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Supporting Information

for

The role of biochar in combating microplastic pollution: a bibliometric analysis in environmental contexts

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Additional data

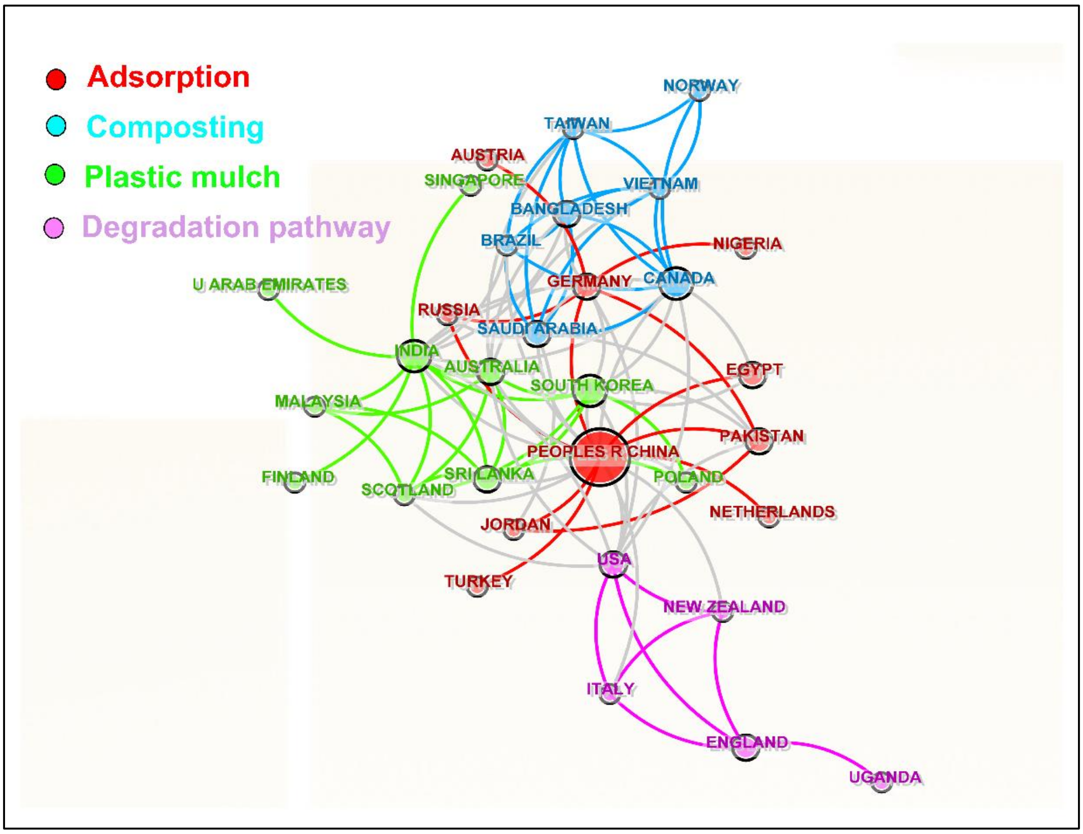

Figure S1: Co-occurrence of regional cooperation networks.

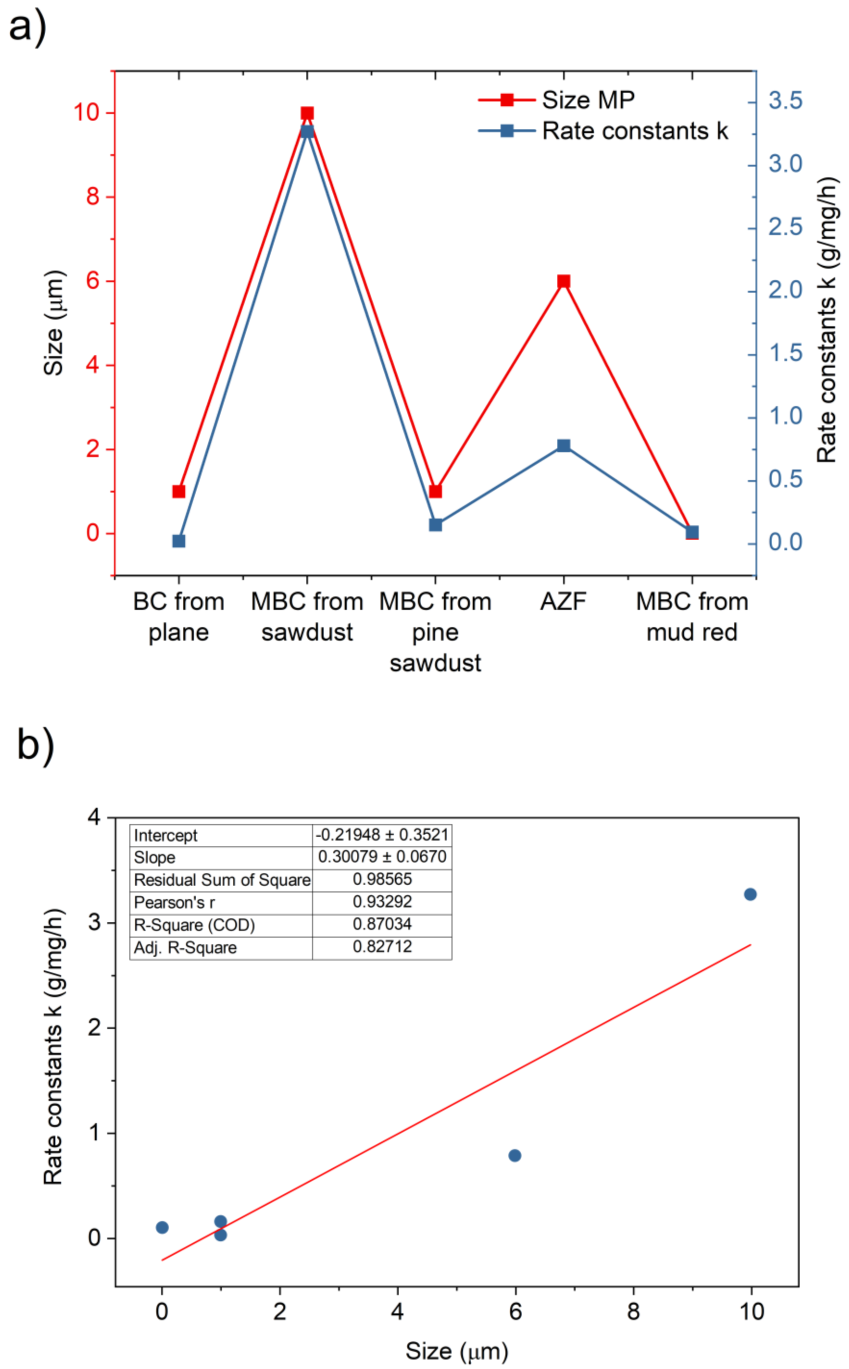

Figure S2: Rate constants for the adsorption kinetics of BC on micro PS (a) and the regression equation based on the rate constant and the size of micro PS (b).

Table S1: Biochar characteristics from different feedstocks.

Biochar	Temperature (°C)/time	pH	C (wt%)	H (wt%)	N (wt%)	O (wt%)	Fe (wt%)	S (wt%)	P (wt%)	H/C	O/C	Specific surface area ($m^2 g^{-1}$)	Pore volume ($cm^3 g^{-1}$)	References
Soil														
BC from rice straw	700 °C, 2 h	-	52.01	1.05	0.57	17.87	-	-	0.24	0.02	0.26	106.41	-	[1]
MEBC-from rice straw	• Heated for 10 h at 160 °C • pyrolyzed at 700 °C under N_2 gas for 2 h	-	18.47	-	2.11	5.96	30.37	33.56	-	-	0.24	120.84	-	
OSR	550 °C	9.78	68.85	1.82	1.29	8.91	-	-	0.29	0.32	0.1	7.3		[2]
	700 °C	10.41	67.74	1.09	1.26	7.84	-	-	0.26	0.19	0.09	25.2		
SWP	550 °C	7.91	85.52	2.77	<0.1	10.36	-	-	0.06	0.39	0.09	26.4		
	700 °C	8.44	90.21	1.83	<0.1	6.02	-	-	0.07	0.24	0.05	162.3		
BC from peanut shells*	450 °C, 4 h	8.85	678.45	-	7.73	-	-	-	1.2	-	-	38.42	0.024	[3]

Biochar	Temperature (°C)/time	pH	C (wt%)	H (wt%)	N (wt%)	O (wt%)	Fe (wt%)	S (wt%)	P (wt%)	H/C	O/C	Specific surface area (m^2 g^{-1})	Pore volume (cm^3 g^{-1})	References
Bulk BC from coconut shell	Commercial	-	78.75	2.16	0.63	-	-	-	-	-	-	902.64	0.26	[4]
Nano BC from coconut shell		-	94.2	-	0.47	-	-	-	-	-	-	77.35	2.65 $\times 10^{-3}$	
BC from food waste	500 °C, 20 min	9.10	55.87	6.5	4.49	-	-	-	-	0.116	-	-	-	[5]
BC from rubber crumb	450 °C, 2h	-	62.49	2.46	2.57	18.08	-	-	-	0.04	0.29	108.02	0.1 (Include medium pore and micropore)	[6]
Corn straw	650–750 °C	9.6	54.5	0.7	0.79	0.79	4.4	-	1.8	0.013	0.014	-	-	[7]

Biochar	Temperature (°C)/time	pH	C (wt%)	H (wt%)	N (wt%)	O (wt%)	Fe (wt%)	S (wt%)	P (wt%)	H/C	O/C	Specific surface area ($m^2\ g^{-1}$)	Pore volume ($cm^3\ g^{-1}$)	References
Corn straw*	500 °C for 2 to 3 h	7.29	55.31	-	1.35	-	-	-	0.243	0.02	0.34	-	-	[8]
Water														
corn straw	300	-	70	-	3.1	18.7	-	0.2	1.2	-	0.27	808.3	-	[9]
	400	-	81.3	-	3.7	11.7	-	0.3	0.2	-	0.14	609.0	-	
	500	-	68.7	-	2.2	19.1	0.1	0.2	1.5	-	0.28	177.5	-	
Hardwood	Produced through a traditional open fire stove	-	84.7	-	0.3	14.1	-	-	-	-	0.166	292	-	
Palm kernel shell	600 °C for 4 h	-	63	1.61	0.24	2.79	-	<0.6	-	0.025	0.04	-	-	[10]
Coconut shell biochar		-	78	1.52	< 0.1	2.94	-	<0.6	-	0.019	0.037	-	-	

Biochar	Temperature (°C)/time	pH	C (wt%)	H (wt%)	N (wt%)	O (wt%)	Fe (wt%)	S (wt%)	P (wt%)	H/C	O/C	Specific surface area ($m^2\ g^{-1}$)	Pore volume ($cm^3\ g^{-1}$)	References
MBC from sawdust	550 °C (with a heating rate of 5 °C/min) for 2 h	-	69.29	-	-	20.38	10.33	-	-	-	0.22	363.8	0.37	[11]
Mg-MBC		-	65.03	-	-	16.93	11.20	-	-	-	0.20	265.47	0.41	
Zn-MBC	550 °C for 2.5 h at a heating rate of 30 °C min^{-1}	-	66.48	-	-	15	12.45	-	-	-	0.17	329.87	0.34	
Amino-Functionalized Zeolite Series/H_3PO_4	H_3PO_4 impregnation Co – pyrolysis waste coffee and ammonium ZSM-zeolite	-	-	-	-	-	-	-	-	-	-	79	0.09	[12]

Biochar	Temperature (°C)/time	pH	C (wt%)	H (wt%)	N (wt%)	O (wt%)	Fe (wt%)	S (wt%)	P (wt%)	H/C	O/C	Specific surface area (m^2 g^{-1})	Pore volume (cm^3 g^{-1})	References
Peanut shells	low pyrolysis at 500 °C for 2 h	8.7	57.35	2.22	1.47	5.44	-	-	-	0.46	0.09		0.02	[13]
MBC from peanut shells	prepared using the co-precipitation method	7.92	43.55	1.93	1.41	6.11	-	-	-	0.53	0.14	205.46	0.3	

Table S2: Biochar application for soil remediation and plant growth in MP-polluted environments.

Soil/ plant class	Biochar category	MPs parent	Efficiency (%)				Note	Reference
			Genes/Enzyme		Bacteria			
			Kind	*Tend	Kind	*Tend		
Soil layer in farmland	Bulk and biochar coconut shell biochar	PE	Aminoglycoside, sulfonamides, tetracycline multiple drug resistance, integrons, transposons	88.57 (Based on total of genes)	*Actinobacteriota, Proteobacteria, Chloroflexi, Acidobacteriota, Firmicutes*	Increased: *Actinobacteriota, Chloroflexi* and *Acidobacteriota*, Decreased: *Proteobacteria, Firmicutes* and *Patescibacteria*.	• Biochar only reduces antibiotic genes caused by MPs. • Nano-biochar has a better inhibitory effect than bulk biochar. • MPs increase multiple drug resistance genes.	[4]

Soil/ plant class	Biochar category	MPs parent	Efficiency (%)				Note	Reference
			Genes/Enzyme		Bacteria			
			Kind	*Tend	Kind	*Tend		
Agricultural field	Oilseed rape straw (ORS), Softwood pellets (SWP)	LDPE	Urease: 77.34 µg N hydrolyzed/ g	OSR: – SWR-700:+	*Acidobacteria*	Increase with SWP-550 and SWP-700	• The difference in alkalinity and EC depends on raw materials. • Larger pore volume allows easier development of urease microorganisms.	[2]
			Fluorescein diacetate: 1.69 µg FDA g ×min	OSR-700: +28.47% SWP-700: + 30.71%	*Proteobacteria*	Decrease		
			Acid phosphatase	ORS-500: – ORS-700: –	*Firmicutes*	Decrease (ORS-500, - 700 and SWP 700)		
Lettuce rhizosphere soil	Charring peanut shells	PS	1677 gen detected in Rhizosphere soil	MPs: Decrease 26.67%	*Chemoheterotrophy*	Increase 10% of the total	• Biochar reduces the inhibitory effects of	[3]
					Aerobic Chemoheterotrophy	Increase 5% of the total		

Soil/ plant class	Biochar category	MPs parent	Efficiency (%)				Note	Reference
			Genes/Enzyme		Bacteria			
			Kind	*Tend	Kind	*Tend		
				Biochar: Increase 5.15%	*Cyanobacteria, oxygenic photoautotrophy*	Decrease 90% of the total	microplastics on plant growth, especially root growth. • Biochar positively affects genes related to antioxidation and nitrogen transport.	
Lettuce cultivated soil	Food waste-derived biochar	PS	Urease	– 46.2% (MPs and BC)	*Chloroflexi, Planctomycetes*	Highest distribution in total experiments surved BC	• PS plastic does not significantly affect soil chemical properties but	[5]
			Fluorescein diacetate	– 94% (MPs and BC)				

Soil/ plant class	Biochar category	MPs parent	Efficiency (%)				Note	Reference
			Genes/Enzyme		Bacteria			
			Kind	*Tend	Kind	*Tend		
			Acid phosphatase	+ 30% (MPs and BC)			causes pressure on microorganisms. • BC enhances root-associated microbial communities and is a suitable choice.	
Peanuts cultivated soil	Corn stalks biochar inter integrated microbial	Tire-derived rubber crumbs	urease	+19.65%	*Pseudomonas, Sheathbacteria, Burkholderia* and *Solibacter*	Significant reduction when MP is added	• Changes in soil bacteria due to SynCom treatment can affect nitrogen cycling. • RC-MP addition alters root	[6]
			dehydrogenase	+115.74%	*Pseudomonas*	Increase three times with BC		

Soil/ plant class	Biochar category	MPs parent	Efficiency (%)				Note	Reference
			Genes/Enzyme		Bacteria			
			Kind	*Tend	Kind	*Tend		
							bacterial populations, influencing peanut plant development.	
Agricultural wheat soil	Cotton stalks (650 – 750ºC)	PVC	urease	+ 14.45 – 26%	Microbio biomass nitrogen	↑ 7 – 30%	• PVC affects carbon distribution in plant stems and roots, leading to reduced yield. It also impacts Gram-positive bacteria and Pseudomonas.	[7]
			dehydrogenase	+ 5 – 15%	Microbio biomass carbon	+ 10%- 13%		

Soil/ plant class	Biochar category	MPs parent	Efficiency (%)				Note	Reference
			Genes/Enzyme		Bacteria			
			Kind	*Tend	Kind	*Tend		
							• Biochar increases urease activity even in the presence of PVC-MPs, reducing the toxic effects of MPs on rRNA 16S or 18S and bacterial diversity.	
Agricultural pepper soil	Corn straw at 500 °C	PP	Pielou index, Shannon index and Observed ASVs	Bacterial α Diversity Increased	*Acidobacteria*	+ 1.32% distribution	• *Proteobacteria, Chloroflexi, Acidobacteriota, Bacteroidota, Actinobacteriota, Gemmatimonadota*	[8]
					Bacteroidetes	+ 1.37% distribution		

Soil/ plant class	Biochar category	MPs parent	Efficiency (%)				Note	Reference
			Genes/Enzyme		Bacteria			
			Kind	*Tend	Kind	*Tend		
							are dominant bacterial phyla. • Biochar treatment can enhance disease resistance in pepper plants and promote root growth.	
Paddy rice field	Magnetic biochar - derived rice straw	PE, PVC	Dehalogenase, benzoate metabolism glyceride and glyceophospholipid,	+	*Candidatus Saccharibacteria, Bacteroidetes*	+	• MEBC promotes nutrient transport and the degradation of	[1]

Soil/ plant class	Biochar category	MPs parent	Efficiency (%)				Note	Reference
			Genes/Enzyme		Bacteria			
			Kind	*Tend	Kind	*Tend		
	and ferrous		ABC transporter genes				microplastic products.	
			alkane monooxygenase, PVA dehydrogenase, alkane dehalogenase	–	*Proteobacteria*	–	• MEBC enhances the growth of benzoate-metabolizing bacteria.	
Agricultural sugarcane soil	Corn stalk (600 °C)	HDPE	Diversity index of 16S rRNA gene	OTUs: + (6.28 – 8.00%) Chao1: + (6.42–7.98%)	Diversity index based on phoD-harboring bacteria	OTUs: – (2.3 -3.67%) Chao1: – (1.54-2.59%)	Biochar increases the relative abundance of Subgroup_10, *Bacillus, Pseudomonas, Amycolatopsis and*	[14]

Soil/ plant class	Biochar category	MPs parent	Efficiency (%)				Note	Reference
			Genes/Enzyme		Bacteria			
			Kind	*Tend	Kind	*Tend		
				Shannon: + (3.8 -4.48%)		Shannon: – (1.52 – 1.85)%	*Bradyrhizobium* in soil microbes, inhibiting harmful bacteria and promoting plant growth.	

**Tend refers to the observed trend in microbial abundance and soil biological indicators.*

+ indicates an increase, while – indicates a decrease.

Table S3: Biochar application for MP removal in water and wastewater.

Wastewater/ microplastic	Biochar	Model	Efficiency (%)	Q_e (mg/g)	Kinetic	Mechanism (optimum conditions)	Reference
PS sphere (10 µm)	Corn straw and sand (300-500°C)	Filter column	99	-	-	• Stuck, Trapped, Entangled. Higher pH in effluent: BC-500 > BC-400 > BC-300 > silica sand.	[9]
PS particles (1 µm)	London Plane bark biochar	Batch	-	60.05	Second order: k = 0.023 g/mg/h	• π-π interaction between PS benzene rings and BC (pH 5)	[15]

Wastewater/ microplastic	Biochar	Model	Efficiency (%)	Q_e (mg/g)	Kinetic	Mechanism (optimum conditions)	Reference
					q_e = 59.9 mg/g		
Rigid polystyrene (PS) (75, 150, 300 µm diameter)	Banana peel (650 °C)	Filter column	100	-	-	• Filtration, pore filling, H-bonding, hydrophobic interaction. Efficiency drops after 17h continuous filtration.	[16]
PS and carboxylate functional	Sand + 1% BC from cellulose (Pyrolysis 700^{o}C)	Filter column	99.6	-	-	• Biochar reduces negative charge of MPs in wastewater,	[17]

Wastewater/ microplastic	Biochar	Model	Efficiency (%)	Q_e (mg/g)	Kinetic	Mechanism (optimum conditions)	Reference
group (<10 µm)						• Increasing retention efficiency. Decreased porosity enhances MPs capture. • Complex surface structure improves retention efficiency.	
Polystyrene (10 µm)	Sawdust BC – modified magnatic	Batch	94.81-99.46	374.57	Second order: k = 2.82 g/mg/h	• Enhanced adsorption via electrostatic interactions. Modified	[11]

Wastewater/ microplastic	Biochar	Model	Efficiency (%)	Q_e (mg/g)	Kinetic	Mechanism (optimum conditions)	Reference
					q_e = 100.60 mg/g	biochar shows better adsorption for $H_2PO_4^-$ ions. • Optimal pH 7. Efficiency > 90% even at pH 9. • Electrostatic interaction and metal-O-PS bonds interaction	
	Sawdust BC – modified magnatic and Mg			334.03	Second order: k = 3.72 g/mg/h q_e = 98.52 mg/g		
	Sawdust BC – modified magnatic and Mg			355.72	Second order: k = 3.72 g/mg/h		

Wastewater/ microplastic	Biochar	Model	Efficiency (%)	Q_e (mg/g)	Kinetic	Mechanism (optimum conditions)	Reference
					q_e = 99.21 mg/g		
Polyamide (aged) (27–307 µm)	Magnetic corncob	Batch	97	1145 – 1173	Elovich kinetic: (R^2 = 0.93 – 0.96) α = 61.84 – 256.9 mg/g/min β = 0.06 – 0.0086 g/mg	• Crystallinity reduction, increased oxygen groups. Optimum pH 5-9. • Optimum pH 5-9. Efficiency highest at pH 5. • Electrostatic shielding, "salting-out" effect and	[18]

Wastewater/ microplastic	Biochar	Model	Efficiency (%)	Q_e (mg/g)	Kinetic	Mechanism (optimum conditions)	Reference
					Second order: (R^2 = 0.73 – 0.88) k = 0.009 – 0.0012 g/mg/h q_e = 151.7 – 991.9 mg/g	buffer effect maintain adsorption efficiency.	
Polystyrene (1 µm)	Magnetic from pine sawdust	Batch	96.2	5.5	Second order:		[19]

Wastewater/ microplastic	Biochar	Model	Efficiency (%)	Q_e (mg/g)	Kinetic	Mechanism (optimum conditions)	Reference
(20 mg/L)					k = 0.152 g/mg/h q_e = 6.388 mg/g	• Adsorption via electrostatic interactions and metal-O-PS-MP formation (pH 3-7). • Adsorption efficiency decreases with anion presence (PO_4^{3-}, CO_3^{2-}, HCO_3^-).	
	Magnetic from pine sawdust and Zn	Batch	84.8	-	-		
Monodispersed polystyrene (6 µm)	Amino-functionalized zeolite	Batch	79 - 94	4.54 – 4.63	Second order: (R^2 = 0.99)	• π-π interactions, electrostatic forces,	[20]

Wastewater/ microplastic	Biochar	Model	Efficiency (%)	Q_e (mg/g)	Kinetic	Mechanism (optimum conditions)	Reference
	series/phosphoric acid-coffee waste biochar (AFZ)				k = 0.78 g/mg/h q_e = 4.653 mg/g Mixed-1,2-order: (R^2 = 1.0) k = 0.42 g/mg/h q_e = 4.898 mg/g	hydrogen bonding, Van der Waals forces. • Functional moieties such as C–H, C–O, C=C, N–H, Al–O and Si–O was majorly responsible for the adsorption process. • pH optimize = 7	

Wastewater/ microplastic	Biochar	Model	Efficiency (%)	Q_e (mg/g)	Kinetic	Mechanism (optimum conditions)	Reference
Agriculture runoff (LDPE, PET, PA, PC, PE, PS, PVC) (> 40 µm)	Sugarcane & pinewood	Filter column	86.6 - 92.6	-	-	• Pinewood BC (900°C) shows better trapping and adsorption due to hydroxyl groups. Efficiency inversely proportional to MP size.	[21]
Polyethylene (10 µm, 2 – 3 mm)	Palm kernel shell / Coconut shell	Filter column	92.3%-94.1%	-	-	• Hydrophobic interactions enhance clustering. Smaller MP particles reduce adsorption efficiency.	[10]

Wastewater/ microplastic	Biochar	Model	Efficiency (%)	Q_e (mg/g)	Kinetic	Mechanism (optimum conditions)	Reference
Polystyrene (1 – 1000 nm)	Peanut shells	Upflow filter	16,47%	-	-	• Rough surface and high SSA improve MP retention. • Humic acid reduces adsorption efficiency. • Calcium ions reduce biochar efficiency compared to sodium ions.	[13]
	Magnatic peanut shells		40,96%	-	-		
Polystyrene (100 nm)	Lignin-modified preparation of	Batch	97.87	353.15	Second order:	• Nanoplastic adsorption strongly influenced by acidic conditions due to	[22]

Wastewater/ microplastic	Biochar	Model	Efficiency (%)	Q_e (mg/g)	Kinetic	Mechanism (optimum conditions)	Reference
	spontaneous magnetic sludge				k = 0.0666 – 0.0948 g/mg/min q = 155.55 – 168.93 mg/g (Temp: 288 – 308 K)	significant zeta potential changes. • Optimum adsorbent dosage: 0.6 g/L. Oxygen-rich functional groups facilitate hydrogen bonding with MPs. • Metal oxides in MBC also form metal-O-PS bonds.	

Table S4: Comparison between BC and another method to remove MP from aqueous environments.

Method	Microplastic	Efficiency (%)	Mechanism	Condition	References
Algal (*Chlorella Vulgaris*)	PS (65.49-328.40 µm)	73.01	Bio – coagulation	• pH: 7.5 • MP concentration: 789.37 mg/L • Time: 31.9 min • Biomass: 274.05 mg/L	[23]
Algal (*Spirulina platensis*)	PS (328.4 µm)	81	Bio – coagulation	• pH: 4 • MP concentration: 500 mg/L • Time: 30 min • Biomass: 250 mg/L	[24]
Activated jute stick charcoal	PVC (250 µm)	94.12	Adsorption	• MPs (5 g/L) • pH 7	[25]

				• Time = 120 min • q_{max} = 4.4668 mg/g • Dose = 10g/L	
*Abelmoschus esculentus (*Okra)	PVC (<85 µm)	80.11	Bio – coagulation	• Dose: 70 mg/L • pH 10 • MP concentration: 20 mg/L	[26]
	PS (<100 µm)	64.46		• Dose: 70 mg/L • pH 3 • MP concentration: 20 mg/L	
Electro-coagulation (Al electrode)	PE (286.7 µm)	93.2	• Adsorption by low degree of polymerization flocculant	• Electrolyte concentration: 0.05M • pH 7.2 • Voltage density = 10V	[27]
	PMMA (6.3 µm)	91.7			
	CA	98.2			

	(1–2 mm)		• MP captured and sweeped by high degree of polymerization flocculant	• Time: 6 h • MP concentration = 0.5 g/L	
	PP (1–2 mm)	98.4			
Electro-coagulation/ Electro-flocculation (Al anode -Fe cathode electrodes)	PE (150 µm) and PVC (250 µm)	100%	MP captured and sweeped by $Al(OH)_3$ and $Fe(OH)_2$	• pH 7 • Time: 20 min • Current density = 20 A/m^2	[28]
PVDF membrane Hydrophobic membrane 0.22 µm)		100%	Filter by pore size	• pH 7 • Pressure 2 bar	

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