oil) activities. Irrigation samples (SI1–AI5): canals 1–2 km from abattoirs (Banga, Tema) or roadside in Sudfa/Tema, prone to runoff. Wastewater samples (SW1–AW8): stagnant canals near abattoirs (Tahta, Elmadmar) in Shandawel/Tema/Shatura, plus roadside dumps (Tireat almalaah) and Assiut treatment plant effluent (Table 1).

Table 1. Sampling locations with their codes from different water type from Sohag and Assiut Governorates.

Site	Location	Code	Water Type	Latitude	Longitude
1	Plasfora	SR1	River	31.74376	26.51898
2	Sohage	SR2	River	31.68628	26.55497
3	Elmaragha	SR3	River	31.60334	26.70914
4	Almunshah	SR4	River	31.80084	26.46166
5	Mishta	SR5	River	31.46541	26.85948
6	Banga	SI1	Irrigation	31.47463	26.80267
7	Tema	SI2	Irrigation	31.45620	26.87126
8	Tema	SI3	Irrigation	31.45620	26.87126
9	Sudfa	AI4	Irrigation	31.2904	26.4944
10	Mawqif Almuealimin	AI5	Irrigation	31.1159	27.1004
11	Gazerit Shandawel	SW1	Waste	31.62558	26.60797
12	Gazerit Shandawel	SW2	Waste	31.62558	26.60797
13	Tahta	SW3	Waste	31.48853	26.75425
14	Elmadmar	SW4	Waste	31.44922	26.82812
15	Elmadmar	SW5	Waste	31.44922	26.82812
16	Shatura	SW6	Waste	31.2216	26.5805
17	Tireat almalaah	AW7	Waste	31.1126	27.1022
18	Mahatat arab almadabigh	AW8	Waste	31.0846	27.0950

2.2. Chemicals and Standards

The standard of MCs (microcystin LR-RR-YR) was purchased from Sigma Aldrich (Darmstadt, Germany), batch number BCCD4609. Methanol HPLC grade (Lot. No. F20C043, Product Code: 90028-2.5L, ADVENT CHEMBIO PVT. Ltd., Maharashtra, In-

dia). Trifluoroacetic acid (TFA) (batch number GSM170411, Qualikems Lifesciences Pvt. Ltd., Delhi, India), Acetonitrile HPLC grade (CHEM-LAB NV | Industriezone “De, Arend”2, Zedelgem, Belgium), Activated charcoal (batch number CS070309, Product no. A067112), Solid-phase extraction C18 cartridge (Strata C18-E (55 μ m, 70A), 500 mg/6 mL, tubes, Reorder part No. 8B-S001-HCH, Phenomenex Inc, Torrance, CA, USA), glass microfiber filters (GF/C) (Diameter 47 mm, Cat No. GF3-047, CHAMLAB Group, Terrassa, Spain) were applied for sample preparation.

2.3. Microcystin Analysis

Extracellular and intracellular microcystins were quantified using ultra-performance liquid chromatography (ACQUITY UPLC H-Class system, Waters Corporation, 34 Maple street, Milford, MA, USA) in the Central Laboratory, Faculty of Veterinary Medicine, Assiut University, following established protocols [31,44,45]. For extracellular toxins, 500 mL of water was filtered and passed through preconditioned C18 cartridges; toxins were eluted with acidified methanol and concentrated before UPLC injection. Intracellular toxins were obtained by freeze–thaw disruption of the retained cells on filters (the observed removal efficiencies reflect the performance of the tested adsorbents rather than the filter material), followed by methanol extraction, sonication at room temperature (70 W) for 15 min three times, and concentration. Chromatographic separation was achieved on a C18 column (1.7 μ m, 50 $^{\circ}$ C), with a gradient of water and acetonitrile at 0.4 mL/min and detection at 238 nm.

Microcystins were assessed as two operational fractions: extracellular and intracellular. The extracellular fraction represented dissolved microcystins in the water phase and was measured in the filtrate obtained after removal of suspended biomass through membrane filtration and solid-phase extraction. The intracellular fraction represented cell-associated microcystins retained on the filter after filtration and was quantified only after cell disruption by freeze–thaw cycles, followed by methanolic extraction. During the adsorption experiments, the natural adsorbents and activated charcoal were applied to real water samples containing both dissolved and cell-bound toxin fractions.

Quality Control: Calibration curves were prepared using five concentrations (10–25 ng/L) of standard MCs, with limits of detection and quantification at 10 ng/L and 30 ng/L, respectively. Recovery tests were performed by spiking real water samples with a known MC concentration (30 ng/L), achieving an average recovery of 80% (detailed method and quality control were published [46]). The standard was run every 10 samples to ensure system reliability [47].

2.4. Adsorbent Materials

Activated charcoal as well as natural adsorbents, including rice straw, corn straw, and sawdust, were tested without any specific treatment. Natural adsorbents were washed with deionized water, dried, ground, and sieved (250 μ m). Characterization included pH, moisture content, iodine removal %, X-ray diffraction (XRD), and scanning electron microscopy (SEM) to assess surface properties [48,49]. Methylene blue adsorption (MB removal %) was evaluated as a proxy for adsorption efficiency [50]. The iodine and methylene blue tests were conducted as qualitative batch screening assays to compare the relative adsorption performance of the tested materials.

2.5. Microcystin Removal Experiments

Adsorption trials were performed following [43] with modifications. For each adsorbent, 4 g of the material was added to 200 mL of real water containing a mixture of MC-LR, MC-RR, and MC-YR (7 μ g/L) as measured in the collected water before treatment. Experiments were conducted in duplicate under neutral (pH 7 ± 0.3) and acidic (pH 4 ± 0.3)

conditions. Samples were agitated at 200 rpm for 10 min at 30 °C, filtered, and analyzed for residual intra- and extracellular MCs using UPLC. For each adsorbent material, removal % and adsorption capacity (q) of MC for intra-, extra-, and total microcystins at pH 4 and pH 7 ($\mu\text{g g}^{-1}$) were calculated based on

$$q = \frac{(C_i - C_f) \times V}{m}$$

where C_i and C_f are initial and equilibrium MC concentrations ($\mu\text{g L}^{-1}$), solution volume (L), and m is adsorbent mass (g).

2.6. Statistical Analysis

Data was analyzed using SPSS version 16.0. Microcystin concentrations were expressed as means $\pm$ SD. Differences among treatments were evaluated using one-way ANOVA, followed by Duncan's post hoc test where appropriate. Significance was considered at $p < 0.05$.

3. Results

Microcystins were detected in all tested water sources, confirming the presence of cyanotoxin contamination in river, irrigation, and wastewater samples. These measurements were used primarily to characterize the study samples and provide the context for the adsorption experiments; therefore, detailed statistical comparison among water types was not considered a main focus of the present work. Therefore, (Table 2) shows intracellular, extracellular and total microcystin (MC) concentrations ($\mu\text{g/L}$) in three water types (river, irrigation, wastewater). Intracellular and extracellular MCs in river, irrigation and wastewater were 1.80 ± 2.61 and 7.56 ± 15.39 , 1.77 ± 1.86 and 1.40 ± 1.57 , and 2.84 ± 2.88 and 8.88 ± 13.90 $\mu\text{g/L}$, respectively. In addition, total MCs in river, irrigation and wastewater were 9.39 ± 17.98 , 3.18 ± 3.29 and 11.70 ± 15.06 $\mu\text{g/L}$, respectively. Moreover, wastewater was higher than river and irrigation water for intracellular MCs and river and wastewater were both higher than irrigation water for extracellular and total MCs.

Table 2. Intracellular, extracellular, and total microcystin (MC) concentrations ($\mu\text{g/L}$) in different water sources.

Type of Water	Intracellular MCs	Extracellular MCs	Total MCs
River water	Min: 0.35–Max: 6.40 Mean $\pm$ SD: 1.80 ± 2.61	Min: 0–Max: 35.05 Mean $\pm$ SD: 7.56 ± 15.39	Min: 0.39–Max: 41.45 Mean $\pm$ SD: 9.39 ± 17.98
Irrigation water	Min: 0–Max: 4.75 Mean $\pm$ SD: 1.77 ± 1.86	Min: 0–Max: 3.62 Mean $\pm$ SD: 1.40 ± 1.57	Min: 0–Max: 8.37 Mean $\pm$ SD: 3.18 ± 3.29
Wastewater	Min: 0–Max: 8.17 Mean $\pm$ SD: 2.84 ± 2.88	Min: 0–Max: 40.00 Mean $\pm$ SD: 8.88 ± 13.90	Min: 0.34–Max: 42.68 Mean $\pm$ SD: 11.70 ± 15.06

X-ray diffraction (XRD) patterns of rice straw, corn straw, and sawdust (Figure 1 R, C and S) confirm that all three adsorbents exhibited predominantly amorphous and porous structures.

Figure 2 represents SEM images of natural adsorbent materials, with rice straw (R), corn straw (C) and sawdust (S) showing small particles with spines and canal-like structures that enhance the surface area for R, moderately sized particles with surface projections that increase the effective surface area for C, and larger, fibrous particles with fewer pores for S compared to rice and corn straw.

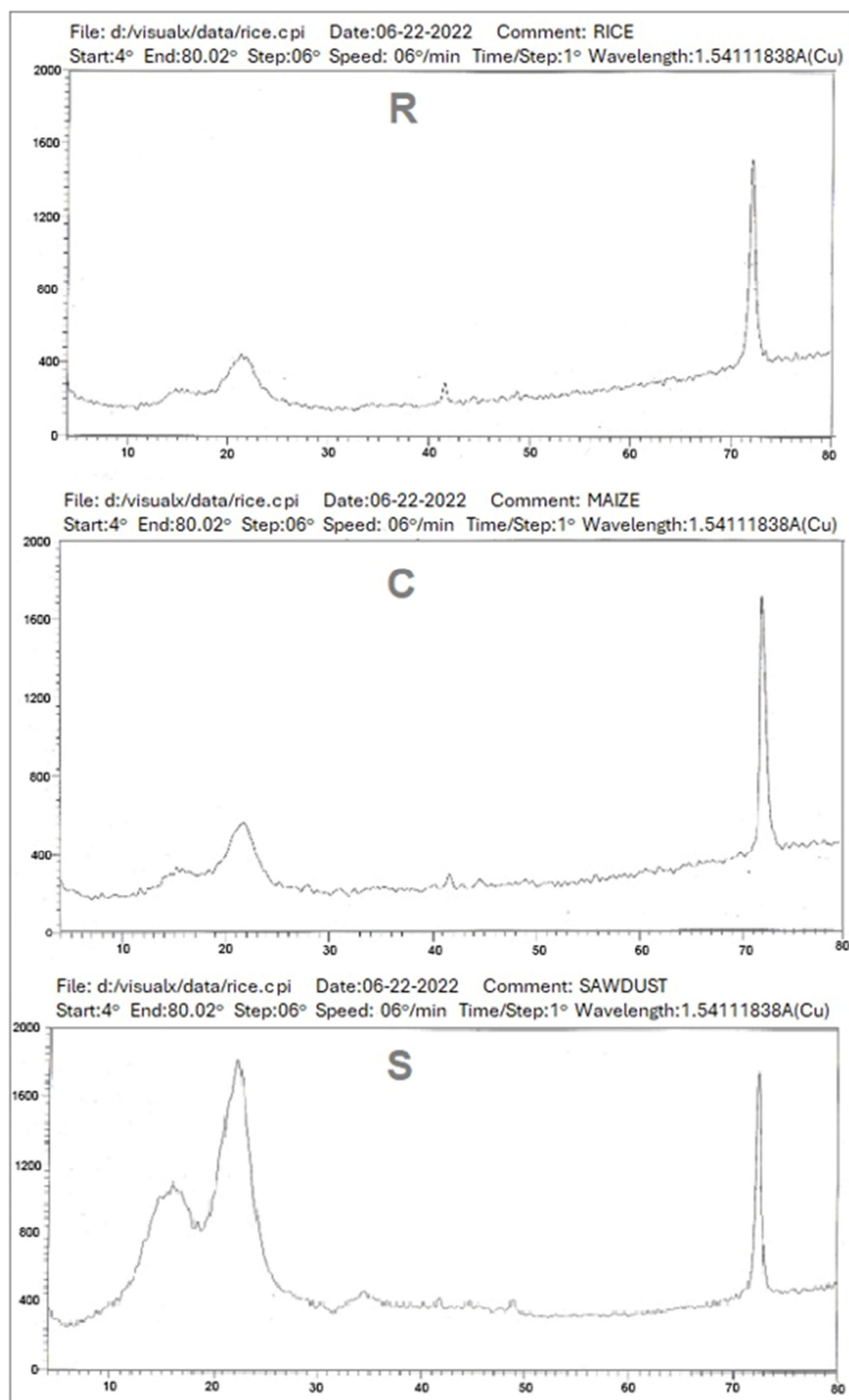


Figure 1. X-ray diffraction (XRD) patterns of adsorbent materials: rice straw (R), corn straw (C), and sawdust (S).

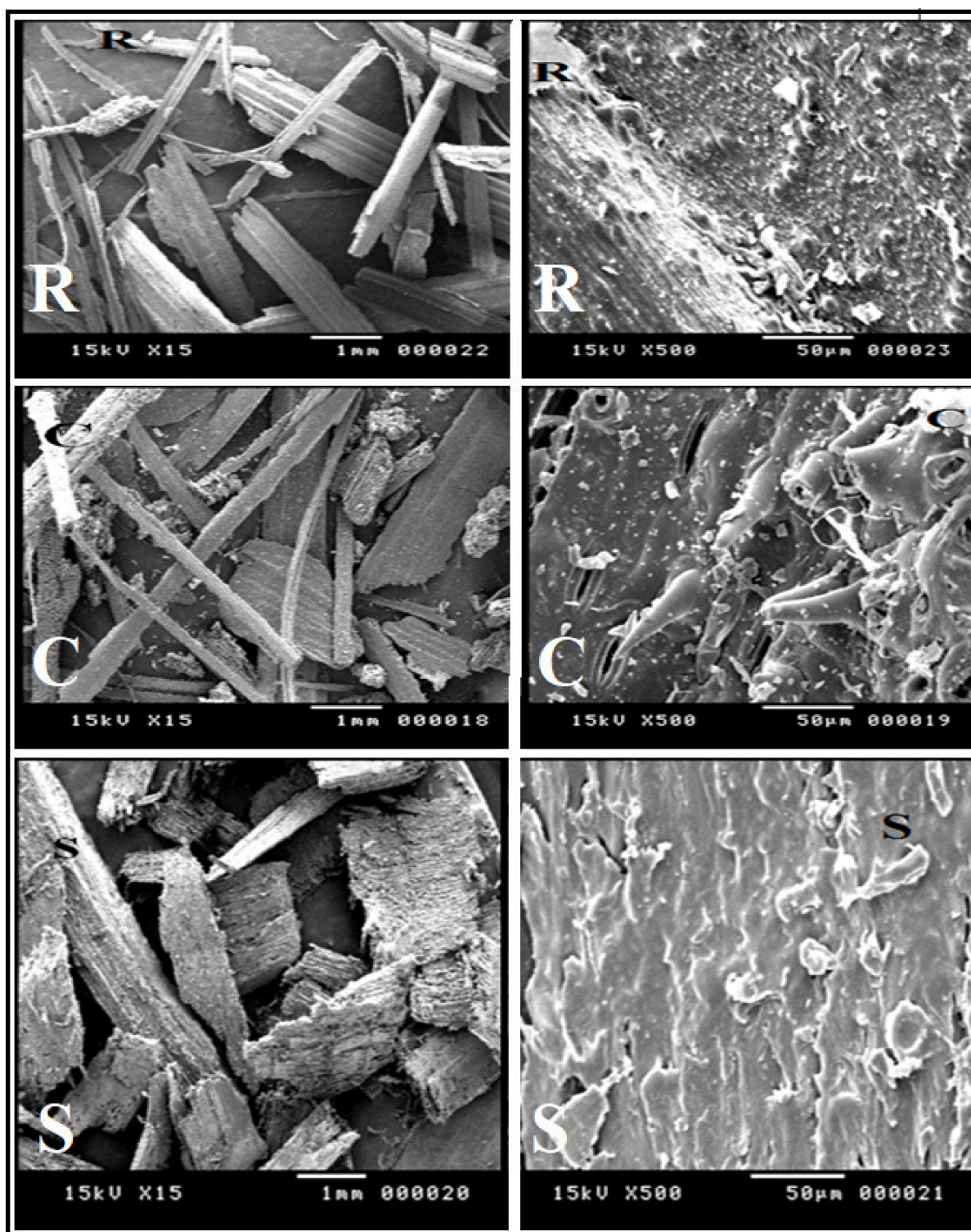


Figure 2. SEM images of natural adsorbent materials; rice straw (R), corn straw (C) and sawdust (S).

Figure 3 represents the pH, iodine, moisture content and dye (Methylene blue) removal % of rice straw, corn straw, sawdust and activated charcoal adsorbent materials. The pH values (Figure 3A) of the characterized adsorbent materials, namely rice straw, corn straw, sawdust, and activated charcoal, were 6.63 ± 0.44 , 6.14 ± 0.17 , 5.48 ± 0.65 , and 6.28 ± 0.20 , respectively. The moisture content% (Figure 3B) of rice straw, corn straw, sawdust, and activated charcoal was $4.5\% \pm 1.00\%$, $5.0\% \pm 1.82\%$, $4.5\% \pm 1.29\%$, and $5.37\% \pm 0.47\%$, respectively, with no statistically significant differences among the adsorbents ($p > 0.05$). The

iodine removal (Figure 3C) percent of rice straw, corn straw, sawdust, and activated charcoal was $13.0\% \pm 9.52\%$, $8.74\% \pm 0.69\%$, $7.36\% \pm 2.87\%$, and $9.2\% \pm 1.19\%$, respectively, with no statistically significant differences among adsorbents ($p > 0.05$). However, the removal efficiency of methylene blue (MB) was $84.87\% \pm 2.36\%$ for rice straw, $88.99\% \pm 1.10\%$ for corn straw, $90.14\% \pm 2.14\%$ for sawdust, and $90.95\% \pm 1.19\%$ for activated charcoal (Figure 3D).

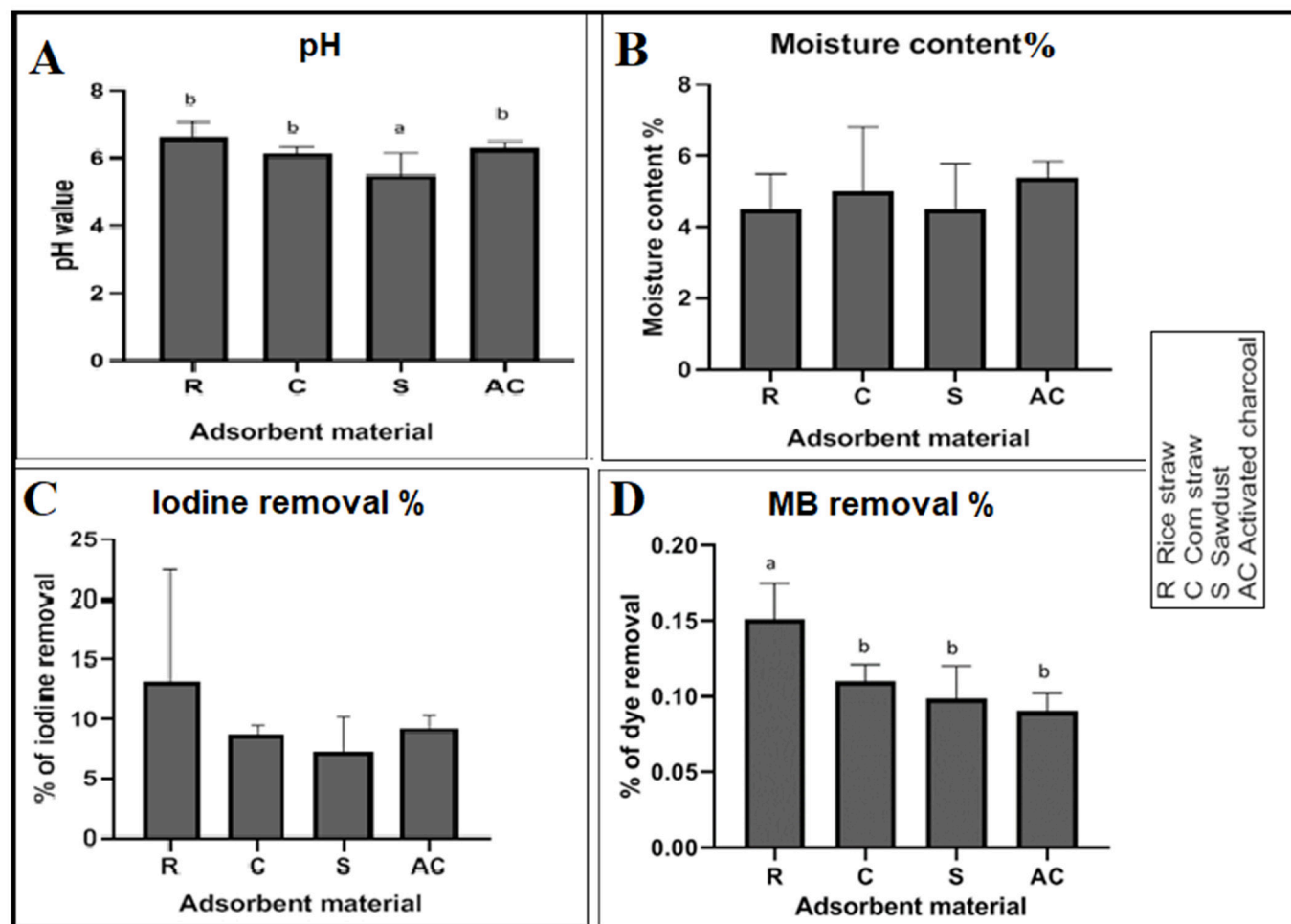


Figure 3. Rice straw (R), corn straw (C), sawdust (S) and activated charcoal (AC) adsorbent materials; pH, moisture content, iodine and methylene blue removal %. (A) pH values of rice straw, corn straw, sawdust and activated charcoal adsorbent materials; (B) moisture content % of rice straw, corn straw, sawdust and activated charcoal adsorbent materials; (C) iodine removal % of rice straw, corn straw, sawdust and activated charcoal adsorbent materials; (D) methylene blue removal % of rice straw, corn straw, sawdust and activated charcoal adsorbent materials; a, b means with different superscripts in the same column indicate significant differences at $p < 0.05$.

Removal efficiency performance indicators under the specific conditions tested, for intracellular and extracellular microcystins, are presented as mean $\pm$ standard deviation based on experiments (Table 3). Activated charcoal exhibited the highest MC removal efficiency, with $88.9 \pm 0.4\%$ in acidified water and $92.36 \pm 3.55\%$ in neutral water, as shown in Figure 4. Moreover, sawdust showed removal efficiencies of $84 \pm 11.3\%$ in acidified water and $86.2 \pm 10.17\%$ in neutral water, corn straw $74.08 \pm 8.56\%$ and $85.27 \pm 0.55\%$, and rice straw $75.41 \pm 7.2\%$ and $74.86 \pm 0.5\%$, respectively (Figure 4).

Table 3. Removal efficiency (%) of rice straw, corn straw, sawdust and activated charcoal adsorbent materials for intra-, extracellular and total microcystins in water.

Material	Intracellular		Extracellular		Total	
	Acidified	Neutral	Acidified	Neutral	Acidified	Neutral
Rice straw	69.33 ± 18.2	61.1 ± 10.9	79.1 ± 20.85	82.4 ± 5.6	75.41 ± 7.2	74.86 ± 0.5
Corn straw	85.8 ± 2	61.93 ± 4.45	60.56 ± 4.25	98.26 ± 1.8	74.08 ± 8.56	85.27 ± 0.55
Sawdust	96.32 ± 0.83	68.03 ± 21.85	77.3 ± 17.15	96.33 ± 3.7	84 ± 11.3	86.2 ± 10.17
A. charcoal	74.86 ± 4.45	95.9 ± 4	97.26 ± 1.55	90.53 ± 3.15	88.9 ± 0.4	92.36 ± 3.55

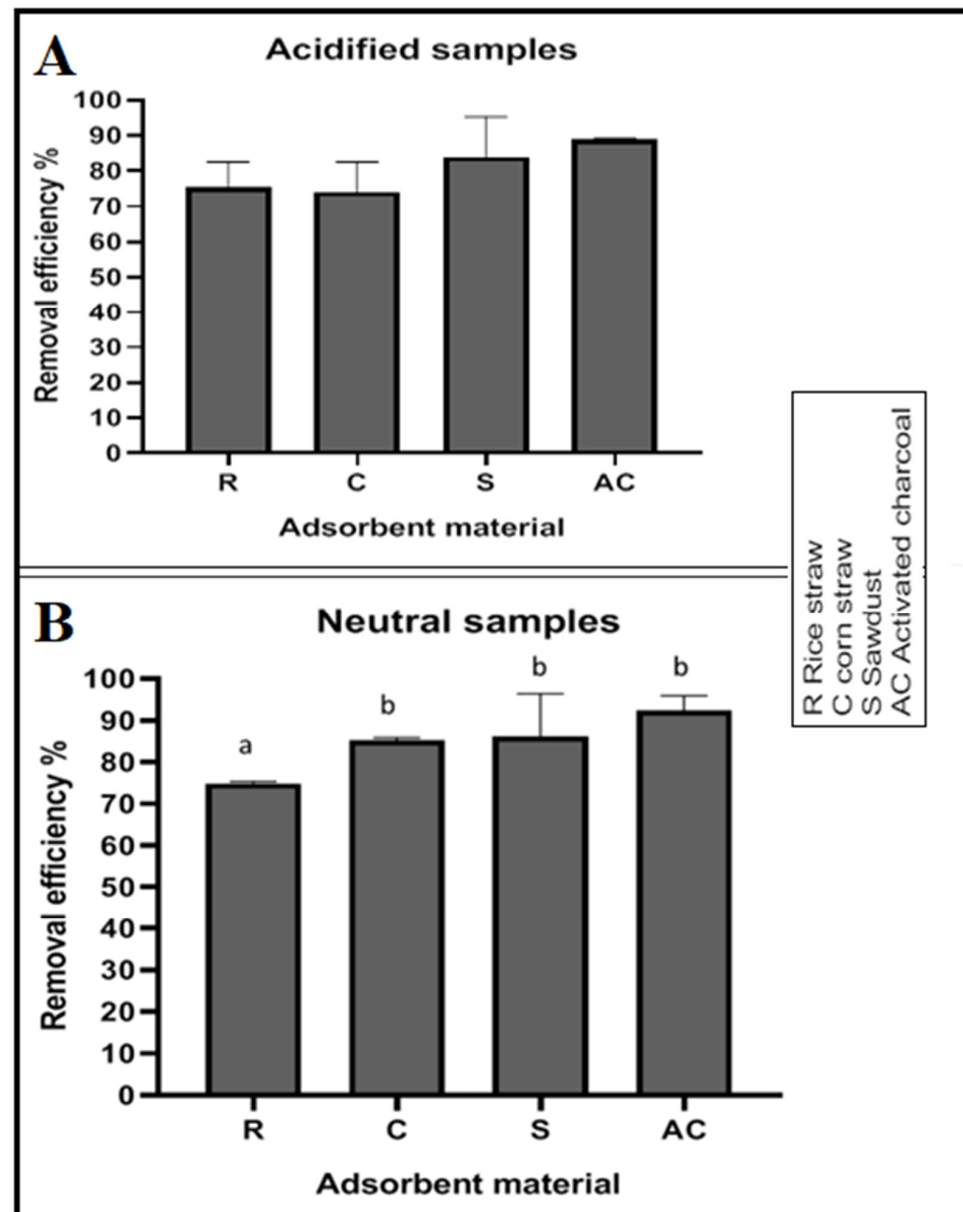
**Figure 4.** Microcystine (MC) removal efficiency percentages of rice straw (R), corn straw (C), saw dust (S) and activated charcoal (AC) adsorbent materials in acidified and natural samples. **(A)** Removal efficiency % for total Microcystine MC from rice straw (R), corn straw (C), saw dust (S) and activated charcoal (AC) adsorbent materials in acidified samples; **(B)** Removal efficiency % for total Microcystine MC from rice straw (R), corn straw (C), saw dust (S) and activated charcoal (AC) adsorbent materials in neutral samples; a, b means with different superscripts in the same column indicate significant differences at $p < 0.05$.

Table 4 shows that adsorption capacity varied slightly with adsorbent type and pH, with activated charcoal giving the highest total microcystin uptake in neutral water ($0.324 \pm 0.01 \mu\text{g g}^{-1}$) and still maintaining the highest value under acidified conditions ($0.312 \pm 0.001 \mu\text{g g}^{-1}$). In neutral water, sawdust and corn straw also showed relatively high total adsorption capacities (0.302 ± 0.03 and $0.299 \pm 0.001 \mu\text{g g}^{-1}$, respectively), while rice straw had the lowest value ($0.263 \pm 0.001 \mu\text{g g}^{-1}$). Under acidified pH 4, sawdust remained high ($0.295 \pm 0.03 \mu\text{g g}^{-1}$), whereas rice straw was nearly unchanged ($0.265 \pm 0.02 \mu\text{g g}^{-1}$) and corn straw decreased to $0.245 \pm 0.01 \mu\text{g g}^{-1}$. For fraction-specific adsorption, extracellular microcystins generally accounted for the larger share of uptake in all adsorbents, especially for rice straw and activated charcoal, indicating that the dissolved fraction was more readily adsorbed than intracellular material.

Table 4. Adsorption capacity for microcystine (μg^{-1}) of rice straw, corn straw, sawdust and activated charcoal adsorbent materials for intra-, extracellular and total microcystins in water.

	Acidified Water			Neutral Water		
	Intracellular MC	Extracellular MC	Total MC	Intracellular MC	Extracellular MC	Total MC
Rice straw	0.084 ± 0.03	0.18 ± 0.04	0.265 ± 0.02	0.075 ± 0.01	0.188 ± 0.01	0.263 ± 0.001
Corn straw	0.106 ± 0.002	0.139 ± 0.009	0.245 ± 0.01	0.077 ± 0.005	0.223 ± 0.004	0.299 ± 0.001
Saw dust	0.119 ± 0.001	0.176 ± 0.04	0.295 ± 0.03	0.084 ± 0.02	0.218 ± 0.008	0.302 ± 0.03
A. Charcoal	0.092 ± 0.005	0.221 ± 0.003	0.312 ± 0.001	0.118 ± 0.004	0.206 ± 0.007	0.324 ± 0.01

4. Discussion

4.1. Microcystins (Mcs) Contamination in Sohag and Assiut Governorates

The results indicate that wastewater and river waters in Sohag and Assiut Governorates harbor significantly higher MC concentrations compared with irrigation water (Table 2), with total means of 11.70 and $9.39 \mu\text{g/L}$, respectively, far exceeding the World Health Organization (WHO) guideline of $1 \mu\text{g/L}$ for MC-LR in drinking water [31]. The elevated intracellular concentrations in wastewater suggest higher cyanobacterial biomass or recent bloom activity, while the elevated extracellular fraction in river and wastewater indicates toxin release due to cell lysis or stress. These findings align with prior reports that dissolved MCs represent a major challenge for treatment because they are not efficiently removed by conventional coagulation and filtration processes [51]. However, large variances (high SD, large min–max ranges) in extracellular and total MCs indicate episodic or spatially heterogeneous bloom events, which, represented by a few samples with very high values, drive the means upward, while many samples are low or below detection.

Comparatively, the concentrations observed in this study are consistent with those reported worldwide. Mohamed (2016) found MCs in Egyptian drinking water ranging between 0.05 and $3.8 \mu\text{g/L}$ [32], while Tian et al. (2013) reported values of $1.846 \mu\text{g/L}$ in river water and $2.298 \mu\text{g/L}$ in ponds in China [34]. Higher concentrations have been documented in eutrophic lakes, such as Taihu Lake, China, where MC levels often exceed tens of $\mu\text{g/L}$ [33]. Reports from Europe and the United States have similarly documented episodic exceedances of WHO guidelines during cyanobacterial blooms [17,29]. The maximum concentrations detected in this study (41 – $43 \mu\text{g/L}$) fall within the range of severe bloom events documented globally [35].

The implications for human and animal health are significant. Elevated extracellular MCs in river and wastewater highlight potential risks of exposure through drinking water and food-chain bioaccumulation. MCs are known to accumulate in fish, shellfish, and even crops irrigated with contaminated water, posing a risk of hepatotoxicity, oxidative stress, and tumor promotion in consumers [11,22]. Wastewater, in particular, may act as a hotspot

for cyanotoxin contamination due to nutrient enrichment from industrial, agricultural, and domestic effluents.

4.2. Structure, Morphological and Chemical Characteristics of Natural Adsorbents and Their Relation with the Adsorption Efficiency

XRD and SEM provided useful information on the crystalline/amorphous nature and surface morphology of the tested adsorbents. The irregular, rough, and porous features observed in these analyses may have contributed to adsorption performance by increasing the availability of accessible sites for toxin interaction.

The absence of sharp crystalline peaks indicates the presence of disordered phases (Figure 1), which favor adsorption due to the abundance of active binding sites and functional groups such as hydroxyl, carboxyl, carbonyl, and amino moieties. These findings are consistent with those of Sackey et al. [52], who reported amorphous structures with silicate phases in rice straw biochar, and with those of Ningthoujam et al. [53], who observed that the absence of sharp XRD peaks in rice straw indicates its amorphous nature.

For amorphous carbonaceous materials derived from agricultural residues, X-ray diffraction (XRD) patterns (Figure 1 R, C and S) of rice straw, corn straw, and sawdust confirmed that all three adsorbents exhibited predominantly amorphous and porous structures. These patterns were generally advantageous for adsorption because their irregular pore structures and abundant oxygen-containing functional groups enhance surface reactivity and pollutant binding capacity [54]. Recent studies have demonstrated that amorphous bio-based adsorbents exhibit excellent performance in removing organic micropollutants and cyanotoxins because of their heterogeneous surfaces and porous structures [55]. Therefore, the amorphous structure confirmed by XRD in this study provides a strong structural basis for the adsorption potential of rice straw, corn straw, and sawdust.

The SEM image of rice straw (Figure 2R) was consistent with that of Ghadir et al. [56], who observed irregular plates and cracks on rice straw surfaces, and with that of Khalilollah and Seyed [57], who reported that raw rice straw possessed visible pores that increase adsorption efficiency by providing more active binding sites. Similar results were reported by Sackey et al. [52] and Ningthoujam et al. [53], who described rice straw as having a heterogeneous, rough, and groove-like morphology with numerous surface cracks and pores, thereby increasing pore volume and facilitating pollutant adsorption. In addition, the SEM image of rice and corn straw (Figure 3 R, C) aligned with that of Umpuch and Jutarat [58], who reported that the external surface of corn straw is characterized by pores and ridges, supporting its potential as an efficient natural adsorbent. Moreover, the SEM image of sawdust (Figure 2S) indicated a smaller effective surface area, consistent with that of Ostaszewski et al. [59], who described sawdust as having a fibrous, less porous morphology. According to Ikenyiri and Ukpaka [60], smaller particle size and greater surface projections enhance adsorption by increasing available binding sites. Consequently, based on SEM morphology, rice straw exhibited the most favorable surface structure for adsorption, followed by corn straw, while sawdust demonstrated the lowest adsorption potential.

These findings are supported by the recent literature showing that agricultural by-products with rough, porous, and heterogeneous morphologies such as rice husk, corn straw, and other lignocellulosic residues offer improved adsorption capacities due to enhanced pore structures and abundant surface functional groups [54,61]. Therefore, the structural characteristics observed in this study further validate the potential of rice straw and corn straw as effective low-cost adsorbents for cyanotoxin removal.

The pH of rice straw in the present study (Figure 3A) was notably lower than the value reported by Ahmedna et al. [62], who found 9.75 ± 0.52 , suggesting that pretreatment methods and raw material variability can strongly influence surface chemistry. The pH of commercial activated charcoal observed here was in close agreement with the results of

Ekpete and Horsfall [49], who reported a value of ~ 7 , but lower than those reported by Ariany et al. [63], who measured alkaline pH values (9.56–10.5) in activated carbon derived from pyrolysis biochar. Such variability underscores the role of precursor material and activation process in determining surface functional groups [61,64].

Adsorption capacity generally increases with higher pH due to enhanced ionization of surface functional groups and reduced competition with H^+ ions [65], supporting the hypothesis that pH influences their adsorption performance. These findings align with recent studies demonstrating that agricultural residues with near-neutral pH values can be effective, sustainable alternatives to commercial activated carbon for cyanotoxin removal [54].

The moisture content of sawdust (Figure 3B) in this study was lower than the 8.09% reported by Ibrahim and Amna [66], while the moisture content of commercial activated charcoal was also lower than that reported by Ekpete and Horsfall [49], who found values of $19.50 \pm 0.02\%$ for fluted activated carbon and $16.67 \pm 0.07\%$ for commercial activated carbon. Similarly, the present results for activated charcoal were at the lower end of the 0–13.06% range reported by Ariany et al. [63].

Moisture content is an important physicochemical property of adsorbents because high moisture levels may reduce surface area availability and adsorption efficiency by occupying pore spaces and blocking functional groups [54]. Conversely, low moisture content is generally favorable for adsorption, as it enhances porosity and maximizes the number of active sites [63]. The relatively low moisture contents observed in this study for rice straw, corn straw, and sawdust indicate their potential suitability as efficient low-cost adsorbents, with performance comparable to that of commercial activated charcoal. These findings reinforce the potential of agricultural by-products as sustainable alternatives to commercial activated carbons for water purification applications [61].

The iodine removal % of rice straw and activated charcoal in this study (Figure 3C) was lower than values reported by Ahmedna et al. [62] for activated carbon derived from rice straw. Since iodine removal % is directly related to the microporous surface area of the adsorbent, higher values typically indicate enhanced adsorption potential for small molecules [67,68]. Although the iodine removal efficiency was relatively low across all tested materials, rice straw performed slightly better than activated charcoal, followed by corn straw and sawdust. This suggests that, despite limited microporosity compared with engineered carbons, agricultural residues such as rice straw can still provide effective low-cost adsorbents, particularly when chemically or thermally modified to enhance microporous structure [54,64].

The MB removal efficiency of rice straw (Figure 3D) was consistent with that reported by Ahmedna et al. [62], who achieved up to 88%. However, it was lower than the findings of Senapati et al. [69], who reported a removal capacity of 94.45% using rice straw-derived biochar, likely due to structural modifications during pyrolysis that enhance porosity and surface functionality. For activated charcoal, our results were comparable to those reported by Ariany et al. [63], who observed MB removal efficiencies ranging from 96.75% to 98.19%. Conversely, they were higher than the values reported by Zahanggir et al. [70], who found only 42.46–59.96% removal using untreated charcoal, again underscoring the importance of precursor type and activation process. Among the studied adsorbents, activated charcoal exhibited the highest MB removal, followed closely by sawdust and corn straw, with rice straw performing the least effectively. Recent studies confirm that surface modification techniques (e.g., acid activation, pyrolysis, or metal impregnation) can significantly enhance the dye adsorption capacity of natural adsorbents [61].

4.3. Efficiency of Microcystin Removal from Water Samples Using Natural Adsorbent Materials

The results presented in Table 3 clearly demonstrated that the removal efficiency of intracellular, extracellular, and total microcystins is significantly influenced by both the type of adsorbent material and the pH. Variations in adsorption performance among rice straw, corn straw, sawdust, and activated charcoal can be attributed to differences in surface area, porosity, and surface functional groups, which govern the dominant adsorption mechanisms.

Activated charcoal exhibited the highest and most consistent removal efficiency across all tested conditions, although no significant differences were observed between conditions. The removal of intracellular microcystins reached 95.9% under neutral conditions, while extracellular removal achieved 97.26% in acidified water. Total microcystin removal also exceeded 88% under both pH conditions. The superior performance of activated charcoal is primarily attributed to its highly developed microporous structure and large specific surface area, which facilitate pore filling and physical adsorption. Additionally, strong hydrophobic interactions and π - π electron donor-acceptor interactions occur between the aromatic surface of activated carbon and the cyclic peptide structure of microcystins. These findings are consistent with previous studies that identified activated carbon as one of the most effective adsorbents for microcystin removal due to its high adsorption affinity and rapid kinetics [71,72]. Our findings are consistent with those of Ibrahim et al. [73], who reported up to 100% removal using algal-activated carbon in column experiments. Activated charcoal remains the benchmark for adsorption due to its high porosity and surface functionality [51,64].

Sawdust also demonstrated high removal efficiencies, particularly for intracellular microcystins under acidified conditions (96.32%) and extracellular toxins under neutral conditions (96.33%). This performance can be explained by the lignocellulosic composition of sawdust, which contains abundant hydroxyl, carboxyl, and phenolic functional groups. These groups promote adsorption through hydrogen bonding and electrostatic interactions. Under acidified conditions, protonation of surface functional groups enhances electrostatic attraction between the adsorbent surface and negatively charged microcystin molecules, thereby improving adsorption efficiency. Moreover, the fibrous and porous structure of sawdust enhances mass transfer and surface contact, contributing to effective toxin removal. Similar adsorption behavior of lignocellulosic materials has been reported, where surface functionality and pore structure were identified as key factors controlling microcystin adsorption [72].

Corn straw showed a pronounced pH-dependent behavior. While intracellular removal was higher in acidified water (85.8%), extracellular removal reached its maximum value (98.26%) in neutral conditions. The high extracellular removal at neutral pH may be attributed to favorable surface charge conditions and enhanced hydrophobic interactions. Corn straw contains relatively higher lignin content compared with rice straw, providing aromatic structures capable of interacting with the hydrophobic Adda side chain of microcystins through π - π interactions. The variability between acidified and neutral conditions suggests that electrostatic interactions and surface charge play a critical role in adsorption performance. Since microcystins are negatively charged at neutral to slightly alkaline pH, adsorption efficiency depends on the surface charge characteristics of the adsorbent [74].

Rice straw exhibited comparatively moderate removal efficiencies under both pH conditions, with total microcystin removal ranging between 74 and 75%. Although rice straw contains similar lignocellulosic components to corn straw and sawdust, its relatively lower surface area and limited porosity likely restricted adsorption capacity. The adsorption mechanism is predominantly governed by physical adsorption and weak electrostatic interactions. Without chemical or thermal activation, the availability of active sites remains

limited, explaining its lower performance relative to activated charcoal and sawdust. Previous studies have emphasized that structural modification or activation significantly enhances adsorption capacity by increasing porosity and surface functionality [72].

Although some adsorbents showed marginally higher removal under acidic conditions, the overall effect of pH was not statistically significant. Acidified conditions of adsorbent materials tested for intracellular microcystin (cell-associated microcystins) promote protonation of surface functional groups, increasing positive surface charge and enhancing attraction toward negatively charged microcystin molecules. Conversely, neutral conditions favor hydrophobic interactions, particularly for extracellular toxins freely dissolved in water. The combined effects of pore structure, hydrophobic affinity, hydrogen bonding, and electrostatic attraction collectively determine overall adsorption efficiency. Overall, the removal efficiency followed the order: Activated charcoal $\geq$ Sawdust > Corn straw > Rice straw. These findings confirm that activated charcoal remains the most effective adsorbent for microcystin removal. However, the high performance of sawdust and corn straw, particularly under optimized pH conditions, highlights their potential as low-cost and sustainable alternatives for water treatment applications.

Although rice straw showed promising removal in our study, its efficiency was lower than that reported in earlier studies. Ningthoujam et al. 2023 and Khalilollah & Seyed (2019) achieved >95% and 96.7% removal using rice husk and rice straw, respectively, likely due to differences in pretreatment or adsorbent surface modification [53,57]. Despite this, its abundance and low cost make rice straw an attractive material for microcystin removal.

To the best of our knowledge, this is the first study demonstrating corn straw's efficacy for microcystin removal. Its performance in neutral water was particularly noteworthy, approaching levels seen with activated charcoal. Prior research has focused on corn straw for heavy metals and dyes, e.g., Cr 87.4 and Cr 62.3 mg/g [58]. Although activated charcoal remained more effective overall, sawdust and corn straw demonstrated high efficiencies, supporting their use as low-cost, sustainable alternatives.

Sawdust achieved the highest efficiencies among natural adsorbents in acidified and in neutral water. These results are consistent with those of Wang et al. [41], who reported >96.47% removal of dissolved MC-LR in a sawdust-based constructed wetland treating Microcystis-laden water, albeit via combined physical, biological, and possible biodegradation processes. In our study, comparable removal was obtained using raw sawdust in short-contact-time batch experiments, highlighting its intrinsic adsorption potential even without engineered systems [41]. Sawdust was more effective than both rice and corn straw for total microcystin removal, though it remained slightly less efficient than activated charcoal in neutral water ($p = 0.025$). Its performance highlights the value of waste wood materials as sustainable adsorbents, offering both high efficiency and environmental benefits.

Activated charcoal (Table 4) showed the highest adsorption capacity because its carbon-rich and more porous surface likely provided the greatest number of accessible adsorption sites, which supports stronger microcystin uptake through hydrophobic interactions and π - π stacking with the aromatic Adda moiety. Its relatively higher iodine and methylene blue removal values also indicate better development of micro- and mesopores and a larger accessible surface, which is consistent with higher q . Sawdust and corn straw showed intermediate adsorption capacities, which can be linked to their lignocellulosic structure and the presence of surface functional groups such as -OH and -COOH that may promote hydrogen bonding, although their lower carbonization and porosity compared with activated charcoal likely limited uptake. Rice straw gave the lowest q , suggesting fewer accessible adsorption sites, lower effective surface area, or more limited pore structure, so the dissolved microcystins were retained less efficiently. The small differences between

neutral and acidified water suggest that pH influenced surface charge and interaction strength, so electrostatic effects likely complemented the dominant hydrophobic and π - π interactions [75].

The high microcystin (MC) removal efficiencies achieved in real Nile-derived water samples demonstrate the practical applicability of the investigated agricultural adsorbents under environmentally relevant conditions. These results are particularly significant because the waters from the Sohag and Assiut regions contain elevated concentrations of natural organic matter (NOM), including approximately 5–20 mg/L humic and fulvic substances derived from agricultural runoff and abattoir discharges. Such organic constituents typically compete with MC molecules for adsorption sites and reduce the performance of many adsorbents.

However, variable SDs (sawdust $\pm$ 11%, rice $\pm$ 7%) suggest matrix heterogeneity (e.g., seasonal algal NOM spikes) influences reproducibility. Unlike synthetic studies showing 20–40% NOM-induced drops, real water performance validates adsorbents' robustness, though breakthrough testing in continuous columns with local effluents (high BOD from abattoirs) would confirm longevity under chronic exposure. Multi-contaminant synergy (e.g., veterinary antibiotics) merits evaluation for comprehensive treatment.

Across all adsorbents, activated charcoal ranked the highest in both acidified and neutral conditions, followed by sawdust, rice straw, and corn straw in acidified water, and by sawdust, corn straw, and rice straw in neutral water. Notably, extracellular microcystins were removed more effectively than intracellular ones across all adsorbents. Corn straw was particularly efficient for extracellular toxin removal, while activated charcoal was most effective for intracellular fractions. Although such raw materials generally exhibit lower adsorption capacity than modified biochars, they offer a simple and sustainable preliminary option for microcystin removal.

4.4. Implications

Although the present study demonstrates the practical potential of rice straw, corn straw, sawdust, and activated charcoal for microcystin removal from real water samples, several experimental limitations should be acknowledged. The adsorption experiments were intentionally designed as a simplified batch test using one adsorbent dose, one short contact time, and two pH conditions to evaluate feasibility under practical treatment conditions and to compare the tested materials directly. Therefore, the study does not provide adsorption capacity values, kinetic or isotherm modeling, dose–response optimization, or regeneration/reuse data. These parameters are important for fully describing adsorption mechanisms and long-term applicability, and they should be investigated in future studies. BET, FTIR, pH_{pzc}, zeta potential, and elemental analysis are needed in future work for full mechanistic confirmation, as XRD and SEM alone cannot directly substantiate mechanistic claims regarding surface area, porosity, charge, or functional groups.

The applied dose and short contact time were selected for comparative screening purposes under standardized batch conditions and should not be interpreted as full-scale operational values. Dose optimization, longer contact-time studies, and continuous-flow evaluation will be required before practical application can be considered.

4.5. Conclusions

Overall, this study highlights the elevated risk of MC contamination in both river and wastewater sources in Upper Egypt, with concentrations often exceeding safe limits. This study demonstrates that microcystin removal efficiency is strongly influenced by both adsorbent type and solution pH. Activated charcoal showed the highest and most consistent removal of intracellular, extracellular, and total microcystins due to its large

surface area, well-developed microporous structure, and dominant pore-filling and hydrophobic interactions. Sawdust exhibited comparably high performance, particularly under acidified conditions, owing to abundant surface functional groups that promote hydrogen bonding and electrostatic interactions. Corn straw displayed pronounced pH-dependent behavior with excellent extracellular removal under neutral conditions, while rice straw showed moderate efficiency, likely due to its lower porosity and limited active sites. Overall, removal efficiency followed the order: activated charcoal $\geq$ sawdust > corn straw > rice straw, highlighting the strong potential of low-cost lignocellulosic wastes as sustainable alternatives for microcystin removal in water treatment systems. Although activated charcoal remains the most reliable adsorbent, sawdust and corn straw demonstrated high efficiencies comparable to commercial carbons, supporting their use as low-cost, sustainable alternatives.

Future research should focus on enhancing the adsorption capacity of lignocellulosic materials (rice straw, corn straw, and sawdust) through physical and chemical activation methods (e.g., thermal treatment, acid/base modification, or biochar production) to increase surface area and functional group availability. Moreover, further studies are required to assess possible leaching of dissolved organic matter, nutrients, or other compounds from untreated agricultural residues, as well as regeneration, reuse, disposal, stability, and continuous-flow behavior. Detailed isotherm, kinetic, and thermodynamic studies are recommended to better elucidate adsorption mechanisms and rate-controlling steps. Investigation of regeneration and reusability performance is essential to assess long-term economic feasibility. Finally, life-cycle assessment and cost-benefit analysis should be conducted to confirm the sustainability and industrial applicability of biomass-derived adsorbents for large-scale microcystin removal.

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References

1. Huisman, J.; Codd, G.A.; Paerl, H.W.; Ibelings, B.W.; Verspagen, J.M.H.; Visser, P.M. Cyanobacterial blooms. *Nat. Rev. Microbiol.* **2018**, *16*, 471–483. [[CrossRef](#)] [[PubMed](#)]
2. Paerl, H.W.; Otten, T.G. Harmful cyanobacterial blooms: Causes, consequences, and controls. *Microb. Ecol.* **2013**, *65*, 995–1010. [[CrossRef](#)] [[PubMed](#)]
3. Melaram, R.; Newton, A.R.; Lee, A.; Herber, S.; El-Khoury, A.; Chafin, J. A review of microcystin and nodularin toxins derived from freshwater cyanobacterial harmful algal blooms and their impact on human health. *Toxicol. Environ. Health Sci.* **2024**, *16*, 233–241. [[CrossRef](#)]

4. Marumure, J.; Gwenzi, W.; Makuvara, Z.; Simbanegavi, T.T.; Alufasi, R.; Goredema, M.; Gufe, C.; Karidzagundi, R.; Rzymiski, P.; Halabowski, D. Global occurrence of cyanotoxins in drinking water systems: Recent advances, human health risks, mitigation, and future directions. *Life* **2025**, *15*, 825. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Catherine, A.; Bernard, C.; Spoof, L.; Bruno, M. *Handbook of Cyanobacterial Monitoring and Cyanotoxin Analysis*; John Wiley & Sons: Hoboken, NJ, USA, 2017.
6. Jochimsen, E.M.; Carmichael, W.W.; An, J.S.; Cardo, D.M.; Cookson, S.T.; Holmes, C.E.; Antunes, M.B.; de Melo Filho, D.A.; Lyra, T.M.; Barreto, V.S.; et al. Liver failure and death after exposure to microcystins at a hemodialysis center in Brazil. *N. Engl. J. Med.* **1998**, *338*, 873–878. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Ueno, Y.; Makita, Y.; Nagata, S.; Tsutsumi, T.; Yoshida, F.; Tamura, S.; Sekijima, M.; Tashiro, F.; Harada, T.; Yoshida, T. No chronic oral toxicity of a low dose of microcystin-LR, a cyanobacterial hepatotoxin, in female BALB/c mice. *Environ. Toxicol.* **1999**, *14*, 45–55. [\[CrossRef\]](#)
8. Svirčev, Z.B.; Tokodi, N.; Drobac, D.; Codd, G.A. Cyanobacteria in aquatic ecosystems in Serbia: Effects on water quality, human health and biodiversity. *Syst. Biodivers.* **2014**, *12*, 261–270. [\[CrossRef\]](#)
9. Briand, J.F.; Jacquet, S.; Bernard, C.; Humbert, J.F. Health hazards for terrestrial vertebrates from toxic cyanobacteria in surface water ecosystems. *Vet. Res.* **2003**, *34*, 361–377. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Stewart, I.; Seawright, A.A.; Shaw, G.R. Cyanobacterial poisoning in livestock, wild mammals and birds—an overview. *Adv. Exp. Med. Biol.* **2008**, *619*, 613–637. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Fischer, W.J.; Hitzfeld, B.C.; Tencalla, F.; Eriksson, J.E.; Mikhailov, A.; Dietrich, D.R. Microcystin-LR toxicodynamics, induced pathology, and immunohistochemical localization in livers of blue-green algae exposed rainbow trout (*oncorhynchus mykiss*). *Toxicol. Sci.* **2000**, *54*, 365–373. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Paulino, M.G.; Rossi, P.A.; Venturini, F.P.; Tavares, D.; Elisabete da Silva Souza, N.; Sakuragui, M.M.; Moraes, G.; Terezan, A.P.; Fernandes, J.B.; Giani, A.; et al. Hepatotoxicity and metabolic effects of cellular extract of cyanobacterium *Radiocystis fernandoi* containing microcystins RR and YR on neotropical fish (*Hoplias malabaricus*). *Chemosphere* **2017**, *175*, 431–439. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Drobac, D.; Tokodi, N.; Lujčić, J.; Marinović, Z.; Subakov-Simić, G.; Dulić, T.; Vazić, T.; Nybom, S.; Meriluoto, J.; Codd, G.A.; et al. Cyanobacteria and cyanotoxins in fishponds and their effects on fish tissue. *Harmful Algae* **2016**, *55*, 66–76. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Gehringer, M.M.; Kewada, V.; Coates, N.; Downing, T.G. The use of *Lepidium sativum* in a plant bioassay system for the detection of microcystin-LR. *Toxicon* **2003**, *41*, 871–876. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Fawell, J.K.; James, C.P.; James, H.A. *Toxins from Blue-Green Algae: Toxicological Assessment of Microcystin-LR and a Method for Its Determination in Water*; Report No. FR 0359/2/DoE 3358/2; Foundation of Water Research: Marlow, UK, 1994.
16. Hou, J.; Su, Y.; Lin, W.; Guo, G.; Xie, P.; Chen, J.; Gu, Z.; Li, L. Microcystin-LR retards gonadal maturation through disrupting the growth hormone/insulin-like growth factors system in zebrafish. *Ecotoxicol. Environ. Saf.* **2017**, *139*, 27–35. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Codd, G.A.; Morrison, L.F.; Metcalf, J.S. Cyanobacterial toxins: Risk management for health protection. *Toxicol. Appl. Pharmacol.* **2005**, *203*, 264–272. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Buratti, F.M.; Manganelli, M.; Vichi, S.; Stefanelli, M.; Scardala, S.; Testai, E.; Funari, E. Cyanotoxins: Producing organisms, occurrence, toxicity, mechanism of action and human health toxicological risk evaluation. *Arch. Toxicol.* **2017**, *91*, 1049–1130. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Ren, Y.; Yang, M.; Chen, M.; Zhu, Q.; Zhou, L.; Qin, W.; Wang, T. Microcystin-LR promotes epithelial-mesenchymal transition in colorectal cancer cells through PI3-K/AKT and SMAD2. *Toxicol. Lett.* **2017**, *265*, 53–60. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Zegura, B. An Overview of the Mechanisms of Microcystin-LR Genotoxicity and Potential Carcinogenicity. *Mini Rev. Med. Chem.* **2016**, *16*, 1042–1062. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Dai, H.; Liu, J.; Wang, S.; Wang, B.; Kai, T.; Wu, P.; Ding, P. Recent advances in optical sensors for microcystin-LR: From recognition elements to signal transduction. *Analyst* **2025**, *150*, 1470–1489. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Zervou, S.K.; Christophoridis, C.; Kaloudis, T.; Triantis, T.M.; Hiskia, A. New SPE-LC-MS/MS method for simultaneous determination of multi-class cyanobacterial and algal toxins. *J. Hazard Mater.* **2017**, *323*, 56–66. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Villalobos, T.; Suárez-Isla, B.; Garcia, C. Health and Environmental Impacts of Cyanobacteria and Cyanotoxins from Freshwater to Seawater. *Toxins* **2025**, *17*, 126. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Lee, S.; Jiang, X.; Manubolu, M.; Riedl, K.; Ludsin, S.A.; Martin, J.F.; Lee, J. Fresh produce and their soils accumulate cyanotoxins from irrigation water: Implications for public health and food security. *Food Res. Int.* **2017**, *102*, 234–245. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Qian, Z.-Y.; Li, Z.-G.; Ma, J.; Gong, T.-T.; Xian, Q.-M. Analysis of trace microcystins in vegetables using matrix solid-phase dispersion followed by high-performance liquid chromatography triple-quadrupole mass spectrometry detection. *Talanta* **2017**, *173*, 101–106. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Faulkner, S.; Sweetman, C.; Hutson, J.; Soole, K.; Hobson, P.; Fallowfield, H. Uptake of the cyanobacterial toxin microcystin by crop plants irrigated with contaminated wastewater: A review. *Rev. Environ. Sci. Biotechnol.* **2025**, *24*, 217–238. [\[CrossRef\]](#)

27. Djediat, C.; Malécot, M.; de Luze, A.; Bernard, C.; Puiseux-Dao, S.; Edery, M. Localization of microcystin-LR in medaka fish tissues after cyanotoxin gavage. *Toxicon* **2010**, *55*, 531–535. [[CrossRef](#)] [[PubMed](#)]
28. Lone, Y.; Bhide, M.; Koiri, R.K. Microcystin-LR induced immunotoxicity in mammals. *J. Toxicol.* **2016**, *2016*, 8048125. [[CrossRef](#)] [[PubMed](#)]
29. Mantzouki, E.; Visser, P.M.; Bormans, M.; Ibelings, B.W. Understanding the key ecological traits of cyanobacteria as a basis for their management and control in changing lakes. *Aquat. Ecol.* **2016**, *50*, 333–350. [[CrossRef](#)]
30. Cai, W.; Zhao, Z.; Li, D.; Lei, Z.; Zhang, Z.; Lee, D.J. Algae granulation for nutrients uptake and algae harvesting during wastewater treatment. *Chemosphere* **2019**, *214*, 55–59. [[CrossRef](#)] [[PubMed](#)]
31. Chorus, I.; Welker, M. (Eds.) *Toxic Cyanobacteria in Water: A Guide to Their Public Health Consequences, Monitoring and Management*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2021. [[CrossRef](#)]
32. Mohamed, Z.A. Harmful cyanobacteria and their cyanotoxins in Egyptian fresh waters—State of knowledge and research needs. *Afr. J. Aquat. Sci.* **2016**, *41*, 361–368. [[CrossRef](#)]
33. Chen, J.; Xie, P.; Zhang, D.; Lei, H. In situ studies on the distribution patterns and dynamics of microcystins in a biomanipulation fish bighead carp (*Aristichthys nobilis*). *Environ. Pollut.* **2007**, *147*, 150–157. [[CrossRef](#)] [[PubMed](#)]
34. Tian, D.; Zheng, W.; Wei, X.; Sun, X.; Liu, L.; Chen, X.; Zhang, H.; Zhou, Y.; Chen, H.; Zhang, H.; et al. Dissolved microcystins in surface and ground waters in regions with high cancer incidence in the Huai River Basin of China. *Chemosphere* **2013**, *7*, 1064–1071. [[CrossRef](#)] [[PubMed](#)]
35. Brooks, B.W.; Lazorchak, J.M.; Howard, M.D.A.; Johnson, M.-V.V.; Morton, S.L.; Perkins, D.A.K.; Reavie, E.D.; Scott, G.I.; Smith, S.A.; Steevens, J.A. Are harmful algal blooms becoming the greatest inland water quality threat to public health and aquatic ecosystems? *Environ. Toxicol. Chem.* **2016**, *35*, 6–13. [[CrossRef](#)] [[PubMed](#)]
36. He, X.; de la Cruz, A.A.; Hiskia, A.; Kaloudis, T.; O'Shea, K.; Dionysiou, D.D. Destruction of microcystins (cyanotoxins) by UV-254 nm-based direct photolysis and advanced oxidation processes (AOPs): Influence of variable amino acids on the degradation kinetics and reaction mechanisms. *Water Res.* **2015**, *74*, 227–238. [[CrossRef](#)] [[PubMed](#)]
37. He, X.; Liu, Y.L.; Conklin, A.; Westrick, J.; Weavers, L.K.; Dionysiou, D.D.; Lenhart, J.J.; Mouser, P.J.; Szlag, D.; Walker, H.W. Toxic cyanobacteria and drinking water: Impacts, detection, and treatment. *Harmful Algae* **2016**, *54*, 174–193. [[CrossRef](#)] [[PubMed](#)]
38. Bullerjahn, G.S.; McKay, R.M.; Davis, T.W.; Baker, D.B.; Boyer, G.L.; D'Anglada, L.V.; Doucette, G.J.; Ho, J.C.; Irwin, E.G.; Kling, C.L.; et al. Global solutions to regional problems: Collecting global expertise to address the problem of harmful cyanobacterial blooms. A Lake Erie case study. *Harmful Algae* **2016**, *54*, 223–238. [[CrossRef](#)] [[PubMed](#)]
39. Falconer, I.R.; Humpage, A.R. Cyanobacterial (blue-green algal) toxins in water supplies: Cylindrospermopsins. *Environ. Toxicol.* **2006**, *21*, 299–304. [[CrossRef](#)] [[PubMed](#)]
40. Mohamed, Z.A.; Deyab, M.A.; Abou-Dobara, M.I.; El-Sayed, A.K.; El-Raghi, W.M. Occurrence of cyanobacteria and microcystin toxins in raw and treated waters of the Nile River, Egypt: Implication for water treatment and human health. *Environ. Sci. Pollut. Res. Int.* **2015**, *22*, 11716–11727. [[CrossRef](#)] [[PubMed](#)]
41. Wang, B.; Peng, Q.; Wang, R.; Yu, S.; Li, Q.; Huang, C. Efficient Microcystis removal and sulfonamide-resistance gene propagation mitigation by constructed wetlands and functional genes analysis. *Chemosphere* **2022**, *286*, 133481. [[CrossRef](#)] [[PubMed](#)]
42. Hassan, A.F.; Youssef, A.M. Preparation and characterization of microporous NaOH activated carbons from hydrofluoric acid leached rice husk and its application for lead (II) adsorption. *Carbon Lett.* **2014**, *15*, 57–66. [[CrossRef](#)]
43. Palagama, D.S.W.; Devasurendra, A.M.; Baliu-Rodriguez, D.; Kirchhoff, J.R.; Isailovic, D. Treated rice husk as a recyclable sorbent for the removal of microcystins from water. *Sci. Total Environ.* **2019**, *666*, 1292–1300. [[CrossRef](#)] [[PubMed](#)]
44. Chaffin, J.D.; Fox, E.L.; Nauman, C.A.; Slodysko, K.N. The ability of household pitcher-style water purifiers to remove microcystins depends on filtration rate and activated carbon source. *Water Supply* **2019**, *19*, 336–343. [[CrossRef](#)]
45. Elbert, A.M.; Titus, A.M.M.; Bhekie, B.M. Quantitative variations of intracellular microcystin-LR, -RR and -YR in samples collected from four locations in Hartbeespoort Dam in North West Province (South Africa) during the 2010/2011 summer season. *Int. J. Environ. Res. Public Health* **2012**, *9*, 3484–3505. [[CrossRef](#)] [[PubMed](#)]
46. Abdel-Mohsein, H.S.; Zaky, Z.M.; Kelini, W.K.; Mahmoud, M.A. Microcystins in different water sources accountable for health risk in Egypt. *Water Air Soil Pollut.* **2026**, *237*, 196. [[CrossRef](#)]
47. Manubolu, M.; Lee, J.; Riedl, K.M.; Kua, Z.X.; Collart, L.P.; Ludsin, S.A. Optimization of extraction methods for quantification of microcystin-LR and microcystin-RR in fish, vegetable, and soil matrices using UPLC-MS/MS. *Harmful Algae* **2018**, *76*, 47–57. [[CrossRef](#)] [[PubMed](#)]
48. Nuruddin, M.; Chowdhury, A.; Haque, S.A.; Rahman, M.; Farhad, S.F.; Sarwar Jahan, M.; Quaiyyum, A. Extraction and characterization of cellulose microfibrils from agricultural wastes in an integrated biorefinery initiative. *Cellul. Chem. Technol.* **2011**, *45*, 347–354.
49. Ekpote, O.A.; Horsfall, M.J.N.R. Preparation and characterization of activated carbon derived from fluted pumpkin stem waste (*Telfairia occidentalis* Hook F). *Res. J. Chem. Sci.* **2011**, *1*, 10–17.

50. Dhuha, H.F.; Ahmed, A.-H.; Emad, Y. Removal of methylene blue dye from water using ecofriendly waste product (eggshell) as an adsorbent and using the optimum adsorption conditions with real water sample from Tigris River. *Al-Nahrain J. Sci.* **2019**, *22*, 9–14. [[CrossRef](#)]
51. Newcombe, G.; Nicholson, B. Water treatment options for dissolved cyanotoxins. *J. Water Supply Res. Technol. AQUA* **2004**, *53*, 227–239. [[CrossRef](#)]
52. Sackey, E.A.; Song, Y.; Yu, Y.; Zhuang, H. Biochars derived from bamboo and rice straw for sorption of basic red dyes. *PLoS ONE* **2021**, *16*, e0254637. [[CrossRef](#)] [[PubMed](#)]
53. Ningthoujam, R.; Jangid, P.; Yadav, V.K.; Sahoo, D.K.; Patel, A.; Dhingra, H.K. Bioethanol production from alkali-pretreated rice straw: Effects on fermentation yield, structural characterization, and ethanol analysis. *Front. Bioeng. Biotechnol.* **2023**, *11*, 1243856. [[CrossRef](#)] [[PubMed](#)]
54. Mohanrasu, K.; Manivannan, A.C.; Rengarajan, H.J.R.; Kandaiah, R.; Ravindran, A.; Panneerselvam, L.; Palanisami, T.; Sathish, C.I. Eco-friendly biopolymers and composites: A sustainable development of adsorbents for the removal of pollutants from wastewater. *NPJ Mater. Sustain.* **2025**, *3*, 13. [[CrossRef](#)]
55. Liu, B.-L.; Fu, M.-M.; Xiang, L.; Feng, N.-X.; Zhao, H.-M.; Li, Y.-W.; Cai, Q.-Y.; Li, H.; Mo, C.-H.; Wong, M.-H. Adsorption of microcystin contaminants by biochars derived from contrasting pyrolytic conditions: Characteristics, affecting factors, and mechanisms. *Sci. Total Environ.* **2021**, *763*, 143028. [[CrossRef](#)] [[PubMed](#)]
56. El-Chaghaby, G.A.; Ramis, E.S.; Ahmad, A.F. Rice straw and rice straw ash for the removal of brilliant green dye from wastewater. *Asian J. Appl. Chem. Res.* **2018**, *1*, 1–9. [[CrossRef](#)]
57. Khalilollah, M.; Seyed, M.M. Removing methylene blue from aqueous solutions using rice husk silica adsorbent. *Pol. J. Environ. Stud.* **2019**, *28*, 2281–2287. [[CrossRef](#)] [[PubMed](#)]
58. Umpuch, C.; Jutarat, K. Adsorption of organic dye from aqueous solution by surfactant-modified corn straw. *Int. J. Chem. Eng. Appl.* **2013**, *4*, 134–139. [[CrossRef](#)]
59. Ostaszewski, P.; Długosz, O.; Banach, M. Analysis of measuring methods of the concentration of methylene blue in the sorption process in fixed-bed column. *Int. J. Environ. Sci. Technol.* **2022**, *19*, 1–8. [[CrossRef](#)]
60. Ikenyiri, P.N.; Ukpaka, C.P. Overview on the effect of particle size on the performance of wood-based adsorbent. *J. Chem. Eng. Process Technol.* **2016**, *7*, 5. [[CrossRef](#)]
61. Yang, X.; Wan, Y.; Zheng, Y.; He, F.; Yu, Z.; Huang, J.; Wang, H.; Ok, Y.S.; Jiang, Y.; Gao, B. Surface functional groups of carbon-based adsorbents and their roles in the removal of heavy metals from aqueous solutions: A critical review. *Chem. Eng. J.* **2019**, *366*, 608–621. [[CrossRef](#)] [[PubMed](#)]
62. Ahmedna, M.; Johns, M.M.; Clarke, S.J.; Marshall, W.E.; Rao, R.M. Potential of agricultural by-product-based activated carbons for use in raw sugar decolourisation. *J. Sci. Food Agric.* **1997**, *75*, 117–124. [[CrossRef](#)]
63. Ariany, Z.; Ghina, H.F.; Amelia, S.R. The potential of activated carbon derived from bio-char waste of bio-oil pyrolysis as adsorbent. *MATEC Web Conf.* **2018**, *154*, 01029. [[CrossRef](#)]
64. Han, M.; Liu, Z.; Huang, S.; Zhang, H.; Yang, H.; Liu, Y.; Zhang, K.; Zeng, Y. Application of biochar-based materials for effective pollutant removal in wastewater treatment. *Nanomaterials* **2024**, *14*, 1933. [[CrossRef](#)] [[PubMed](#)]
65. Selmi, T.; Seffen, M.; Celzard, A.; Fierro, V. Effect of the adsorption pH and temperature on the parameters of the Brouers–Sotolongo models. *Environ. Sci. Pollut. Res.* **2020**, *27*, 23437–23446. [[CrossRef](#)] [[PubMed](#)]
66. Ibrahim, Y.E.; Amna, A.I. Removal of chromium (VI) ions from aqueous solution using wood sawdust as adsorbent. *SUST J. Nat. Med. Sci.* **2016**, *17*, 1858–6805. [[CrossRef](#)] [[PubMed](#)]
67. Foo, K.Y.; Hameed, B.H. Insights into the modeling of adsorption isotherm systems. *Chem. Eng. J.* **2010**, *156*, 2–10. [[CrossRef](#)]
68. Gergova, K.; Petrov, N.; Eser, S. A comparison of adsorption characteristics of various activated carbons. *J. Chem. Technol. Biotechnol.* **1993**, *56*, 77–82. [[CrossRef](#)]
69. Senapati, S.; Giri, J.; Mallick, L.; Singha, D.; Bastia, T.K.; Rath, P.; Rana, M.K.; Panda, A.K. Rapid adsorption of industrial cationic dye pollutant using base-activated rice straw biochar: Performance, isotherm, kinetic and thermodynamic evaluation. *Discov. Sustain.* **2025**, *6*, 46. [[CrossRef](#)]
70. Zahanggir, A.; Niamul, B.; Sayera, K. Statistical optimization of methylene blue dye removal from a synthetic textile wastewater using indigenous adsorbents. *Environ. Sustain. Indic.* **2022**, *14*, 100176. [[CrossRef](#)]
71. Donati, C.; Drikas, M.; Hayes, R.; Newcombe, G. Microcystin-LR adsorption by powdered activated carbon. *Water Res.* **1994**, *28*, 1735–1742. [[CrossRef](#)]
72. Ho, L.; Lambling, P.; Bustamante, H.; Duker, P.; Newcombe, G. Application of powdered activated carbon for the adsorption of cylindrospermopsin and microcystin toxins from drinking water supplies. *Water Res.* **2011**, *45*, 2954–2964. [[CrossRef](#)] [[PubMed](#)]
73. Ibrahim, W.M.; Salim, E.H.; Azab, Y.A.; Ismail, A.H. Monitoring and removal of cyanobacterial toxins from drinking water by algal-activated carbon. *Toxicol. Ind. Health* **2016**, *32*, 1752–1762. [[CrossRef](#)] [[PubMed](#)]

74. Chen, W.; Song, L.; Peng, L.; Wan, N.; Zhang, X.; Gan, N. Reduction in microcystin concentrations in large and shallow lakes: Water and sediment-interface contributions. *Water Res.* **2006**, *40*, 865–873. [[CrossRef](#)] [[PubMed](#)]
75. Murphy, O.P.; Vashishtha, M.; Palanisamy, P.; Kumar, K.V. A Review on the Adsorption Isotherms and Design Calculations for the Optimization of Adsorbent Mass and Contact Time. *ACS Omega* **2023**, *8*, 17407–17430. [[CrossRef](#)] [[PubMed](#)]

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