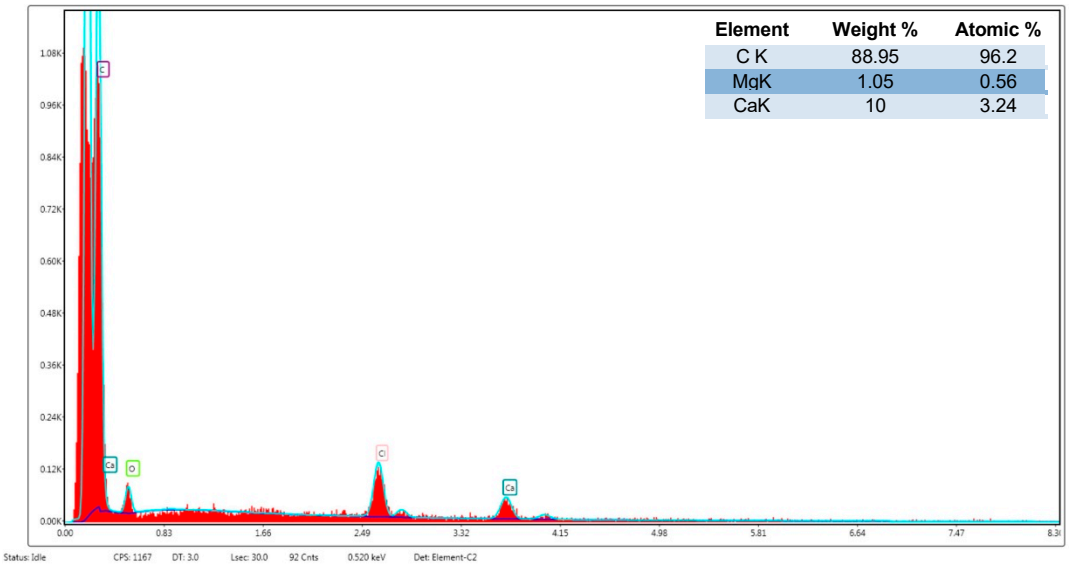
Supplementary Methods S1. Characterization of nanobiochar

Surface morphology and functional group characteristics of nanobiochar (NB) and nitrogen-modified nanobiochar (NB-AC3 and NB-AN3) were analyzed using Fourier transform infrared spectroscopy (FTIR) and scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM–EDX). FTIR spectra were recorded using a Magna-IR 750 spectrometer (Thermo Nicolet Co., USA). Surface morphology and elemental mapping were examined using a scanning electron microscope (S3400N, Hitachi, Japan) equipped with an EDX detector over a 10 × 10 mm^2 scan area.

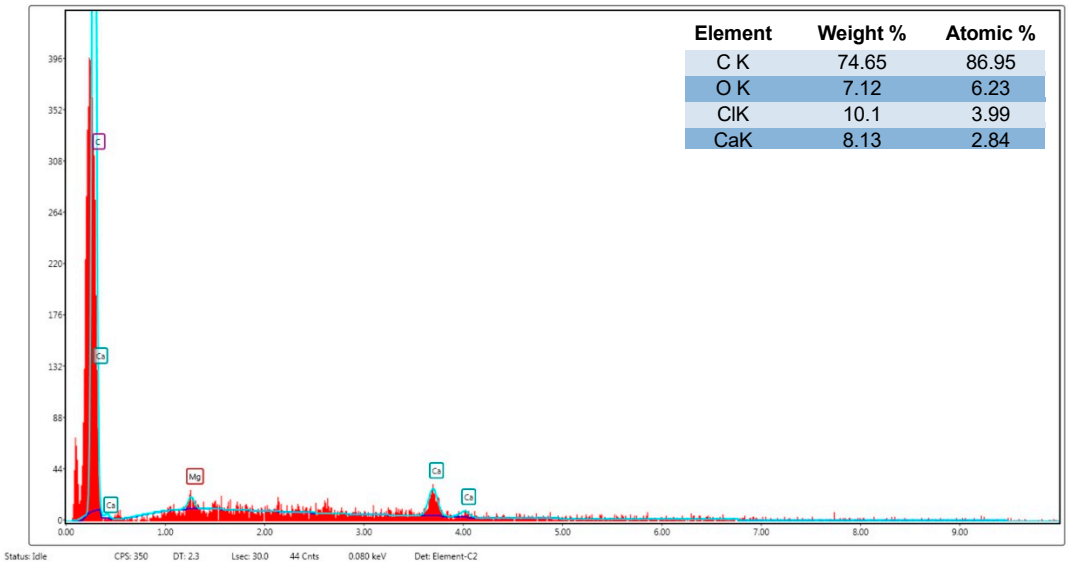
Particle size distribution of NB was determined in a previous study and ranged from 8.7 to 586 nm (Tayyab et al., 2025). The elemental composition of nanobiochar was previously characterized using a CHNS analyzer (Elementar, Vario Micro Cube, Germany) and ICP-OES (Agilent Technologies 5110-vdv). The nanobiochar consisted primarily of carbon (62.5%) and oxygen (28.8%), with minor contributions of hydrogen (1.92%), nitrogen (0.19%), and sulfur (0.15%). Inorganic mineral constituents included calcium (0.86%), sodium (0.49%), silicon (0.30%), phosphorus (0.27%), potassium (0.15%), iron (0.14%), and magnesium (0.10%), with trace amounts of aluminum, strontium, and chromium, as previously reported (Khaliq et al., 2023).

a



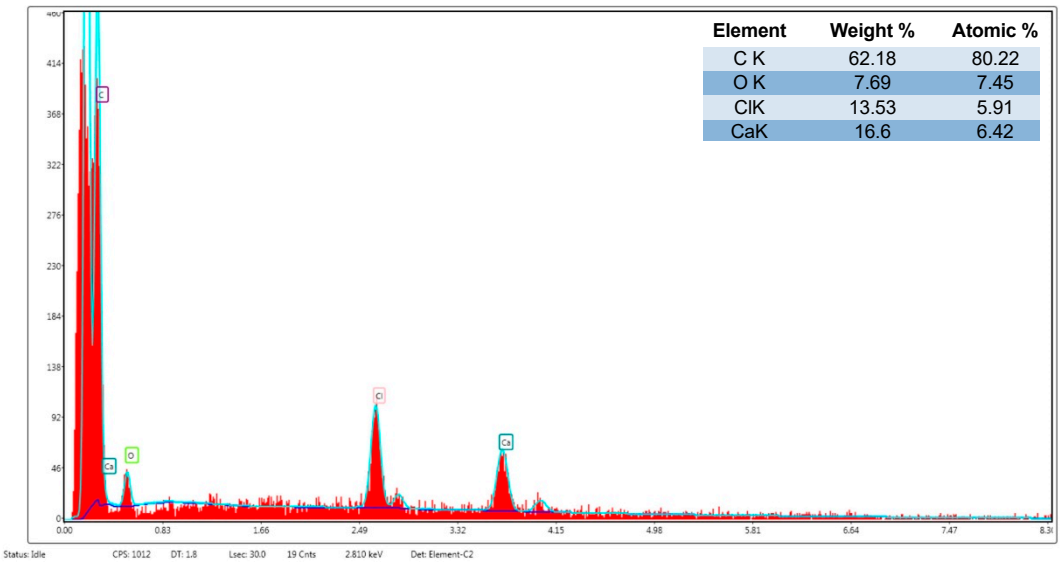
Element	Weight %	Atomic %
C K	88.95	96.2
MgK	1.05	0.56
CaK	10	3.24

b



Element	Weight %	Atomic %
C K	74.65	86.95
O K	7.12	6.23
ClK	10.1	3.99
CaK	8.13	2.84

c



Element	Weight %	Atomic %
C K	62.18	80.22
O K	7.69	7.45
ClK	13.53	5.91
CaK	16.6	6.42

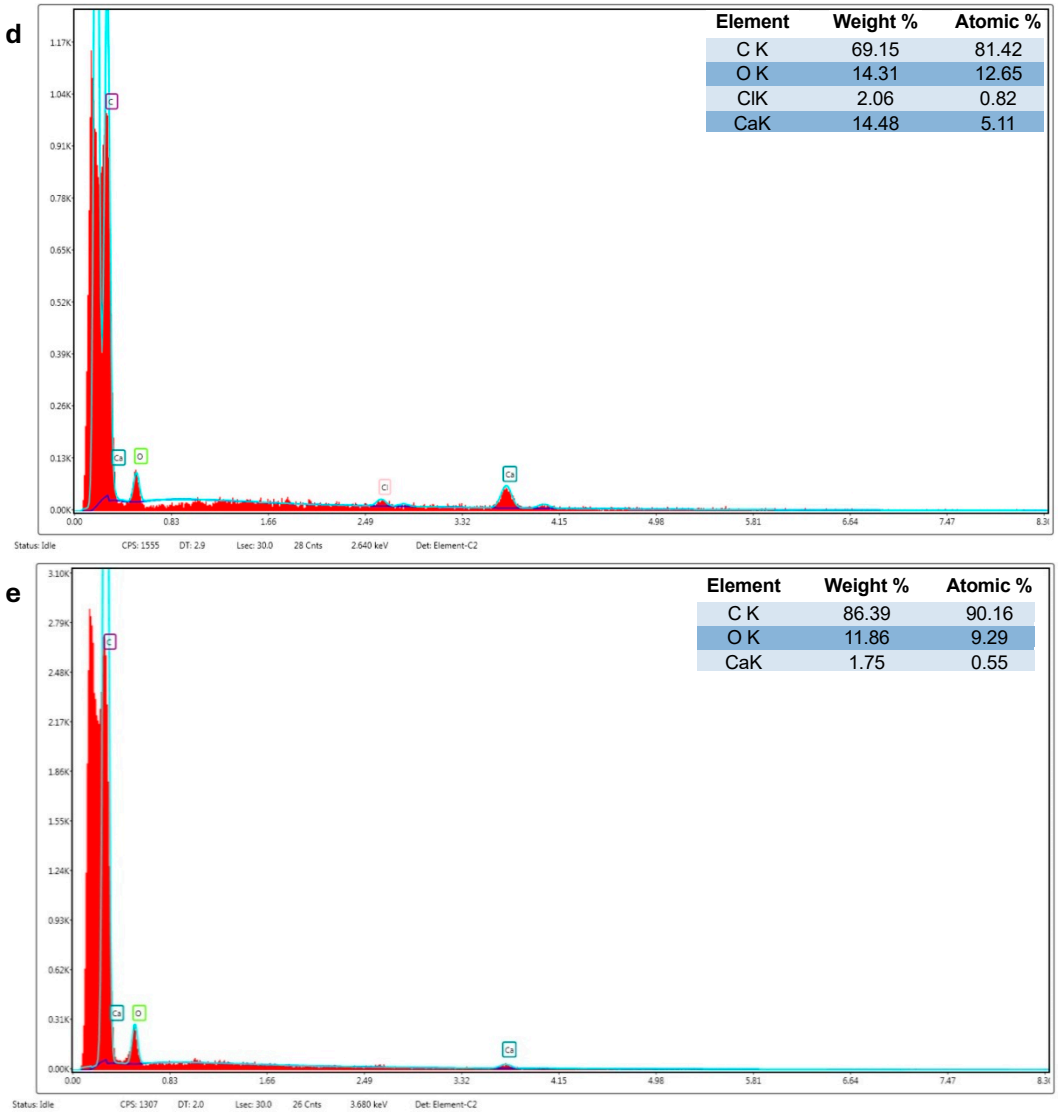


Figure S1. EDX spectra of **(a)** unmodified nanobiochar, **(b)** ammonium chloride-modified nanobiochar with 0.06g N g^{-1} of NB, **(c)** ammonium chloride-modified nanobiochar with 0.12 g N g^{-1} of NB, **(d)** ammonium nitrate-modified nanobiochar with 0.06 g N g^{-1} of NB, and **(e)** ammonium nitrate-modified nanobiochar with 0.12 g N g^{-1} of NB.

Table S1. Growth and biomass of spinach plants after 15 and 30 days of sowing following the application of nanobiochar and nitrogen-modified nanobiochar.

DAS (days)	Treatments	Shoot length (cm)	Root length (cm)	Shoot fresh weight (mg)	Root fresh weight (mg)
15	No-NB	$10.06^{c} \pm 0.18$	$3.31^{a} \pm 0.03$	$287.75^{b} \pm 2.31$	$10.30^{ab} \pm 0.01$
	NB	$12.13^{b} \pm 0.06$	$2.70^{a} \pm 0.09$	$424.5^{a} \pm 4.14$	$10.74^{ab} \pm 0.03$
	NB-AC1	$13.40^{ab} \pm 0.50$	$3.44^{a} \pm 0.01$	$413.7^{ab} \pm 2.29$	$11.21^{ab} \pm 0.10$
	NB-AC2	$12.12b^{c} \pm 0.03$	$3.18^{a} \pm 0.02$	$334.9^{ab} \pm 1.59$	$13.57^{a} \pm 0.01$
	NB-AC3	$14.29^{ab} \pm 0.06$	$2.99^{a} \pm 0.03$	$293.15^{ab} \pm 3.72$	$9.80^{ab} \pm 0.02$
	NB-AN1	$14.20^{ab} \pm 0.03$	$3.47^{a} \pm 0.02$	$258.25^{ab} \pm 1.51$	$7.85^{b} \pm 0.07$
	NB-AN2	$15.25^{a} \pm 0.06$	$3.69^{a} \pm 0.003$	$370.35^{ab} \pm 0.35$	$11.97^{ab} \pm 0.04$
	NB-AN3	$15.78^{a} \pm 0.02$	$4.24^{a} \pm 0.02$	$323.05^{ab} \pm 3.12$	$9.47^{ab} \pm 0.03$
	ANOVA (*F*-value)	10.0^{**}	1.28^{ns}	6.01^{*}	3.28^{*}
30	No-NB	$14.30^{de} \pm 0.08$	$6.61^{b} \pm 0.01$	$399.5^{d} \pm 2.96$	$12.42^{a} \pm 0.01$
	NB	$13.51^{e} \pm 0.02$	$6.40^{b} \pm 0.02$	$674^{bc} \pm 3.18$	$15.91^{a} \pm 0.04$
	NB-AC1	$18.29^{bc} \pm 0.03$	$7.28^{ab} \pm 0.01$	$652.25^{bc} \pm 6.69$	$15.82^{a} \pm 0.06$
	NB-AC2	$16.65^{cd} \pm 0.04$	$6.73^{ab} \pm 0.02$	$685^{bc} \pm 3.18$	$13.69^{a} \pm 0.02$
	NB-AC3	$17.89^{bc} \pm 0.44$	$6.1^{b} \pm 0.02$	$591.25^{c} \pm 9.21$	$15.14^{a} \pm 0.03$
	NB-AN1	$18.38^{bc} \pm 0.07$	$7.33^{ab} \pm 0.01$	$749.25^{bc} \pm 0.88$	$14.40^{a} \pm 0.04$
	NB-AN2	$19.66^{ab} \pm 1.10$	$7.30^{ab} \pm 0.04$	$825.5^{b} \pm 1.15$	$16.37^{a} \pm 0.03$
	NB-AN3	$21.96^{a} \pm 0.03$	$8.96^{a} \pm 0.06$	$1152^{a} \pm 1.76$	$15.44^{a} \pm 0.02$
	ANOVA (*F*-value)	28.7^{***}	3.22^{***}	27.9^{***}	2.28^{ns}

No-NB: no nanobiochar; NB: nanobiochar; NB-AC1, NB-AC2, and NB-AC3 indicate modification of nanobiochar with 0.03, 0.06, and 0.12 g N g^{-1} nanobiochar using ammonium chloride; NB-AN1, NB-AN2, and NB-AN3 indicate modification of nanobiochar with 0.03, 0.06, and 0.12 g N g^{-1} nanobiochar using ammonium nitrate. Each value is the average of 4 replicates ± standard error. Different letters on mean values indicate significant differences within a harvest at $p \leq 0.05$ by the Tukey HSD test.