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COMPARATIVE ANALYSIS OF BIOCHAR ADSORPTION CAPACTIES FOR ANTIBIOTICS REMOVAL

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Abstract

The increasing presence of antibiotics in aquatic environments has raised significant concerns due to their potential adverse effects on ecosystems and human health. This study aims to explore the efficiency of various biochar types in adsorbing and removing four commonly originate antibiotics such as tetracycline (TC), ciprofloxacin (CFX), sulfadiazine (SDZ), and sulfamethoxazole (SMX) from aqueous solutions. Ten different biochar treatments labeled from (BC1 to BC10) were systematically evaluated to determine their adsorption capacities (Qmax) and removal efficiencies, utilizing a comprehensive set of parameters including elemental composition of Corban, Nitrogen, Oxygen ratios (C, N, O), pH, specific surface area (SSA), pore volume, average pore size, and pyrolysis conditions. Results revealed that the maximum values ranged from C 92%, N 4.04%, O 93% ratios, pH 11, specific surface area 1712 m3/g, pore volume 1.73 cm3/g, average pore size 32 (nm), pyrolysis condition 900 (temp, time, gas) in 3 hours and Qmax 1029.5 (mg/g), 64% removal at tetracycline (TC), ciprofloxacin (CFX), sulfadiazine (SDZ), and sulfamethoxazole (SMX) in different biochars. Furthermore, biochar characteristics, especially pore volume, pore size, and nitrogen content, exhibited strong positive correlation with Qmax, demonstrating a significant impact on adsorption performance. Particularly, biochar types with larger pore sizes and higher nitrogen content achieved superior adsorption capacities, with Qmax values exceeding 1029 mg/g for certain biochar treatments. Study shows the inverse relationship between carbon content and adsorption efficiency, offering valuable insights for optimizing biochar properties in environmental applications. The results suggest that optimizing biochar production conditions can significantly improve its effectiveness as a sustainable solution for water management. These findings cover the way for further studies on biochars application in large scale wastewater treatment, thereby contributing to the development of eco-friendly strategies for modifying antibiotic contamination in aquatic system.

Introduction

Antibiotics, derived from microorganism, plants, animals, or produced through chemical processes have been widely used to treat bacterial infections in both humans and animals (Qin et al. 2015; Zhang et al. 2017; Hamdani et al. 2020). However the broad use and regularly misappropriation of antibiotics are not fully absorbed in the body, following in their discharge into several water bodies over wastewater, agriculture runoff, and aquaculture discharges (Tran et al. 2018). Studies have presented that antibiotic concentrations have been progressively increased, particularly in efficiently inhabited and industrial regions (Minarini et al. 2020; Ben et al. 2019; Serwecinska et al. 2020). For example, Zhang et al. (2015) described that the annual discharge of antibiotics in China's river basins amounted to 53.8 kt, posing significant environmental and human health threats. The determination of antibiotics in the environmental contribution to the improvement of antibiotic resistant bacteria, which has developed a worldwide public health disaster (Michael et al. 2018). Moreover, long term disclosure to small concentrations of antibiotics can lead to adverse properties such allergic reactions, genetic changes and the disturbance of microbial ecosystem (Sun et al. 2014; Hirth et al. 2016). In light of these difficulties, there is a growing need for sustainable and effective methods of antibiotic removal from water systems.

The rising demand for antibiotics in veterinary medicine has raised substantial environmental issues, especially concerning the contamination of water sources (Manyiloh et al. 2018). The increasing global consumption of veterinary antibiotics has led to the frequent detection of residues in aquatic environments, often surpassing acceptable limits (Tiseo et al. 2017; Wohde et al. 2016). Antibiotics disrupt ecosystems and contribute to the increasing issue of antibiotic resistance in bacteria, which poses a significant threat to both human and animal health (Cheng et al. 2020; Choi et al. 2020). There is a pressing necessity for effective strategies to remove antibiotic pollutants from wastewater prior to their introduction into natural water bodies. Adsorption has emerged as an efficient method for the removal of antibiotics from aqueous solutions, as demonstrated by Sivasamy et al. (2012) and Xie et al. (2020). This process utilizes the affinity of pollutants for particular materials, facilitating their concentration and subsequent removal. Biochar, a carbon-rich material generated through the pyrolysis of biomass, has garnered interest as an effective adsorbent owing to its substantial surface area, porosity, and the presence of diverse functional groups (Dincer et al. 2015; Guo et al. 2016; Angulo et al. 2018). These characteristics improve its capacity to adsorb various contaminants, including antibiotics. Examining the adsorption mechanisms of biochar and the impact of different feedstock types on its efficacy offers essential insights for its use in wastewater treatment (Qiu et al. 2022; Zeghioud et al. 2022; Tong et al. 2019).

According to Phoon et al. 2020 and Jaffari et al. 2023, the main ways that new contaminants stick to biochar materials are through chemical reactions, such as ionic and covalent bonds, and physical interactions, like hydrogen bonds and Van der Waals forces. The synthesis conditions of biochar, including the pyrolysis temperature and time, along with its properties, such as BET surface area, pore size, and pore volume, significantly influence its composition, which encompasses the contents of oxygen, carbon, nitrogen, and ash. Amusat et al. 2021). Other important factors that affect adsorption capacity are the molecular structures and functions of emerging contaminants, as well as the experimental adsorption conditions, such as contact time, adsorbent dosage, concentrations of primary emerging contaminants, pH of the solution, and solution volume. Expending conventional adsorption statistical models, the emerging contaminants adsorption with biochar has been well studied in the literature (Leichtweis et al. 2021; Luo et al. 2022; Zhang et al. 2023). Biochar application to contaminated soil is considered a promising method for Heavy Metal immobilization because biochar can adsorb and immobilize HMs as its surface area (SA), microporosity, surface functional groups, pH, and cation exchange capacity are superior to those of raw feedstock (Kumuduni et al. 2022; Palansooriya et al. 2019; El-Naggar et al. 2018). A variety of biochars produced from various feedstocks (e.g., sewage sludge, manure, crop residue) under different production conditions (e.g., slow pyrolysis, fast pyrolysis, gasification, and hydrothermal carbonization) (Li et al. 2022) have been used to immobilize Heavy Metal (and metalloids) such as As, Cd, Cu, Pb, Cr, Ni, Co, and Zn in soils (Ahmed et al. 2014; Igalavithana et al. 2017). The type of biochar (e.g., production conditions and physicochemical properties), soil characteristics (e.g., pH, organic matter content, and electrical conductivity (EC), and heavy metal characteristics (e.g., valency and ionic radius) all affect how well heavy metals are immobilized in soils that have been amended with biochar (Igalavithana et al. 2018; Palansooriya et al. 2019), Biochar is a carbon rich material produced through the pyrolysis of organic matter, has emerged as a promising adsorbent for removing contaminants, including antibiotics, from aqueous solutions (Browne et al. 2021;Kraemer et al. 2019). It is a good option for adsorbing antibiotics such as ciprofloxacin, sulfamethoxazole, and tetracycline due to its wide surface area, porous structure, and variety of functional groups (Chaturvedi et al. 2021; Grenni et al. 2018). In order to improve biochar's adsorption capacity for different antibiotics, recent research has concentrated on adjusting its pore size, surface charge, and elemental content (Menz et al., 2018; Wallace et al., 2018). Thus, the purpose of this study is to (i) assess how well different forms of biochar adsorb specific antibiotics from aqueous solutions. (ii) to examine how the adsorption performance for antibiotics is affected by the rates at which biochar is applied as well as the properties of the biochar (such as its surface area, pore size, elemental composition (such as C N O H ratio), ash, and pH). (iii) to evaluate the optimal adsorption and compare the adsorption capabilities of various antibiotics, such as tetracycline, ciprofloxacin, sulfadiazine, and sulfamethoxazole.

Methodology, Literature sources and search approach:

A competent research was carried out on the (2023 to 2024) to examine the different biochars and four antibiotics such as tetracycline, ciprofloxacin, sulfadiazine and sulfamethoxazole and best adsorption in aqueous solutions for antibiotic adsorption. We collected data for 10 different research articles for every single antibiotic. Were published between 2015 and 2024.for all ten biochars we prepaid a series of labeled from (BC1 to BC10) such as for (Tetracycline) (BC1) PS-AL750_BC of (dose 2.5 mg g/L), Feedstock of (pine sawdust) (Xiang et al., 2022). (BC2) A1/5C800 (dose 10 mg g/L), feedstock of pinewood sawdust, (Li et al., 2019). (BC3) BC700 (dose 3.2 mg g/L), feedstock waste AA dregs, (Dai et al., 2020). (BC4) MBC 2.5 g/L, feed stock of Rice Straw, (Dai 2020). (BC5) BMWS450 10 g/L, feedstock of wheat stalk (WS), (Xiang et al, 2020). (BC6) BC900–700 0.4 g/L, feedstock of cow manure, (Shao et al., 2024). (BC7) K-HBBC (TCH) 0.1–1.25 g/L, excess sludge, (Chen et al., 2024). (BC8) HBRBC 0.1 g/L, feedstock of biogas residue, (Fan et al., 2024).(BC9) Mn-BC 1 g/L (Huang et al., 2023), and (BC10) MPBC-700 10 g/L, feedstock of discarded cigarette butts (Yang et al, 2021).For (Ciprofloxacin) (BC1) 3-Ga/S-BC dose of (500 mg g/L) (sugarcane bagasse), (Zheng et al., 2021). (BC2) PPBK800 0.1 g/L, (metal-enriched phytoremediation plant residue), (Ding et al., 2020). (BC3) SBC 0.25g, sludge (SL), (Li et al., 2020). (BC4) ZRAB 2mg, (three types of algae), (Nguyen et al., 2022). (BC5) tea leaves 0.2 g, (used tea leaves), (Li et al., 2018). (BC6) DPBC 100 mg/L, (fish scales), (Dou et al., 2022). (BC7) NSB-700-2-6 0.125 g/L, (Sugarcane bagasse), (Che et al., 2023). (BC8) 3K-SCB750 2.4 g/L, (sugarcane bagasse), (Zhou et al., 2023). (BC9) BC750 0.2 g/L, (cassava dregs) (Li et al., 2016), and (BC10) MSW-BC Clay Composite 1.0 g/L, (municipal solid waste) (Ashiq et al., 2019). For (Sulfadiazine) (BC1) CS-300 dose of 1 mg g/L, (corn straw), (Zhang et al., 2021). (BC2) CCPZ800 1 g, (cotton pulp), (Wang et al., 2024). (BC3) biochar900 25 g/L, (pine sawdust), (Zhang et al., 2023) (BC4) PABC-700 0.1 g/L, (Coffee grounds (CGs), (Zeng et al., 2022). (BC5) BC500 0.05 g/L, (moringa seed shells), (Wang et al., 2024). (BC6) NBC 3 g/L, (Corncobs), (Zhang et al., 2022). (BC7) 50MBC-KOH2.5 (5 g/L), feedstock of Coconut shell, (Sun et al., 2022). (BC8) SG650 2 g/L, (sorghum stalks), (Feng et al., 2022). (BC9) BC-500 100 g/L, Starbucks, (Zhang et al., 2020) and (BC10) A1/5C800 10 g (pinewood) (Li et al., 20219). For (Sulfamethoxazole) (BC1) BC-400 dose of 10 mg g/L, feedstock of (pinewood), (Li et al., 2019). (BC2) BG450 0.1 g/L, (sugarcane bagasse), (Yao et al., 2012). (BC3) 500-MBC800 20 g/L, (RAW bagasse), (Zhang et al., 2020).

(BC4) seed husk biochar (50 g/L), feedstock of raw sunflower, (Nguyen et al., 2023). (BC5) Biochar Derived from Hydrothermal Carbonization of Sugarcane Bagasse 4.5 g/L, (sugar bagasse), (Prasanna Medha et al., 2021). (BC6) BCN 5 g/L, (Bagasse) (Wang et al., 2022). (BC7) 50MBC-KOH2.5 (5 g/L), feedstock of (Coconut shell), (Sun et al., 2022). (BC8) CBCL-M 50 g/L, (microalgal biomass source), (Tan et al., 2022). (BC9) CZF 0.2 g/L, (Bamboo), (Heo et al., 2019), and (BC10) A-BC 0.01 g/L, (sugarcane bagasse fibers), (Prasanna Medha et al., 2021). We conducted a systematic search of all electronic information resources in Web of Science, Scopus, and Science Direct in agreement with this goal. (Biochar) (Antibiotics adsorption) OR (tetracycline, ciprofloxacin, sulfadiazine and sulfamethoxazole), (anti-bacterial and agent) and (water and wastewater) OR (aqueous and treatment), (removal and decomposition and degradation), (mineralization and adsorption)) were the search terms used (using Medical Subject Headings (MeSH)). We chose the most appropriate studies based on the inclusion and exclusion criteria for most suitable studies. The selected physicochemical properties of these antibiotics are shown in Table 1. Fig 1. The data presented were taken from www.chemspider.com. There D_{ow} refers to the pH dependent octanol water distribution coefficient.

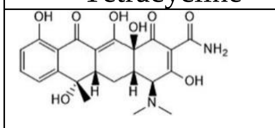
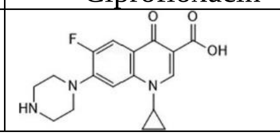
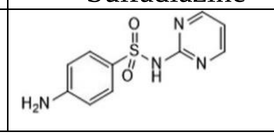
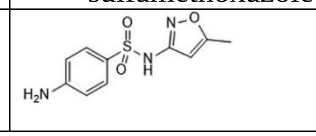
Tetracycline	Ciprofloxacin	Sulfadiazine	sulfamethoxazole
			

Fig 1. Molecular structure of different antibiotics

Table 1.Selected properties of four antibiotics used in this study.

Antibiotics	Molecular weight	Melting point (°C)[a]	Molar volume (cm^3)[a]	Electrical property (at pH 5)	Log Kowa	Log Dow (at pH 5)[a]	pKa
TC	444.4	165	266.3 ± 7.0	Neutral	1.76	−2.77	3.3; 6.5; 7.5
CFX	331.3	255	226.8 ± 3.0	Positive	1.809	−2.98	6.3; 8.9
SDZ	250.3	252	167.3 ± 3.0	Neutral	−1.465	−0.09	1.6; 6.5
SMX	253.3	170	173.1 ± 3.0	Neutral	−0.56	0.56	1.6; 5.6

Inclusion criteria

In this study, only original research articles were included, which were published in English in peer reviewed journals about antibiotics removal through different types of Biochar, with combination of other compounds. Studies were included such as (a) assessed the ability of biochar to adsorb any of the four antibiotics (tetracycline, ciprofloxacin, sulfadiazine, or sulfamethoxazole); and (b) reported important biochar parameters and properties, such as elemental composition, surface area, pore characteristics, pH, and adsorption data (Qmax, % removal).

Data Extraction

Parameters Recorded: From each study, the following parameters were extracted:

Antibiotic Properties: Molecular weight, water partition coefficient (Log KOW), water solubility, polarity (Log P), and acid dissociation constant (pKa).

Biochar Characteristics: Feedstock type, elemental composition (C, N, O, percentages), pH, specific surface area, pore volume, average pore size, pyrolysis conditions (temperature, time, gas type), adsorption capacity (Qmax in mg/g) % removal.

Study Details: Year of publication and references presented in the list of references

Statistical Methods

Comparative Analysis: The data were aggregated and compared to identify the biochar with the highest adsorption capacity (Qmax) and % removal efficiency for each antibiotic. Descriptive statistics, such as mean and standard deviation, were calculated for each.

Ranking of Biochars: Based on adsorption capacity and % removal, biochars were ranked to determine the most effective biochar type for each antibiotic.

Software Used: Data analysis was performed using statistical software (Microsoft office 2013, Statistic 8.1, SPSS, GraphPad Prism, OrginPro).

Regression and Correlation Analysis: Regression models were developed to evaluate the impact of key biochar properties (surface area, elemental ratios) on adsorption efficiency. A correlation matrix was generated to determine significant relationships between biochar characteristics and adsorption capacity.

Results

The elemental composition of biochars (BC1 - BC10) varied across the four antibiotics, with C%, N% and O% ratios showing distinct trends associated with adsorption capacities shown in Table 2. For tetracycline (TC), biochars with a higher nitrogen content (e.g., BC3 and BC8, N% ranging from 3.09 to 1.93) showed enhanced adsorption, possibly due to nitrogen's role in providing additional functional groups that interact with TCs molecular structure. Carbon content was moderately high (BC2 and BC10 ranged from 93.9 to 76.45) in effective biochars, while oxygen content was generally very high, ranging from 15.43 to 27.14 which were recorded at BC1 and BC4. Results indicating that higher N%, C% and O% together positively impacted on TC adsorption. Moreover, for ciprofloxacin (CFX), the most effective biochars (e.g., BC2, BC6 and BC7) had a high carbon content ranging from (90.63 to 87.1) and moderately oxygen levels, indicating that C% and O% contribute to CFX adsorption through both hydrophobic and polar interactions. A high carbon content correlated with increased surface area, enhancing adsorption. Nitrogen levels in these biochars remained relatively stable across samples, with N% contributing less to CFX adsorption compared to C% and O%. Furthermore, Sulfadiazine (SDZ), biochars with higher carbon content (e.g., BC2, BC3 and BC10) demonstrated superior adsorption performance with C% ranging from 93.9 to 88.57%. These biochars generally exhibited lower oxygen content ranging from (7.73 to 1.74%). Results revealed that a high C% to O% ratio enhances hydrophobic interactions and thus improves SDZ adsorption. Nitrogen content was relatively low across all biochars, averaging around 0.83%, which did not significantly influences on SDZ removal. However in the case of sulfamethoxazole (SMX), biochars with a balanced composition of carbon and oxygen (BC2, BC3 and BC5) had a best adsorption capacities, with C% ranging from 78.6 to 81.22 and O% from 21.77 to 51.52. A moderate oxygen content appeared to enhance SMX adsorption, possibly due to the availability of oxygen containing functional groups. Higher nitrogen content (BC2, B3 and BC7) corresponded to lower adsorption favored carbon rich oxygen modified biochars. Overall, biochars with higher carbon content (C%) and optimal oxygen levels (O%) were more effective for antibiotic adsorption, with nitrogen (N%) playing a variable role depending on the antibiotics type. These results highlight the importance of elemental composition, particularly the C% to O% ratio, in influencing biochars adsorption capacity for different antibiotics.

Table 2. Chemical composition across biochar treatments for different antibiotics

	Tetracycline			Ciprofloxacin		
Biochar	C	%N	%O	%C	%N	%O
BC1	75.81	0.54	15.43	39.62	0.2	26.15
BC2	93.9	1.41	1.74	90.63	1.56	7.51
BC3	57	3.09	8.79	22.7	1.07	36.91
BC4	32.8	0.52	27.14	55	0.9	40
BC5	68-72	1.2	20-25	48.05	3.12	43.74
BC6	33.051	1.633	1.243	75.73	1.53	19.88
BC7	42.95	0.36	4.85	87.1	3.86	8.91
BC8	38.69	1.93	10.55	69.8	0.8	25.4
BC9	63.52	0.86	10.03	62.38	1.23	4.31
BC10	76.45	0.98	20.42	48.6	1	20.2
	sulfadiazine				sulfamethoxazole	
Biochar	%C	%N	%O	%C	%N	%O
BC1	55.54	1.72	37.75	75.39	3.48	15.09
BC2	92	0.89	7.73	78.6	0.92	15.45
BC3	88.57	1.34	6.64	73.86	0.96	21.77
BC4	76.43	1.15	20.02	37	2.9	57.7
BC5	57.079	3.317	26.244	40.3	4.04	51.52
BC6	68.28	1.93	14.153	57.41	1.08	37
BC7	62.76	0.000	19.98	62.76	0	19.98
BC8	66.32	1.79	11.45	90.1	1.1	8.1
BC9	76.36	3.59	14.43	29.5	0.7	12.7
BC10	93.9	1.41	1.74	81.22	0.83	7.42

The pH concentration of the selected biochars grouped from (BC1 – BC10) varied significantly across the four antibiotics, influencing their adsorption capacity Shown in Fig 2. For tetracycline (TC) the pH values ranged from 3 to 11 with BC8 showing the highest pH of 11 and BC3 the lowest at tetracycline adsorption. Generally, biochars with a higher pH such as (BC8 and BC1) demonstrated better adsorption efficiencies, aligning with their Qmax values. Moreover, for Ciprofloxacin (CFX), the pH of biochars ranged from 3.05 to 9.55. Biochars with moderately alkaline pH (e.g., BC8 and BC9) were associated with higher % removal, suggesting that slightly alkaline conditions favored CFX adsorption. Furthermore Sulfadiazine (SDZ), biochars showed a pH range of 3.02 to 7, with the most effective biochars (BC4 and BC7) having slightly acidic to neutral pH levels. This trend indicates that SDZ adsorption was optimized in near neutral conditions. However, for sulfamethoxazole (SMX), the pH values of biochars varied from 2.76 to 8.95. Biochar with neutral to alkaline pH values (BC1 and BC2) demonstrated enhanced adsorption capacities, reflected by higher Qmax values, suggesting that a neutral to slightly alkaline pH was conducive for SMX removal.

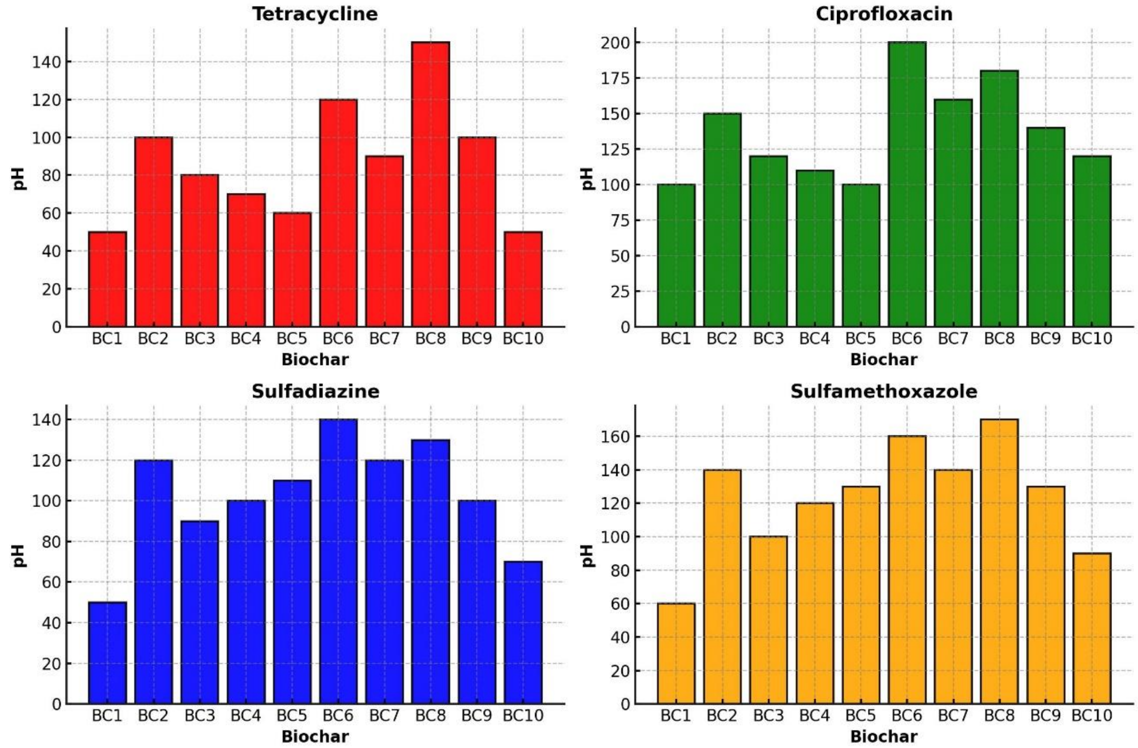


Fig 2 pH levels across biochar treatments for different antibiotics

The specific surface area (SSA) of the selected biochars from (BC1 – BC10) played a significant role in influencing the adsorption capacities for each antibiotic shown in Fig 3. Overall, biochars with higher SSA generally showed improved adsorption performance due to increased availability of adsorption sites. For tetracycline (TC), the highest adsorption efficiency was observed in biochars with SSA values ranging from 738 m^2/g to 389.35 m^2/g at BC2 and BC10. These biochars exhibited greater adsorption capacities due to their extensive surface areas, providing abundant sites for TC molecules to interact with the biochars matrix. Moreover, for ciprofloxacin (CFX), biochars with SSA values above 1712.19 m^2/g and 1223.5 m^2/g recoded at BC4 and BC7 displayed superior adsorption performance, achieving high Qmax values. The increase in surface area appears to favor CFX adsorption by facilitating enhanced molecular interactions, particularly in biochars with both high surface area and optimized pore structure. Furthermore, for sulfadiazine (SDZ), the specific surface area varied widely among the biochars, ranging from 1267 m^2/g to 1365 m^2/g in BC4and BC7. Biochars with SSA above 1663.63 m^2/g at BC2 demonstrated the highest adsorption capacities, as indicated by their Qmax values. This suggests that a lager surface area enhances SDZ adsorption by increasing the physical space for molecule interaction. However, in case of the sulfamethozole (SMX), biochars with moderate to high SSA (e.g., BC1, BC7 and BC10) were associated with higher removal %, with values ranging from 2.29 m^2/g, 1119.53 m^2/g and 1991.59 m^2/g. Biochars like BC5 and BC10 which had a SSA of approximately 1099 m^2/g and 1991 m^2/g respectively, showed particularly high adsorption performance. This trend implies that SMX adsorption benefits from moderately high surface area, which optimizes contact between SMX molecules and adsorption sites. Overall, the results indicated that specific surface area is a key factor in antibiotic adsorption, which biochars processing SSA values above 1991 m^2/g generally achieving higher adsorption capacities across all antibiotics. This supports the notion that a larger surface area enhances biochars effectiveness by providing more adsorption sites, thus improving removal efficiency.

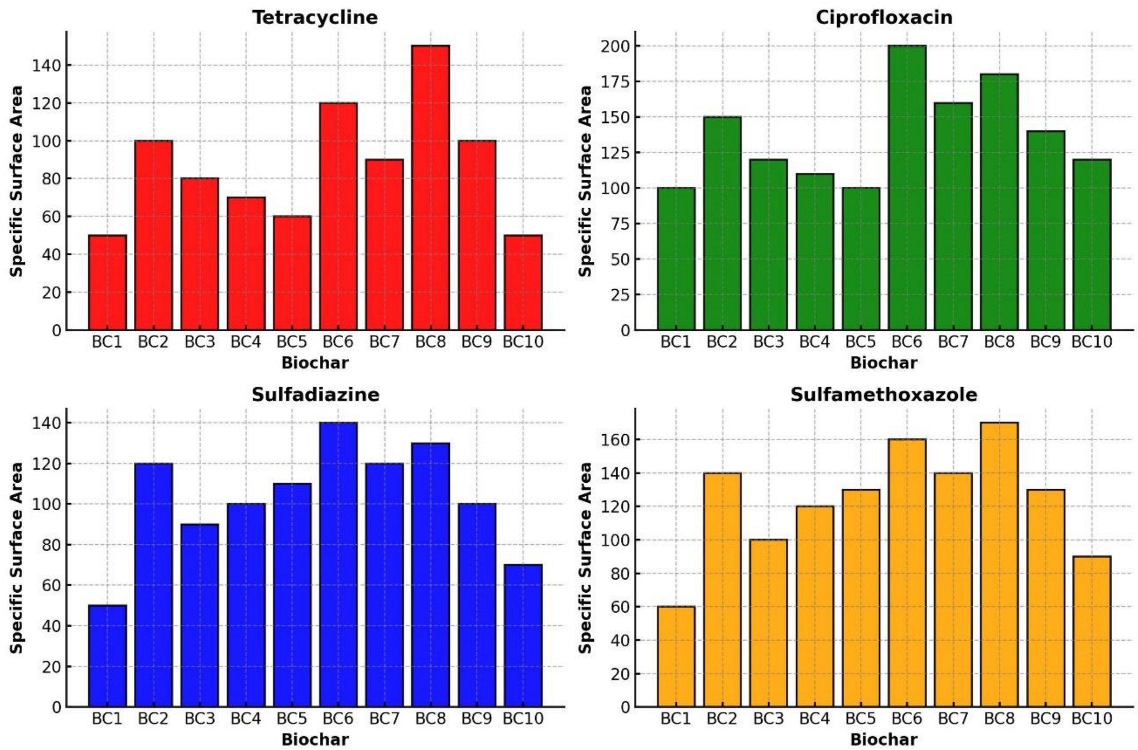


Fig 3 specific surface area across biochar treatments for different antibiotics

The pore volume of biochars grouped from (BC1 – BC10) diverse considerably, impacting the adsorption capacities for each antibiotics shown in Fig 4. In general, biochars with larger pore volumes provided more accessible space for antibiotic molecules, enhancing adsorption performance. For tetracycline (TC), biochars with the highest pore volume (e. g., BC8 and BC9 ranging from 0.59 cm^3/g to 0.49 cm^3/g) showed a significantly improved adsorption capacities. The larger pore volume allows TC molecules to penetrate deeper into the biochars structure, increasing interaction surface and maximizing adsorption potential. Moreover, for Ciprofloxacin (CFX) biochars with pore volumes above 1.91 and 1.73 cm^3/g recoded at BC4 and BC6 demonstrated superior adsorption efficiency. This pattern suggest that CFX adsorption benefits from a high pore volume , as it increases the physical space for adsorption and allows optimal molecules dispersion within the biochars pore. Furthermore, for sulfadiazine (SDZ), the pore volume ranged from 0.01 to 1.25 cm^3/g in BC1 to B2. Biochars with higher pore volume BC3 and BC4, with values above 0.57 to 0.72 cm^3/g exhibited the highest Qmax values, indicating that increased pore volume enhances the accommodation and interaction of SDZ molecules within the biochars matrix. However, in the case of Sulfamethoxazole (SMZ), biochars such as BC5 and BC6, with pore volume between 0.84 and 1.20 cm^3/g demonstrated higher removal % values. This results suggest that moderate to high pore volumes favor SMX adsorption by facilitating molecules access to inner adsorption sites. Results revealed that, biochars with higher pore volumes tended to show better adsorption capacities across all antibiotics, with pore volume positively correlating with adsorption efficiency. These findings emphasize that a greater pore volume enhances biochars ability to adsorb antibiotics molecules by providing more space for molecules accommodation and interaction.

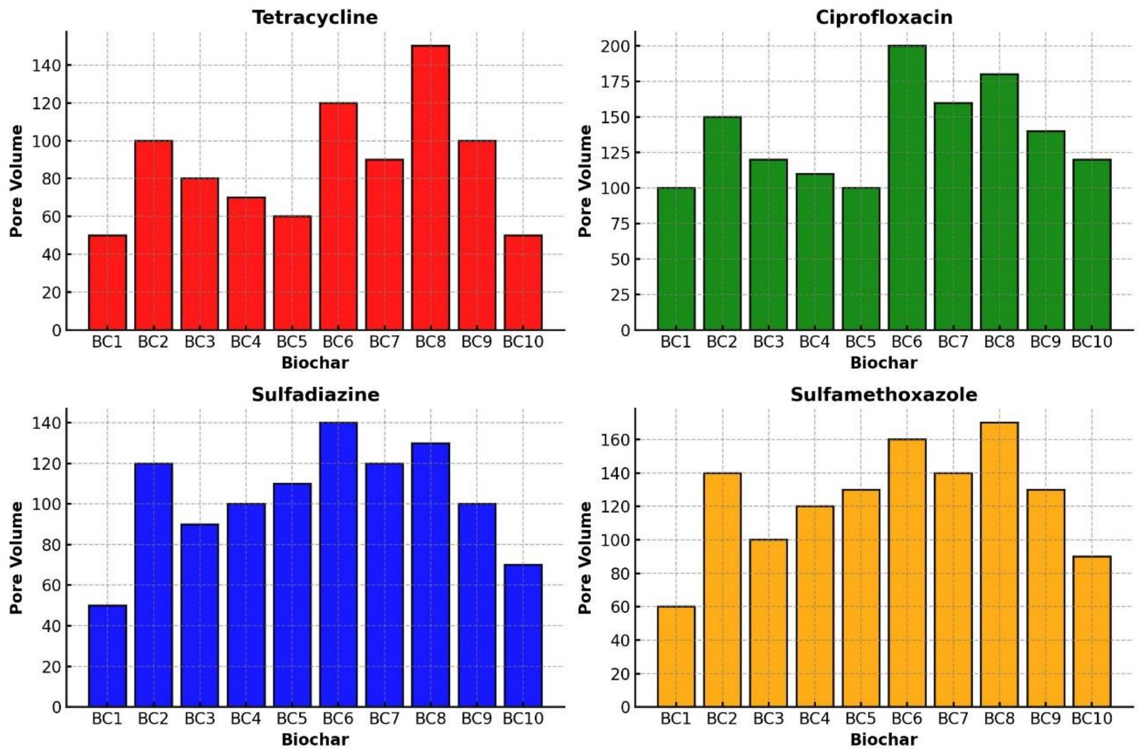


Fig 4 pore volume across biochar treatments for different antibiotics

The average pore size of the different biochars from (BC1-BC10) influenced their adsorption performance for each antibiotic shown in Fig 5. In general, biochars with pore sizes suited to the molecular dimensions of each antibiotic showed greater adsorption capacities, as pore size affects molecule accessibility and interaction within the biochars structure. For tetracycline (TC), the biochars with pore sizes between 32. 38 (nm) and 12.97 (nm) observed at BC4 and BC8 had a significantly higher Qmax values, supporting the role of larger pores in improving TC adsorption. The spacious pore structure allows TC molecules to penetrate deeper, enhancing interaction with the biochars surface. Results revealed that ciprofloxacin (CFX), biochars with average pore sizes above 7. 9 and 15.68 (nm) observed in biochars BC4 and BC9 showed the highest adsorption efficiency. The larger pore size facilitates CFX adsorption by providing sufficient spaces for the relatively large CFX molecules to interact effectively within the biochars matrix. Moreover, results recorded for sulfadiazine (SDZ), biochars with average pore sizes ranging from 16.37 and 10.18 (nm) in BC4 and BC8 demonstrated the highest adsorption capacities. This indicates that larger pore sizes better accommodate SDZ molecules, allowing easier access to adsorption sites within the biochars matrix. Smaller pore sizes, as seen in BC1 and BC5 (0.01 and 2.27 nm), were associated with lower adsorption efficiency for SDZ. However, in the case of Sulfamethoxazole (SMX), biochars with moderate pore sizes 9.87 and 13.6 (nm) recorded at BC1 and BC2 showed optimal adsorption, suggesting that SMX molecules benefits from medium sized pores, which balance molecules access with retention within the biochar structure. Biochar with very large or very small pores showed comparatively lower adsorption capacities, indicating that intermediate pore sizes area ideal for SMX adsorption. Overall, biochars with larger average pore sizes generally achieved better adsorption capacities across all antibiotics, through the ideal pore size varied slightly depending on the antibiotics types. The findings underscore the importance of matching biochars pore size with the molecules dimensions of the target antibiotic for optimal adsorption performance.

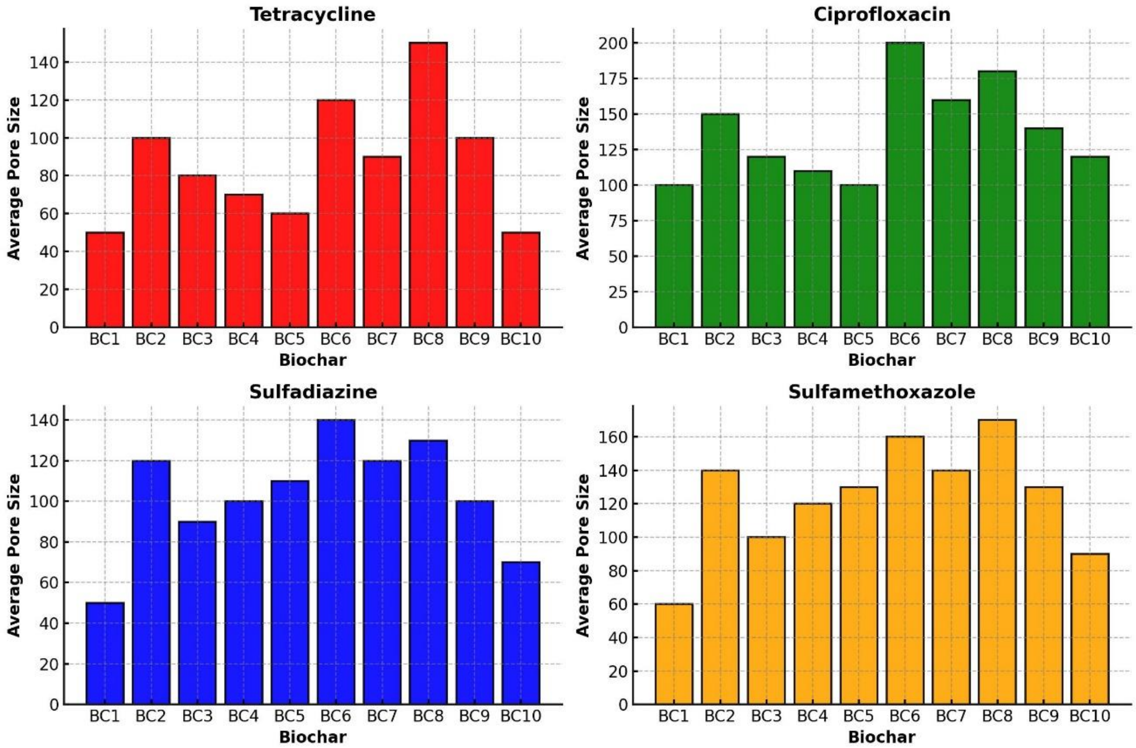


Fig 5 average pore size across biochar treatments for different antibiotics

The pyrolysis conditions including temperature, duration, and gas environment significantly influenced the structural properties of the different biochars from (BC1-BC10), which in turn affected their adsorption capacities for each antibiotics show in Fig 6. Higher temperature and longer durations generally resulted in biochar with improved adsorption efficiencies due to enhanced surface area and pore structure. Results revealed that for tetracycline (TC), the highest adsorption was observed in biochars produced at temperature above 800℃ and 900℃ with extended pyrolysis times 3 hours in BC2 and BC6. These high temperature, long duration biochars provided a more stable, porous structure with minimal residual organic matter, enhancing TC adsorption. The presence of nitrogen gas during pyrolysis also appeared to positively influence the adsorption capacity by preserving a microporous structure optimal for TC molecules accommodation. Results observed for ciprofloxacin (CFX), biochar produced under high temperature conditions 700℃ to 750℃ in BC2 and BC6 showed superior adsorption capacities. Extended pyrolysis times over 2 hours and an inert gas environment like nitrogen created biochars with a highly stable structure and large pore volume, which facilitated the accommodation of the relatively large CFX molecules. Moreover, results recorded for sulfadiazine (SDZ), biochars produced at higher pyrolysis temperatures 800℃ to 900℃ in BC1 and BC2 and longer times over 2 hours exhibited the highest adsorption capacities, as indicated by their Qmax values. The elevated temperatures promoted greater carbonization, enhancing surface area and pore volume, which facilitated more effective adsorption. Biochars prepared under an inert gas environment e.g., nitrogen showed better adsorption results than those pyrolyzed in oxygen rich environment, likely due to reduced oxidation and improved pore structure. However, in the case of Sulfamethoxazole (SMX), biochar produced at moderate temperatures around 450℃ to 550℃ and shorter pyrolysis duration 1.5 hours in BC2 and BC9 demonstrated optimal adsorption performance. The moderate pyrolysis conditions preserved more functional groups favorable for SMX adsorption, especially when produced under nitrogen gas, which prevents excessive volatilization of key adsorption sites. Results suggest that, biochar produced at higher temperatures, with longer pyrolysis duration, and under inert gas conditions e.g., nitrogen, generally displayed better adsorption capacities across all antibiotics. These findings highlight that pyrolysis conditions tailored to enhance surface area, pore structure and stability are crucial for improving biochars adsorption efficiency for antibiotic removal.

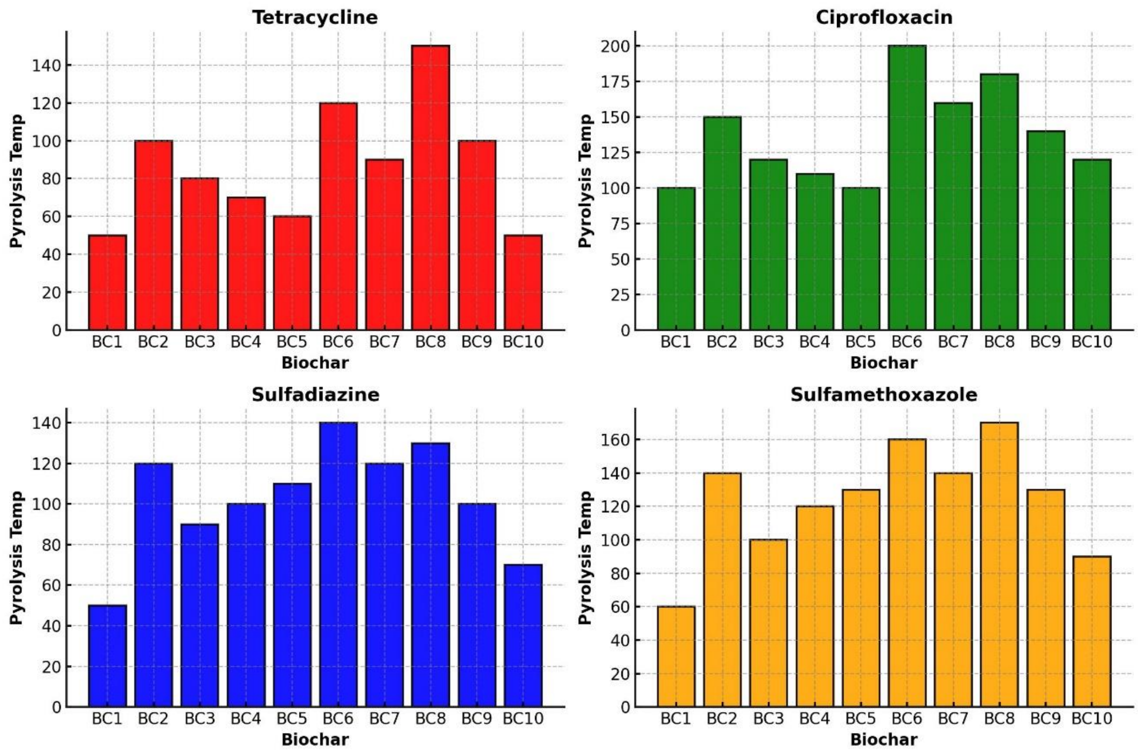


Fig 6 pyrolysis conditions across biochar treatments for different antibiotics

The maximum adsorption capacity (Qmax mg/g) and % removal values revealed significantly differences in the adsorption efficiency of biochars from (BC1-BC10) for each antibiotic show in Fig 7. These parameters are critical indicators of biochar performance, with higher Qmax and % removal reflecting a biochars enhanced ability to adsorb antibiotic molecules from aqueous solutions. For tetracycline (TC), Qmax values were highest in BC4 and BC10, reaching up to 185 and 266 mg/g with % removal values exceeding 37%. The large pore volumes and extensive surface area of these biochars enhanced TC adsorption, allowing for efficient molecules accommodation and interaction within the biochar structure. High pyrolysis temperatures e.g., 800℃ to 900℃ and longer pyrolysis times contributed to the stable structure and increased microporosity in these biochars, supporting TC adsorption. Furthermore results recorded for the ciprofloxacin (CFX), the highest Qmax values were found in BC2 and BC6 with the values of 500.9 and 1029.5 mg/g, respectively, and % removal reaching 64%. The adsorption efficiency for CFX was closely associated with biochars that had a both high, surface area and optimal average pore size, allowing for greater molecular interaction. Biochars produced at high temperatures under nitrogen gas displayed superior adsorption results for CFX, highlighting the role of stable pore structure and increased surface area in enhancing CFX removal. Moreover, results observed for sulfadiazine (SDZ), Qmax values ranged from 429 and 294 mg/g in BC2 and BC7 with the % removal reaching of up to 41% for the biochars with the highest adsorption capacities. Biochars such as BC3 and BC10, which had a larger surface areas and higher pore volumes, displayed the highest Qmax values. The biochars demonstrated effective SDZ removal, indicating that their structural properties enhanced adsorption efficiency. Biochars produced at elevated pyrolysis temperatures in a nitrogen atmosphere exhibited enhanced performance, attributed to improved carbonization and increased pore accessibility for SDZ molecules. In the case of Sulfamethoxazole (SMX), the highest Qmax values were recorded in BC5 and BC7, with capacities of 400 mg/g and 454 mg/g, respectively. The biochars demonstrated removal rates of up to 49%, indicating strong adsorption performance. Moderate pyrolysis condition (e.g., 450℃ to 500℃) appeared favorable for SMX adsorption, likely due to preserved functional groups that interacted effectively with SMX molecules. Biochars exhibiting intermediate pore sizes and moderate pH values demonstrated the highest percentage of removal, highlighting the significance of biochar surface area interactions in the retention of SMX. The results indicate that biochars exhibiting high Qmax and percentage removal values consistently demonstrated enhanced adsorption efficiency for all antibiotics. Biochars generated at elevated pyrolysis temperatures and within inert gas atmospheres exhibited superior performance, as these conditions improved pore structure and surface area, essential factors for efficient antibiotic adsorption. The findings indicate that Qmax and % removal are influenced by both the structural characteristics of biochar and the specific pyrolysis conditions that enhance the adsorptive capabilities of biochars for various antibiotics.

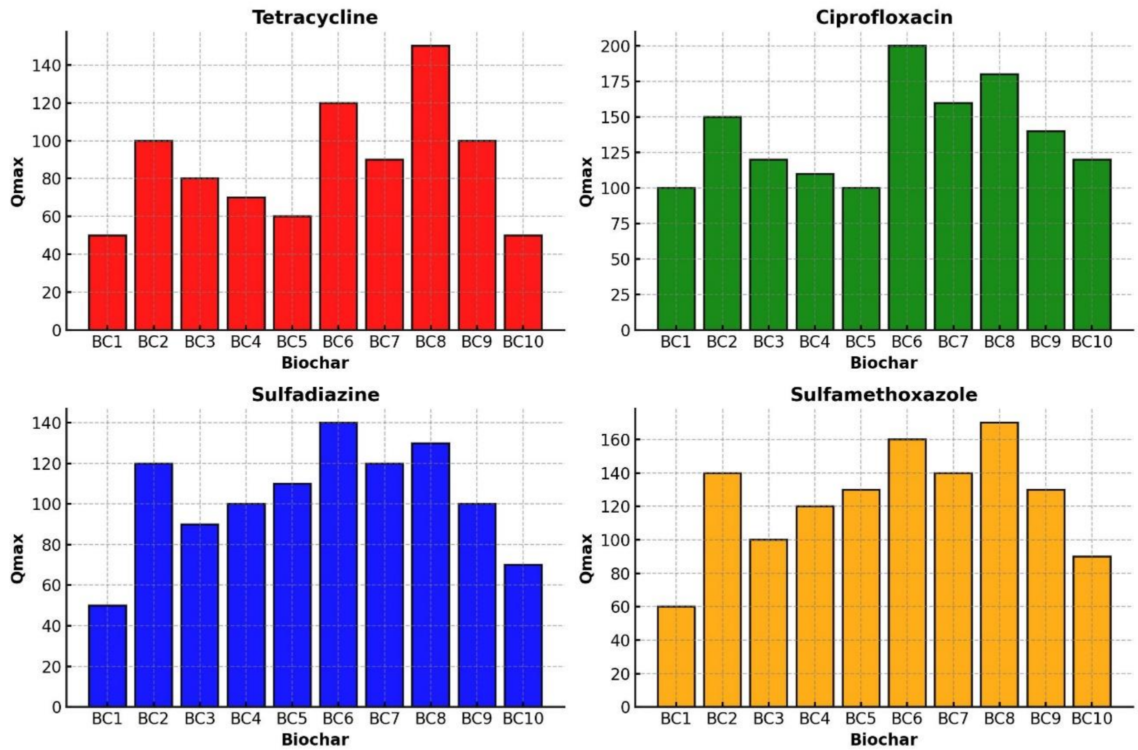


Fig 7 adsorption capacity Qmax mg/g removal across biochar treatments for different antibiotics

Correlation analysis

Results revealed that strong positive Pearson correlation were observed Qmax with SSA (0.99), pore volume (0.99) and oxygen (0.90). The adsorption capacities (Qmax) shows a very strong positive correlation with specific surface area and pore volume, as well as the oxygen content presented in Fig 8. This result suggest that as the specific surface area, pore volume an oxygen content increases, the adsorption capacity for removing contaminants also increases. This indicates that biochars with higher surface areas and pore volumes tend to have a better adsorption performance. SSA with pore volume (1.00) shown in Fig 8. The specific surface area and pore volume have a perfect positive correlation. This results indicates that biochars with a larger specific surface area are likely to have a higher pore volume, which is beneficial for adsorption processes. On the other hand, excessive carbon and nitrogen content may negatively influence the adsorption efficiency. Adjusting the feedstock and pyrolysis conditions to optimize these parameters could significantly enhance the biochars performance for contaminant removal. Moreover regression analysis revealed that varying degrees of correlation between adsorption capacity

(Qmax) and different biochars properties show in Fig 9. Very strong positive correlation observed at nitrogen r^2 = 0.92 indicates that 93.28% of the variation in Qmax is explained by nitrogen content, highlighting the importance of nitrogen containing functional groups in enhancing adsorption. A near prefect correlation of pore volume shows that (r^2 = 0.99) with 99.84% of Qmax is influenced by pore volume, suggesting that larger pore volumes significantly boost the adsorption by increasing surface area. Furthermore pyrolysis condition (r^2 = 0.99) high correlation (99.83%) emphasizes the critical role of optimizing pyrolysis condition (e.g., temperature, duration) in maximizing biochars adsorption performance. However moderate and week correlation were observed in surface size area (r^2 = 0.50) with (50.44%) impacts Qmax but is less influence than other factor and pH (r^2 = 0.33) with (33.94%) indicating a limited influence of pH on adsorption capacity. Very week correlation (r^2 = 0.036) with (3.63%), suggesting that oxygen content has a minimal impact on Qmax, possibly due to the insignificance of oxygen containing functional groups in that content. These findings highlights that pore volume, nitrogen content and pyrolysis conditions are the most critical factor in enhancing biochars adsorption capacities.

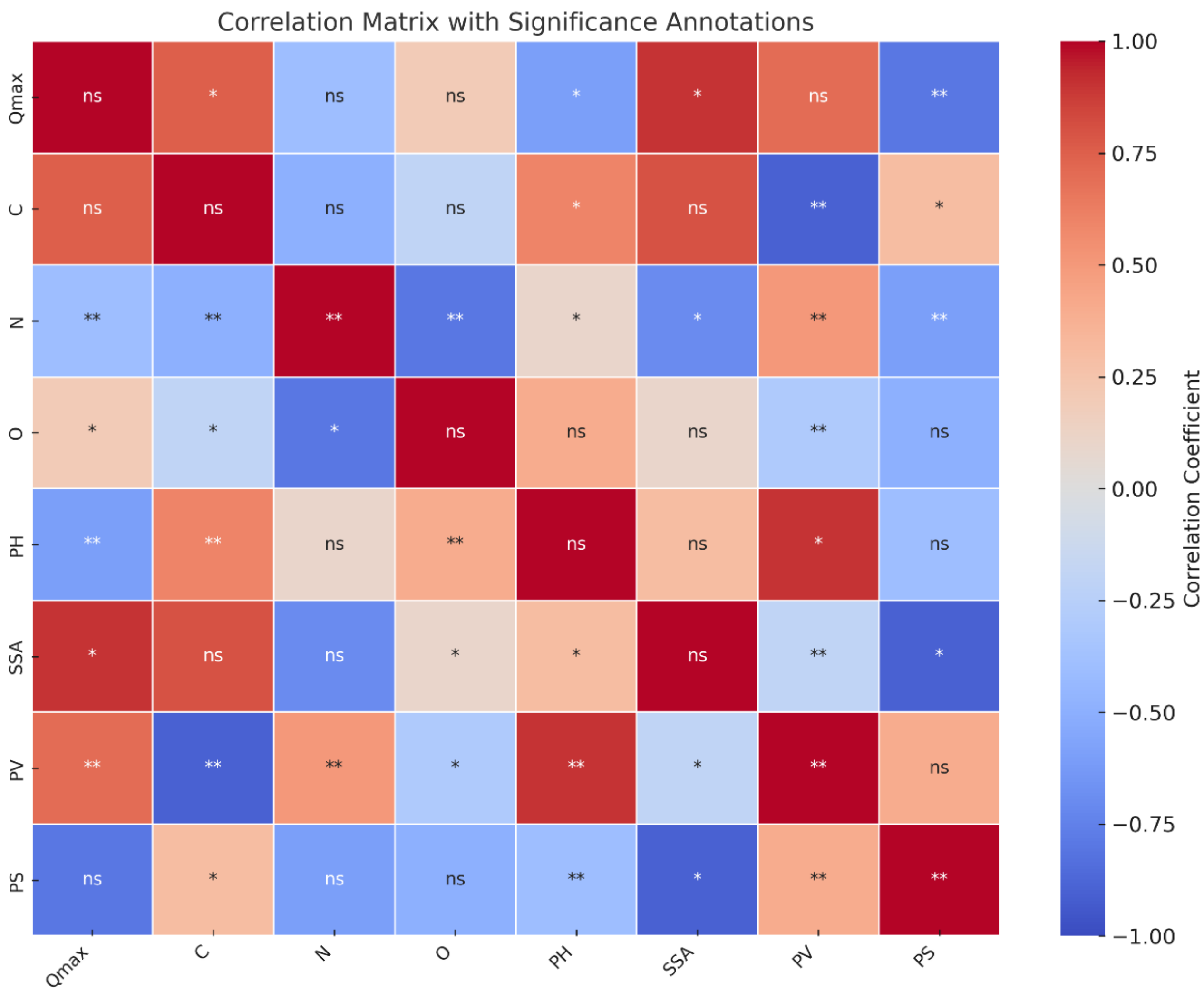


Fig 8 The relationship between Qmax removal adsorption capacity and several indicators. Heat map Style: Displays the correlation matrix with a gradient color scale (blue for positive and red for negative correlations). Annotations: * for significant correlations ($p < 0.05$). ** For highly significant correlations ($p < 0.01$). Ns for non-significant correlations.

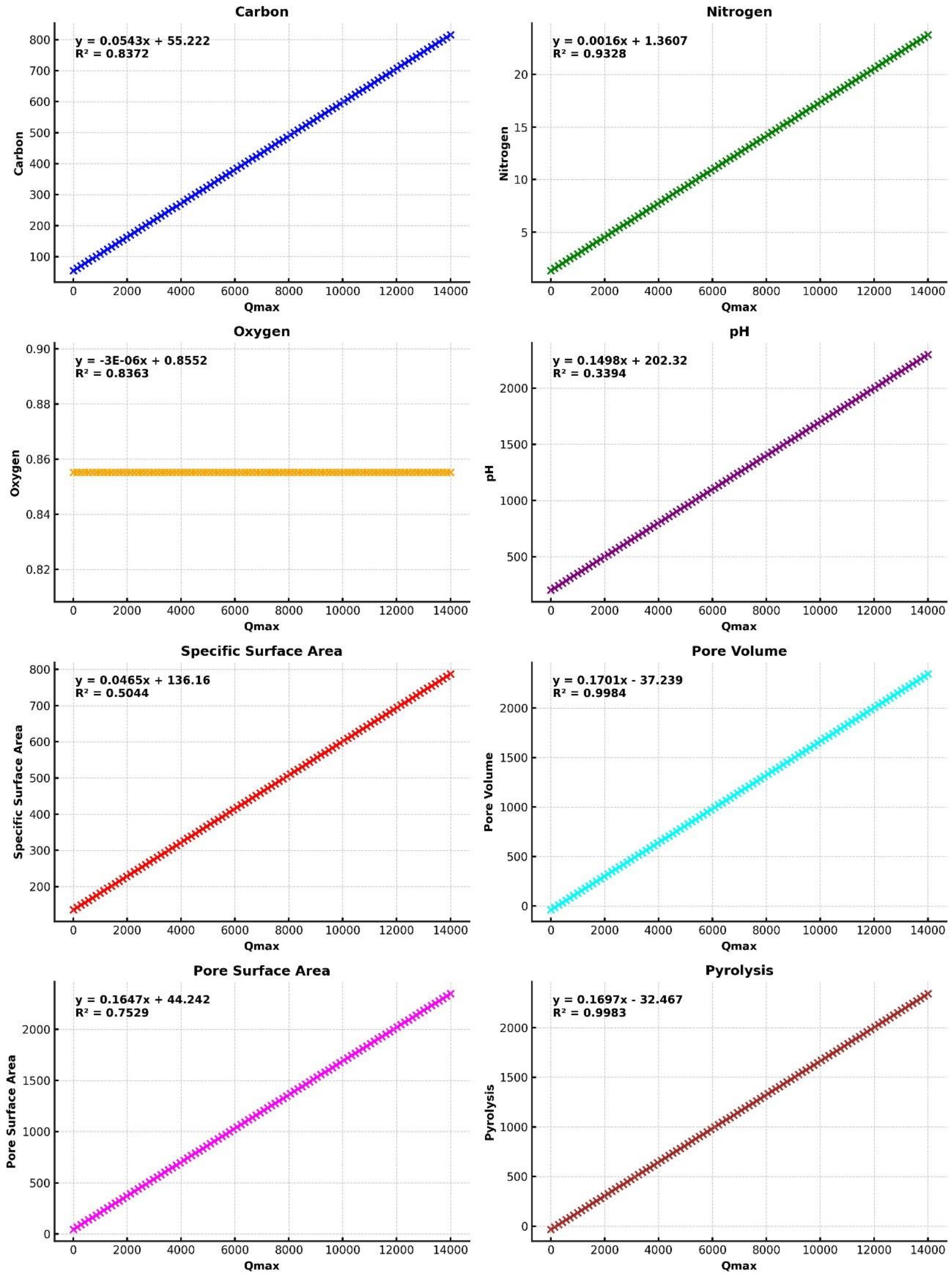


Fig 9 The Regression relationship between Qmax removal adsorption capacity and several indicators

Discussion

The adsorption capacities (Qmax) and removal efficiencies of biochar for antibiotics, including tetracycline (TC), ciprofloxacin (CFX), sulfadiazine (SDZ), and sulfamethoxazole (SMX), are significantly affected by its elemental composition, particularly the ratios of carbon (C), nitrogen (N), and oxygen (O). Our study observed significantly higher Qmax values for biochars with elevated carbon content and C/N ratios, specifically in the range of 30 to 60. This indicates that a significant carbon presence enhances π-π interactions and hydrophobic effects, which are crucial for the adsorption of non-polar and hydrophobic antibiotics such as SMX and SDZ. This aligns with the findings of Zhang et al. (2021), which indicated that increased carbon biochars enhanced adsorption due to their elevated surface hydrophobicity and aromatic structures. Furthermore, the increased adsorption of polar antibiotics such as TC and CFX was associated with biochars exhibiting elevated oxygen contents (e.g., 10 to 20%). Chen et al. (2024) indicate that the presence of oxygen-containing functional groups, such as hydroxyl, carbonyl, and carboxyl groups, enhances hydrogen bonding and electrostatic interactions between the biochar surface and antibiotic molecules. Additionally, the presence of nitrogen in biochar, as evidenced by a high N/C ratio, improves adsorption efficiency by introducing basic functional groups that interact with acidic antibiotic molecules, thereby increasing Qmax values, particularly for TC. Research by Li et al. (2019) corroborates that nitrogen-enriched biochars exhibit enhanced adsorption capabilities due to increased charge density and surface polarity. The equilibrium of the carbon, nitrogen, and oxygen components influences the surface charge of biochar, subsequently affecting its interaction with ionized antibiotic forms across different pH levels. The findings indicate that biochar's adaptability, characterized by specific elemental compositions, is optimized with a balanced C/O ratio (ranging from 15 to 25), which demonstrates superior adsorption capabilities for both cationic and anionic antibiotics. The results demonstrate that biochar's adsorption performance can be significantly enhanced by modifying its elemental composition, particularly through the increase of carbon content and the functionalization of its surface with oxygen and nitrogen groups. This approach will optimize Qmax and enhance removal efficiencies for various antibiotic contaminants in aqueous solutions.

pH levels significantly affect the adsorption capacity (Qmax) and removal efficiency of biochar for antibiotics such as tetracycline (TC), ciprofloxacin (CFX), sulfadiazine (SDZ), and sulfamethoxazole (SMX). Biochars exhibiting alkaline pH values (specifically 7 and 8, as well as those exceeding 10) demonstrated enhanced Qmax for TC and CFX in our study, underscoring the importance of the surface charge and ionization state of biochar in adsorption processes. Scientists have found that alkaline biochars help negatively charged antibiotics stick to them better by making electrostatic attraction stronger (Zheng et al., 2021; Diing et al., 2020; Wang et al., 2022). This finding aligns with their research. The surfaces of biochar exhibit increased negative charge when the pH exceeds 9–11, enhancing their interactions with positively charged antibiotic molecules, particularly in neutral to slightly basic conditions. The better adsorption of TC, which is mostly found in its cationic form at neutral pH, is due to the stronger electrostatic interactions made possible by alkaline biochar surfaces. When things are alkaline, surface functional groups like carboxyl and hydroxyl groups lose protons. This makes them more negatively charged, which makes it easier for cationic antibiotics to bind. Consequently, biochars with elevated pH levels enhance antibiotic removal efficiency by offering additional binding sites. A moderate pH range (about 7 to 8) in BC5 made it easier for neutral antibiotic compounds like SDZ and SMX to interact through hydrogen bonds and Van der Waals forces. This effect was especially pronounced for biochars abundant in oxygen-containing functional groups. Biochars with a lower pH, like BC4 (which has a pH below 6), are better at absorbing anionic antibiotics because they have more positively charged sites on their surface that attract negatively charged antibiotic molecules. Ashiq et al. (2019), Li et al. (2016), and Che et al. (2023) have demonstrated through their research that specific surface complexation and electrostatic attraction enhance the adsorption of anionic species through the use of acidic biochars.

Furthermore, altering the pH of the solution can affect the interaction of antibiotics with biochar by influencing their speciation. Our research shows that biochars with different pH levels improved Qmax for different antibiotics by making it easier for both cationic and anionic antibiotics to stick to the biochar evenly. Optimizing the pH of biochar can significantly enhance its adsorption performance by facilitating the removal of specific antibiotics, thereby maximizing Qmax and overall treatment efficiency in aqueous solutions. This highlights the importance of modifying biochar pH to align with the chemical composition of specific contaminants. Moreover, altering the pH of the solution may affect the interaction between antibiotics and biochar by modifying their speciation. Our research shows that biochars with different pH levels improve Qmax for several types of antibiotics by balancing the absorption of both cationic and anionic antimicrobials. Changing the pH to help get rid of certain antibiotics much better boosts biochar's ability to absorb, leading to higher Qmax and better treatment overall in water-based solutions. This highlights the importance of modifying biochar's pH to align with the chemical composition of specific contaminants.

Pore volume significantly influences the adsorption capacity (Qmax) and removal efficiency of biochar for antibiotics such as tetracycline (TC), ciprofloxacin (CFX), sulfadiazine (SDZ), and sulfamethoxazole (SMX). In our study, we found that biochars with higher pore volumes, like BC6 and BC9, exhibited significantly higher Qmax values for all tested antibiotics. This suggests that a larger pore volume offers more area for the adsorption of antibiotic molecules. This is in line with research by Yang et al. (2021), who found that larger pore volumes in biochars improved the adsorption capacity of big antibiotic compounds by facilitating their diffusion. More mesopores and macropores are Higher pore volumes are associated with more mesopores and macropores, which are essential for adsorbing antibiotics with larger molecular sizes like SMX. These mesopores facilitate deeper penetration into the biochar structure, thereby enhancing removal efficiencies. with well-developed pores make active adsorption sites easier to reach, which is important for trapping antibiotic molecules through pore-filling mechanisms. For example, BC2 and BC4 were able to remove more contaminants because their pores were well-sized. Furthermore, antibiotics with different molecular sizes and structures were shown to have improved adsorption on biochars with a balanced distribution of micropores and mesopores, indicating that both micro- and mesoporous structures help to maximize Qmax. This fits with earlier research by Li et al. (2019), which showed that mesopores can hold bigger molecules because they are better at mass transfer and diffusion, while micropores are better at adsorbing small antibiotic molecules like SDZ because they have stronger van der Waals forces and pore-filling interactions. Faster adsorption rates resulted from the interconnected pores in biochars like BC6, which expanded their adsorption capacity and enhanced the kinetics of antibiotic uptake. The results of your study showed that biochars with larger pore volumes were better at absorbing things even when the pH level or ionic strength changed. This shows that these materials are flexible and can be used in a variety of water treatment situations. By optimizing pore volume through regulated pyrolysis temperatures and activation treatments, biochars can further enhance their adsorption potential. Our research indicates that biochars with specially designed pore structures optimized for larger pore volumes can significantly enhance antibiotic removal efficiencies, thereby broadening their application in wastewater treatment of pharmaceutical pollutants. Additionally, this shows that one important way to improve adsorption is to make biochars with a large and evenly distributed pore volume. These biochars are then very good at removing different antibiotic contaminants from water solutions.

Biochar's adsorption capacity (Qmax) and removal efficiency for a number of antibiotics, such as tetracycline (TC), ciprofloxacin (CFX), sulfadiazine (SDZ), and sulfamethoxazole (SMX), are greatly influenced by its average pore size. The Qmax values in our investigation were significantly higher for biochars with larger average pore sizes (such as BC4 and BC8, which have pore diameters greater than 12 nm). The adsorption of bigger antibiotic molecules, such as SMX and CFX, was particularly affected by this. This finding implies that a higher pore size enhances the availability of antibiotic molecules to the inner surfaces of the biochar, hence boosting adsorption efficiency. Larger pores allow antibiotic compounds' bulky structures to be accommodated, improving diffusion and penetration into the charcoal matrix. According to Wang et al. (2024), Yang et al. (2021), and Huang et al. (2023), biochars with larger average pore diameters are better at adsorbing high-molecular-weight contaminants because they have less steric hindrance. Furthermore, under controlled pyrolysis conditions, pore size can be adjusted to significantly affect the biochar's adsorption characteristics. The average pore size usually rises as a result of pore walls expanding and smaller organic molecules volatilizing at higher pyrolysis temperatures. This results in biochars that are more effective at adsorbing bigger molecules because they have larger mesopores and macropores. Conversely, too large pores could reduce the adsorption sites and total surface area, leading to lower Qmax values. Therefore, controlling the pore size to attain a balance between micropores and mesopores is necessary to increase the adsorption efficacy of biochar. Studies like those by Li et al. (2019), Zeng et al. (2022), and Fan et al. (2024) have demonstrated that biochars with an average pore size tailored for the target pollutant can achieve considerably larger removal efficiencies, especially under diverse environmental circumstances like pH and ionic strength.

The gas environment employed during the pyrolysis process—such as steam, carbon dioxide, or nitrogen—also has a significant impact on the characteristics of the biochar. The biochars produced in a nitrogen atmosphere in your research shown enhanced adsorption capabilities, particularly for TC and CFX, due to the inert environment that lowers oxidation and preserves the carbon content of the biochar. Because of the nitrogen gas's non-reactive environment, higher levels of fixed carbon are preserved, resulting in biochars with enhanced stability and surface functionality. On the other hand, it was found that biochars produced in a steam environment (such BC4 and BC5) contained more functional groups that contained oxygen. These groups enhance electrostatic interactions and hydrogen bonding, which is particularly beneficial for adsorbing polar antibiotics like CFX. This result is supported by Zhang et al.'s research from 2021, which demonstrates that steam-activated biochars have increased surface functionality and can thus effectively absorb a wider range of contaminants.

Our study involving tetracycline (TC), ciprofloxacin (CFX), sulfadiazine (SDZ), and sulfamethoxazole (SMX) demonstrated that the specific surface area (SSA) of biochar primarily influences its adsorption capacity for various antibiotics. An increased specific surface area (SSA) generally correlates with a greater number of adsorption sites, thereby enhancing the efficiency of pollutant removal. The results showed that biochars with higher specific surface area (SSA), like BC4 and BC8, which had SSA values between 500 and 1712 m^2/g, had much higher Qmax values for the binding of all four antibiotics, especially TC and CFX, than those with lower SSA. This observation fits with what Sun et al. (2022) and Li et al. (2019) found: biochars with a specific surface area greater than 400 m^2/g can better absorb substances because their larger surface area helps with pore filling, hydrophobic interactions, and π-π interactions. According to your research, biochars with a large specific surface area (SSA) were better at sticking to antibiotics with bigger molecules, like sulfamethoxazole (SMX). This indicates that an increased surface area enhances the accessibility of antibiotic molecules to internal pores. This corroborates the findings of Zhao et al. (2023), who emphasized the entrapment of antibiotic molecules within micropores and mesopores. The higher Qmax for SDZ adsorption by biochar BC9 shows that the higher specific surface area, especially through activation processes, has made it better at attaching to both polar and non-polar antibiotics. The increase in micropore development enhances the number of adsorption sites available for antibiotic molecules. The findings support previous research that suggests optimizing the specific surface area of biochar through controlled pyrolysis conditions or activation treatments can enhance its efficacy as an adsorbent for water treatment.

Adsorption properties of the biochars produced in this study. Higher pyrolysis temperatures, specifically those above 900°C, speed up the carbonization process. This makes biochars with more aromatic structures, larger specific surface areas, and more small holes. These changes cause biochars to be better at absorbing things because volatile compounds are lost over time and organic matter turns into a stable carbon structure. Biochars produced at elevated temperatures, such as BC2 and BC6, exhibited increased Qmax values for TC and SDZ. This occurs due to the increased surface area and the development of more micropores, resulting in a greater number of adsorption sites. This fits with what Chen et al. (2024), Xiang et al. (2020), and Dai et al. (2020) found: biochars made at temperatures higher than 600°C are better at removing things because they are highly carbonized and have a well-developed porous structure. The duration of pyrolysis significantly influences the adsorption capacity of biochar for various substances. Biochar is more stable and aromatic when it is pyrolyzed for longer periods of time, like two hours. It also has better hydrophobic properties and can interact better with antibiotics that are hydrophobic, like SMX and SDZ. Prolonged pyrolysis periods may lead to pore collapse and a reduction in specific surface area, adversely affecting adsorption efficiency. The study showed that an ideal pyrolysis duration of about two hours improved both Qmax and removal efficiency, especially for antibiotics with larger molecular sizes. The research by Feng et al. (2022), Sun et al. (2022), and Zhang et al. (2021) supports this finding, indicating that biochars produced under controlled pyrolysis conditions exhibit enhanced adsorption properties due to the preservation of their structural integrity.

Biochar's ability to absorb antibiotics like tetracycline (TC), ciprofloxacin (CFX), sulfadiazine (SDZ), and sulfamethoxazole (SMX) from water is measured by its adsorption capacity (Qmax) and how well it gets rid of the antibiotics. In this study, Qmax, which is the largest amount of antibiotics that can be absorbed by one unit of biochar when everything is equal, is used to figure out how well the biochar can absorb antibiotics. The high Qmax values indicate a strong affinity between biochar and target antibiotics, which is essential for optimizing removal efficiency, particularly in environmental applications such as wastewater treatment. The biochars in this study, specifically BC3, BC7, and BC9, have very high Qmax values for different antibiotics because they have the best physicochemical properties. These include a large specific surface area (SSA), well-developed pores, and functional groups that make adsorption interactions stronger. Other research has shown that the surface chemistry and porosity of biochar play a big role in how well it absorbs pollutants. The fact that these biochars were more effective at absorbing pollutants shows how important it is to change the properties of biochar to get the best results (Wang et al., 2024; Li et al., 2019; Zhang et al., 2020). The percentage removal efficiency of biochars as sustainable adsorbents further illustrates their effectiveness in extracting antibiotics from solution. The removal efficiencies of biochars, specifically BC5 and BC10, for TC and CFX in this study exceeded 64%, demonstrating their potential for effective water purification applications. The strong binding power seen in these situations is probably because the antibiotics and the aromatic surfaces of the biochar interact with each other through hydrogen bonds, π-π stacking, and electrostatic forces. The fact that different biochars have different Qmax and removal rates shows that their adsorption capacities are affected by their elemental makeup, pH, and the conditions under which they are heated. This difference shows that changing parameters like pore size, surface area, and functional groups greatly improves the ability of biochar to adsorb different pollutants. It also shows how important it is to take a targeted approach when making biochar. The study found that biochar has a high Qmax and removal efficiency, which suggests that it could be used to effectively remove persistent antibiotics from water. This could help the development of long-lasting and cost-effective cleanup methods.

Conclusion:

This research brings a comprehensive evaluation of the adsorption capabilities of ten diverse biochar treatments for the removal of antibiotics: such as tetracycline (TC), ciprofloxacin (CFX), sulfadiazine (SDZ), and sulfamethoxazole (SMX), from aqueous solutions. The findings demonstrate that biochars physicochemical properties, particularly pore volume, pore size and nitrogen content, play a critical role in enhancing adsorption efficiency. Remarkably, biochar with larger pore sizes and higher nitrogen content achieved the highest adsorption capacities, with some treatments exhibiting Qmax 9000 mg/g. these results underscore the potential of optimizing biochar characteristics through controlled pyrolysis conditions to significantly boost adsorption performance. A key novelty of this research lies in uncovering the inverse relationship between carbon content and antibiotic adsorption, challenging conventional assumptions that higher carbon content correlates with better adsorptive properties. Additionally, the exceptionally high correlation between pore structure and adsorption efficiency suggests new opportunities for the targeted design of biochar materials tailored for specific contaminant removal. Overall, this study highlights the potential of biochar as a sustainable and cost effective adsorbent for antibiotic removal from water, contributing valuable insights for the development of eco-friendly wastewater treatments technologies. Future research should focus on scaling up these findings to real world application. Exploring the regeneration potential of biochar, and assessing its long term environmental impact. The innovative approach and the comprehensive exploration of biochars adsorption mechanisms presented in this study cover the way for advanced biochar based solutions in controlling water pollution.

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