A Micro-Nano Formulation of Multi-Micronutrients- and Carbon Nanofiber-Modified Biochar for Enhanced Plant Growth

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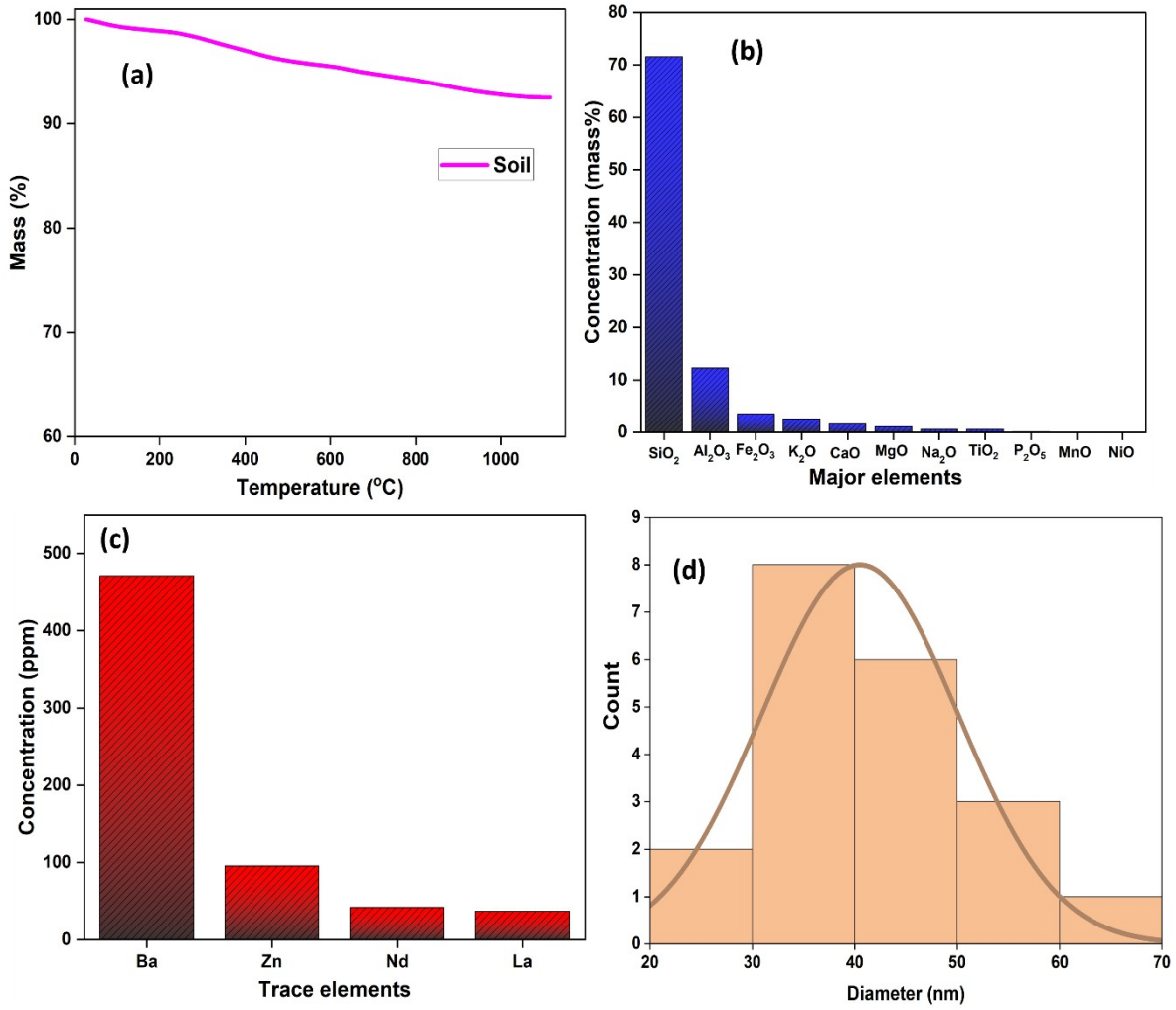

Fig. S1 (a) TGA; mass percent distribution of (b) major and (c) trace elements in soil, and (d) fibre dia of CNF.

The TGA spectra of the dried soil sample indicated a negligible weight-loss over 25 – 30 °C, confirming the complete removal of moisture from soil (Fig. S1a). X-ray fluorescence spectroscopy (WD-XRF, Rigaku, Japan) was used to analyse the elemental composition of the soil. The results indicated SiO_2, Al_2O_3, and Fe_2O_3 as major elements, with mass percentage of 71.57, 12.27, and 3.51%, respectively (Fig. S1b). The barium (Ba) and lanthanum (La) trace elements were also detected, with the concentrations of 471 and 37 ppm, respectively (Fig. S1c).

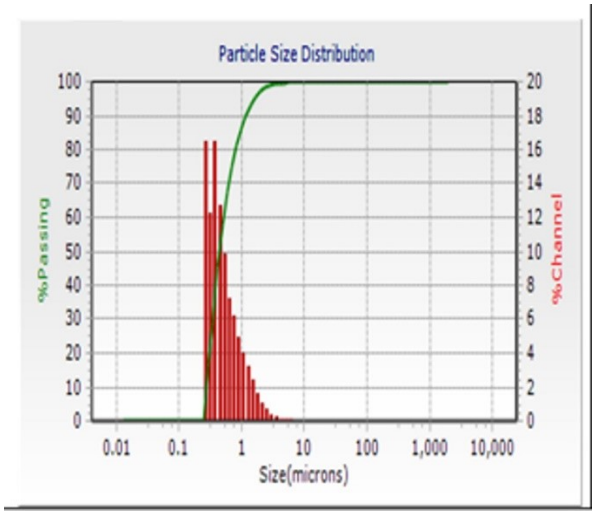

Fig. S2 Hydrodynamic particle size analysis of M_CNF/dolomite.

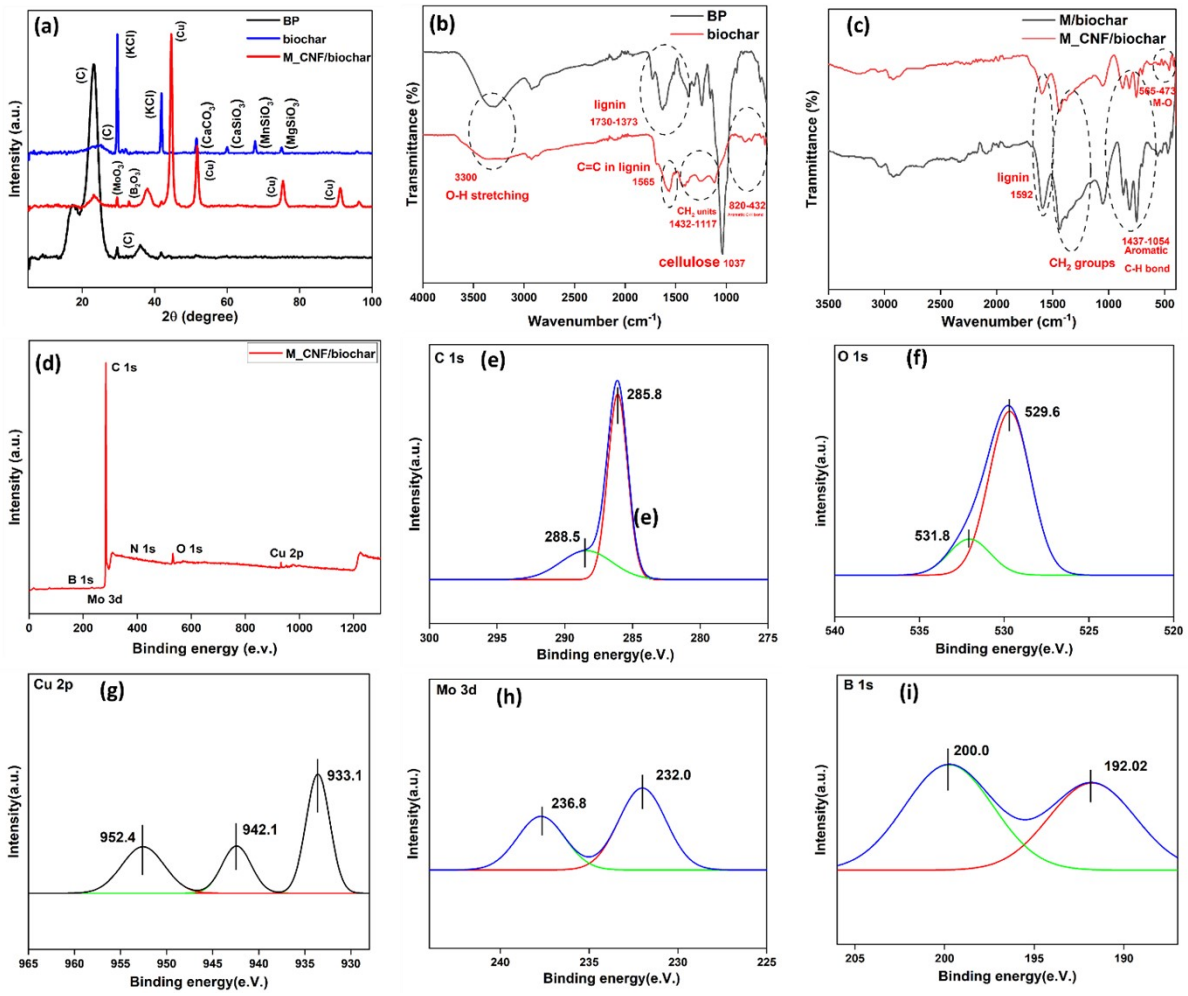

Fig. S3 (a) XRD spectra of bamboo powder (BP), biochar, and M_CNF/biochar; FTIR spectra of (b) BP and biochar, (c) M-biochar and M_CNF/biochar; (d) XPS survey scan of M_CNF/biochar, and (e-i) high resolution deconvoluted spectra of C 1s, O 1s, Cu 2p, Mo 3d, and B 1s of M_CNF/biochar.

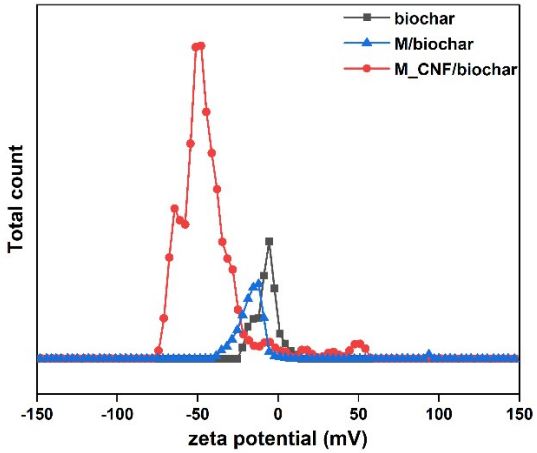

Fig. S4 Zeta potenatial of biochar, M/biochar, and M_CNF/biochar.

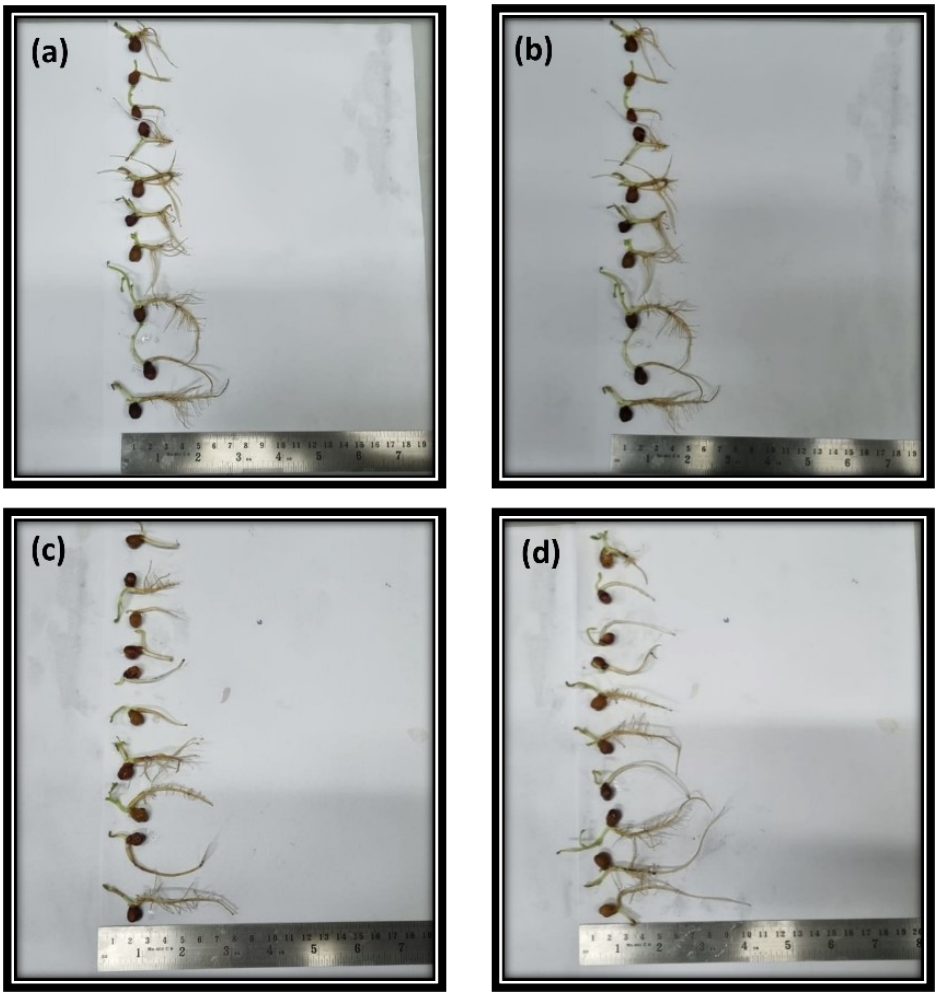

Fig. S5 Radicle growth of the germinated seed treated with (a) control, (b) biochar, (c) M/biochar, and (d) M_CNF/biochar.

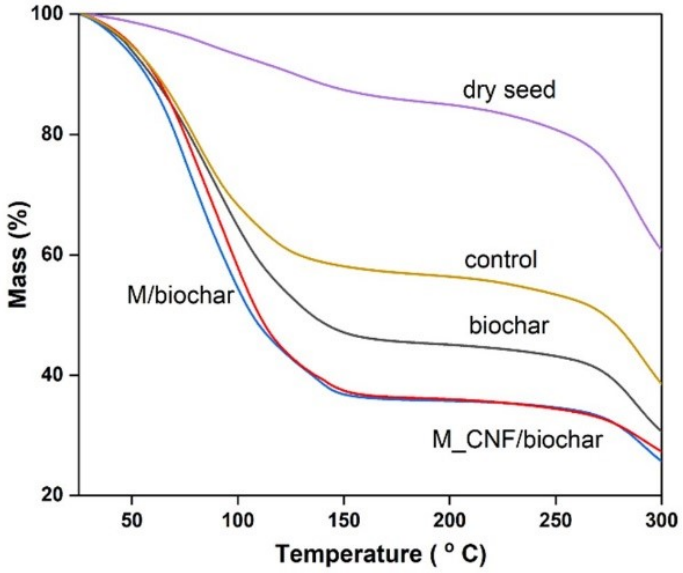

Fig. S6 TGA of seeds soaked with different treatments.

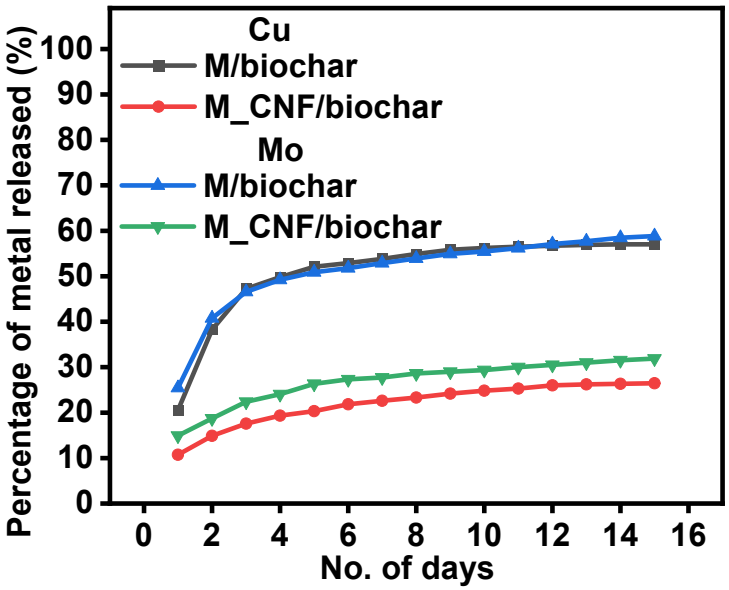

Fig. S7 Normalized metal release profiles of the M/biochar and M_CNF/biochar formulations for Cu and Mo, prepared with the initial concentrations of approximately 74.5 mg Cu and 7.9 mg Mo per g of the formulation.

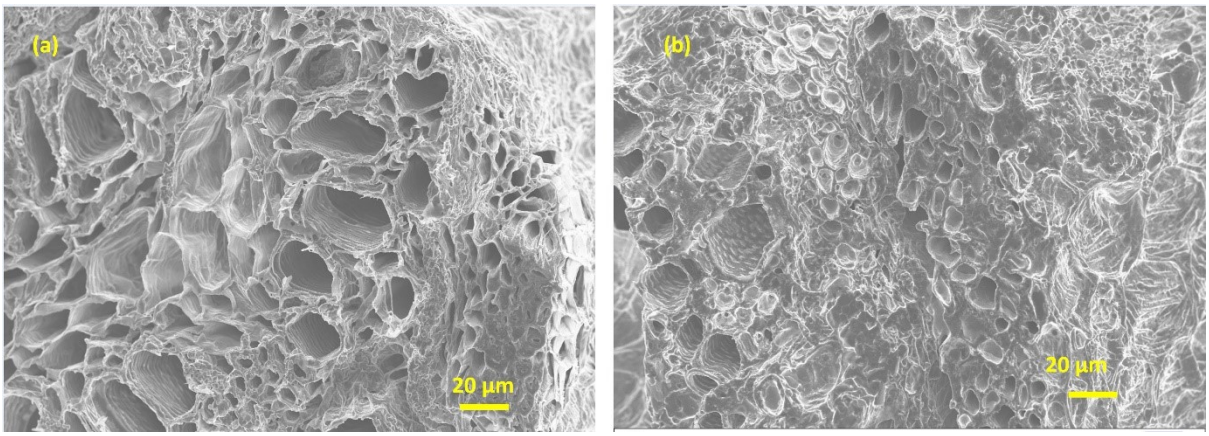

Fig. S8 SEM image of shoot of the plant treated with (a) biochar and (b) M/biochar.

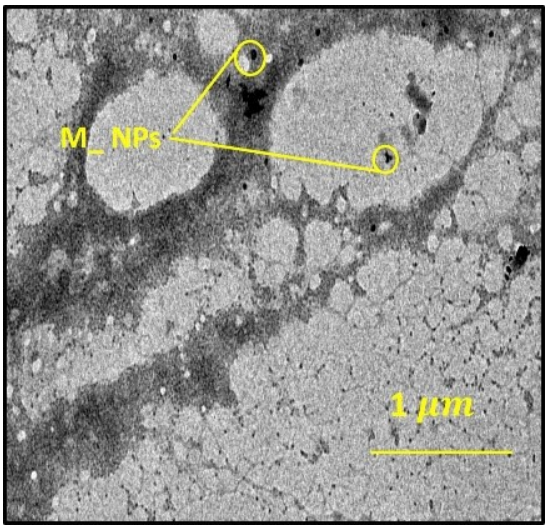

Fig. S9 TEM image of the leaf of the plant treated with M_CNF/biochar.

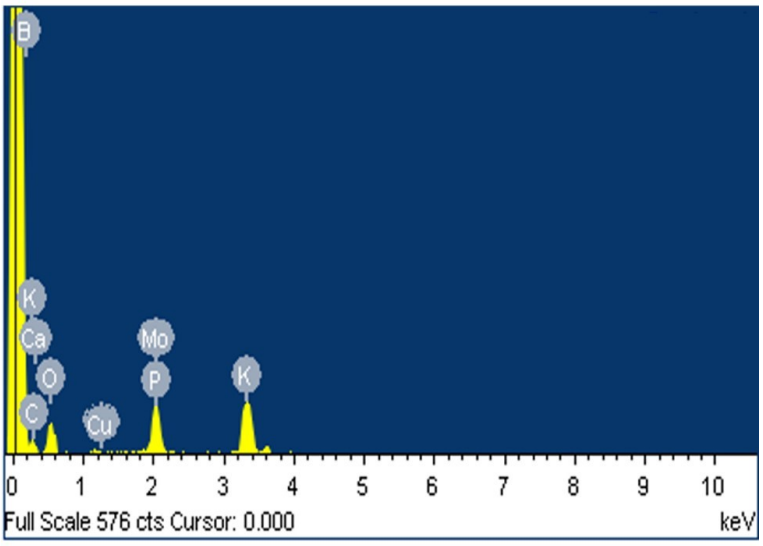

Fig. S10 SEM-EDS spectra of M_CNF/biochar indicating the inclusion of B in the materials.

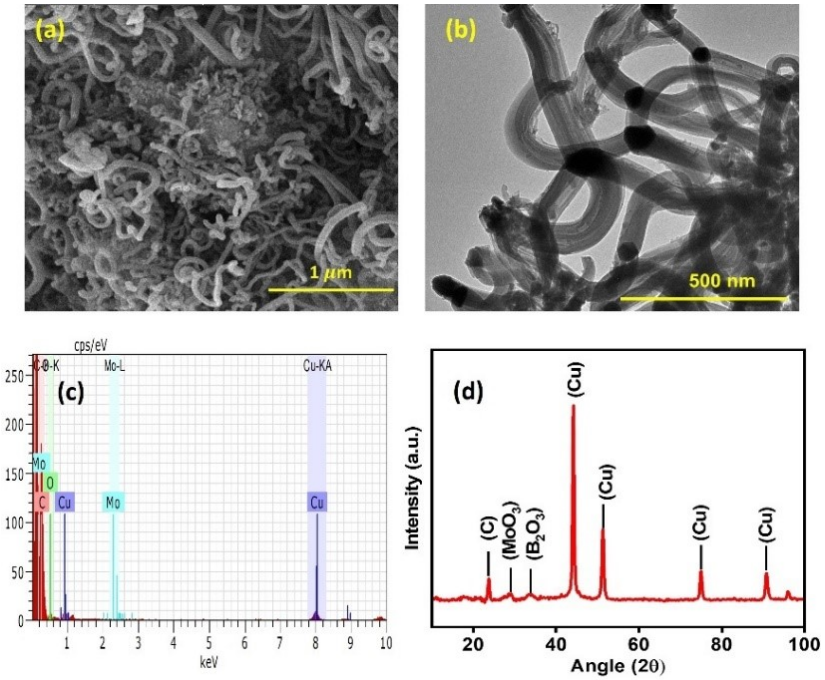

Fig. S11 (a) SEM, (b) TEM, (c) TEM-EDS, and XRD spectra of M_CNF/biochar after 2 months of storage.

Table S1: Composition of the precursors mixed with bamboo shoot powder, desired micronutrient content in the M_CNF/biochar formulation, and the corresponding threshold values for Cu, Mo, and B.

Desired micronutrient	Threshold value (mg/kg of soil)	Precursor compound	Amount of precursor taken (mg/ kg of soil)	Amount of desirable component (mg/kg of soil)	Reference
Cu	75	$Cu(NO_3)_2.3H_2O$	442.5	74.51	(24)
Mo	10	$(NH_4)_6Mo_7O_{24}$	18.44	7.87	(25)
B	2	H_3BO_3	0.50	0.66	(26)

Table S2: Surface charge values of the various CNF-based materials reported in the literature.

S.No.	Material	Surface charge (mV)	Reference
1	M_CNF/biochar	-47.7	This study
2	Cu-CNF	-17.5	(16)
3	Fe-CNF	-21.6	(29)
4	Cu-Zn-CNF	-25	(32)

Table S3 Comprehensive comparison of micro-nano biofertilizer performance across the conventional and nano-enabled formulations.

S. No.	Fertilizer	Name of crop/plant	Particle size (nm)	Micronutrients (MN) and translocator (TL)		Period of study (Days)	Plant growth parameters			Biochemical properties		Soil properties		Ref.
				MN	TL		Biomass content (g/plant)	Root length (R_L, cm)	Shoot length (S_L, cm)	Protein content ($\frac{mg}{g}$)	Chlorophyll content ($\frac{mg}{g}$)	Total N content ($\frac{mg}{kg}/\frac{kg}{hec}$)	Water holding capacity (mg/g)	
1	**M_CNF/biochar**	***Cicer arietinum***	**42**	**Cu, Mo, and B**	**CNF**	**30**	**20.4**	**7.5**	**29.7**	**10.8**	**1.9**	**148.18/ 326.0**	**1386.7**	**This study**
2	Magnesium ammonium phosphate/biochar	Cabbage	-	-	-	30	-	$R_L + S_L = 36$		-	-	33/72.6	-	(21)
3	Biochar/ urea	Sunflower	-	-	-	90	604.3 g/m^2	$R_L + S_L = 190$		-	-	-	-	(62)
4	Fe_3O_4/ urea	Rice	35-45	Fe	-	24	-	$R_L + S_L = \sim 32$		~130	0.9	-	-	(63)
5a	Mg-doped hydroxyapatite/ urea	Wheat	382	-	-	160	~9.8	$R_L + S_L = \sim 101$		-	-	~181.8/400	-	(64)
5b	Zn-doped hydroxyapatite/ urea	Wheat	473	Zn	-	160	~12.3	$R_L + S_L = \sim 98$		-	-	~204.5/450	-	(64)
6	CNT-MnO_2-Fe_3O_4	*Lactuca sativa*	-	Fe	CNT	40	~21.5	-		-	~0.485	-	-	(65)

7	Urea-MWCNTs	Paddy	-	-	MWCNT	110	~34	$R_L + S_L$ = ~ 570		-	-	-	-	(66)
8	ZnO-MWCNTs	Onion	4	Zn	-	10	~44	2.83	~7.1	-	-	-	-	(67)
9	MoO_3 NPs	Soyabean	47	Mo	-	70	~11.5	$R_L + S_L$ = ~45		-	-	~128/281.6	-	(68)
10	AHL/Fe-CNF	*Cicer arietinum*	10-100	Fe	CNF	30	~6.0	~9.5	~8.8	~5.3	~62 µg /L	-	-	(55)
11	Fe-CNF/Mo-MOF	*Cicer arietinum*	-	Fe and Mo	CNF	30	~2.8	~15	~13	~1.9	-	~97.7/215	-	(7)
12	Cu-CNF	*Cicer arietinum*	230	Cu	CNF	20	-	10.6	16.7	~ 6.2	~ 4	-	-	(16)

Abbreviations: CNF: Carbon nanofibers; CNT: Carbon nanotubes; MWCNT: Multi walled carbon nanotubes; NPs: Nanoparticles; AHL: Acylated homoserine lactones; MOF: Metal organic framework.