

Table S1: Effect of different treatments on Soil pH, EC, SOC and CEC after wheat harvesting in 2024 and 2025.

Treatments	pH			EC (dS m ⁻¹)*			SOC (%)*			CEC (cmol kg ⁻¹)*		
	2024	2025	combine	2024	2025	combine	2024	2025	combine	2024	2025	combine
N. Fertilization												
N0	8.21±0.049b	8.19±0.047b	8.2±0.048b	6.41±0.303a	6.03±0.387a	6.22±0.342a	0.97±0.103d	0.98±0.15d	0.97±0.125d	34.35±2.15c	33.52±4.04b	33.94±2.99c
N1	8.28±0.101a	8.24±0.076a	8.26±0.088a	6.45±0.303a	6.13±0.42a	6.29±0.361a	1.06±0.09c	1.1±0.087c	1.08±0.088c	37.55±1.46b	37.86±1.36a	37.7±1.39b
N2	8.31±0.093a	8.26±0.062a	8.28±0.076a	6.48±0.306a	6.2±0.4a	6.34±0.351a	1.18±0.089b	1.23±0.094b	1.2±0.091b	37.98±1.46ab	38.17±1.62a	38.07±1.53ab
N3	8.31±0.093a	8.27±0.063a	8.29±0.078a	6.54±0.314a	6.27±0.406a	6.41±0.359a	1.32±0.112a	1.43±0.148a	1.38±0.13a	38.53±1.65a	39.19±1.95a	38.86±1.76a
Amendments												
C	8.18±0.038d	8.16±0.04d	8.17±0.037d	6.55±0.232c	6.28±0.327b	6.42±0.278c	1.01±0.132d	1.03±0.179d	1.02±0.154d	35.34±1.85c	34.38±3.87c	34.86±2.84d
S	8.24±0.033c	8.22±0.028c	8.23±0.03c	6.38±0.228bc	6.06±0.314ab	6.22±0.268bc	1.09±0.14c	1.14±0.165c	1.12±0.152c	36.02±2.18c	36.53±2.5b	36.27±2.28c
B	8.38±0.082a	8.31±0.055a	8.34±0.068a	6.75±0.242a	6.47±0.34a	6.61±0.289a	1.18±0.126b	1.25±0.161b	1.22±0.143b	37.79±1.42b	38.16±2.05a	37.98±1.72b
S+B	8.32±0.064b	8.27±0.043b	8.29±0.053b	6.19±0.228ab	5.82±0.354a	6±0.29ab	1.25±0.148a	1.31±0.197a	1.28±0.172a	39.25±1.62a	39.67±1.63a	39.46±1.58a
Interaction												
N0+C	8.14±0.031e	8.12±0.037f	8.13±0.033g	6.49±0.196a	6.18±0.335a	6.34±0.265a	0.84±0.037i	0.76±0.022j	0.8±0.019i	32.31±0.64e	27.83±1.41f	30.07±0.85g
N0+S	8.21±0.017e	8.2±0.014cdef	8.21±0.015efg	6.32±0.23a	5.9±0.296a	6.11±0.262a	0.93±0.068hi	0.95±0.116i	0.94±0.092h	32.77±1.98e	33.79±3.76e	33.28±2.86f
N0+B	8.25±0.034bcde	8.23±0.021cde	8.24±0.027cde	6.69±0.236a	6.29±0.289a	6.49±0.259a	1.04±0.016fgh	1.07±0.025ghi	1.06±0.019gh	35.64±0.43d	35.4±0.48de	35.52±0.45ef
N0+S+B	8.23±0.034de	8.2±0.021cdef	8.22±0.027ef	6.14±0.226a	5.73±0.342a	5.93±0.283a	1.08±0.012ef	1.11±0.017fghi	1.1±0.014fg	36.67±0.58d	37.08±0.57bcde	36.87±0.53de
N1+C	8.15±0.021e	8.14±0.025ef	8.15±0.023fg	6.51±0.233a	6.23±0.328a	6.37±0.28a	0.94±0.041ghi	0.99±0.037hi	0.97±0.039h	36.02±0.8d	36.32±0.47cde	36.17±0.63de
N1+S	8.23±0.039cde	8.22±0.034cde	8.23±0.036efg	6.38±0.233a	5.99±0.324a	6.19±0.278a	1.04±0.037fgh	1.05±0.031ghi	1.05±0.033gh	36.68±0.81d	37.3±0.63abcde	36.99±0.69de
N1+B	8.4±0.029a	8.32±0.029ab	8.36±0.029a	6.72±0.235a	6.48±0.343a	6.6±0.289a	1.11±0.017def	1.15±0.031efgh	1.13±0.023fg	37.99±0.4bcd	37.96±0.2abcd	37.98±0.21bcde
N1+S+B	8.33±0.04abcd	8.29±0.017abcd	8.31±0.029abcd	6.17±0.212a	5.8±0.338a	5.99±0.274a	1.17±0.021cdef	1.2±0.031cdefg	1.18±0.025def	39.48±0.03abc	39.85±0.29abc	39.67±0.16abc
N2+C	8.2±0.029e	8.19±0.017ef	8.2±0.007efg	6.57±0.233a	6.3±0.289a	6.44±0.26a	1.07±0.033efg	1.12±0.025fgh	1.09±0.029fg	36.38±0.35d	36.38±0.47cde	36.38±0.41de
N2+S	8.24±0.025bcde	8.22±0.021cde	8.23±0.023de	6.39±0.196a	6.15±0.285a	6.27±0.237a	1.13±0.037def	1.18±0.053defg	1.16±0.045efg	37.26±0.33cd	37.43±0.32abcde	37.35±0.31cde
N2+B	8.42±0.033a	8.33±0.033a	8.38±0.033a	6.76±0.24a	6.5±0.316a	6.63±0.278a	1.23±0.037cd	1.3±0.058cde	1.27±0.047cde	38.03±0.2bcd	38.26±0.74abcd	38.15±0.46bcd
N2+S+B	8.35±0.041abc	8.29±0.024abc	8.32±0.033abc	6.2±0.226a	5.84±0.373a	6.02±0.298a	1.28±0.033bc	1.32±0.025cd	1.3±0.029cd	40.23±0.33ab	40.59±0.21ab	40.41±0.06ab
N3+C	8.21±0.021e	8.19±0.012def	8.2±0.014efg	6.63±0.236a	6.41±0.306a	6.52±0.27a	1.18±0.022cde	1.24±0.025cdef	1.21±0.022cdef	36.64±0.4d	37.01±0.08bcde	36.83±0.23de
N3+S	8.25±0.033bcde	8.23±0.029bcde	8.24±0.031bcde	6.44±0.233a	6.2±0.253a	6.32±0.243a	1.29±0.037bc	1.36±0.029bc	1.32±0.033bc	37.35±0.01cd	37.58±0.5abcde	37.46±0.25cde
N3+B	8.43±0.037a	8.34±0.037a	8.39±0.037a	6.82±0.24a	6.59±0.339a	6.7±0.289a	1.36±0.045ab	1.48±0.037ab	1.42±0.041b	39.5±0.25abc	41.03±0.21ab	40.26±0.02ab
N3+S+B	8.35±0.034ab	8.29±0.021abc	8.32±0.027ab	6.26±0.23a	5.89±0.343a	6.08±0.286a	1.47±0.041a	1.63±0.029a	1.55±0.035a	40.64±0.62a	41.16±0.59a	40.9±0.12a

* Electrical conductivity (EC), Soil organic carbon (SOC), Cation exchange capacity (CEC). N0%: 0; N1: 50%; N2: 75%; N3: 100% of the recommended rate of 168 kg N ha⁻¹. C: no amendment; S: seaweed extract; B: biochar; S+B: biochar combined with seaweed extract. Bars represent mean ± standard deviation. Different letters indicate significant differences according to Tukey's test at P≤0.05.

Table S2: Effect of different treatments on Soil N, P, and K availability after wheat harvesting in 2024 and 2025.

Treatments	Ava N (mg kg ⁻¹)			Ava P (mg kg ⁻¹)			Ava K (mg kg ⁻¹)		
	2024	2025	combine	2024	2025	combine	2024	2025	combine
N. Fertilization									
N0	20.02±1.01d	18.5±0.63c	19.26±0.82c	6.68±0.27b	6.58±0.28b	6.63±0.27b	268.67±12.01d	263.52±15.36d	266.09±13.66d
N1	34.53±3.25c	33.55±5.09b	34.04±4.15b	7.62±0.47a	8.38±0.98a	8±0.71a	292.62±7.2c	296.47±9.65c	294.54±8.4c
N2	35.64±3.6b	35.61±5.06a	35.63±4.33a	7.7±0.47a	8.57±1.09a	8.14±0.76a	314.23±23.69b	325.08±20.41b	319.66±20.67b
N3	36.75±3.5a	36.43±5.19a	36.59±4.31a	7.95±0.53a	8.73±1.06a	8.34±0.78a	337.02±8.3a	330.36±19.71a	333.69±13.27a
Amendments									
C	28.24±5.42d	26.03±4.78d	27.14±5.09d	6.96±0.38b	7.21±0.66b	7.08±0.52b	290.85±26.77b	282.2±20.51c	286.52±22.78c
S	30.3±6.36c	29.11±6.81c	29.7±6.54c	7.3±0.51b	7.37±0.66b	7.33±0.56b	294.07±27.37b	302.04±35.43b	298.06±30.36b
B	32.89±7.11b	32.76±8.03b	32.82±7.57a	7.8±0.6a	8.69±1.16a	8.25±0.87a	312.3±26.56a	313.88±27.28a	313.09±26.89a
S+B	35.52±8.48a	36.21±10.01a	35.86±9.24a	7.9±0.63a	8.99±1.3a	8.45±0.95a	315.31±27.56a	317.31±28.18a	316.31±27.83a
Interaction									
N0+C	19±0.64h	17.84±0.4f	18.42±0.51g	6.39±0.21g	6.29±0.23f	6.34±0.22f	256.76±6.58d	248.64±6.58d	252.7±6.57e
N0+S	19.4±0.67h	18.12±0.5f	18.76±0.59g	6.52±0.14fg	6.4±0.14ef	6.46±0.14ef	259.18±6.2cd	249.61±6.32d	254.4±6.26e
N0+B	20.69±0.41h	18.99±0.16f	19.84±0.28g	6.86±0.11efg	6.81±0.06def	6.83±0.08def	279.17±4.21bc	277.75±3.9c	278.46±4.05d
N0+S+B	20.99±0.52h	19.06±0.16f	20.03±0.34g	6.93±0.11efg	6.83±0.04def	6.88±0.07def	279.55±4.2bc	278.09±3.86c	278.82±4.03d
N1+C	30.5±0.93g	28.21±0.91e	29.36±0.91f	7.05±0.13defg	7.38±0.4def	7.22±0.27def	287.16±3.15b	289.62±4.14bc	288.39±3.64cd
N1+S	32.76±0.58fg	29.23±0.14e	30.99±0.36f	7.39±0.13cdef	7.58±0.14de	7.48±0.03cdef	289.43±4.12b	291.62±3.55bc	290.53±3.82bcd
N1+B	36.09±0.56de	36.62±0.28cd	36.35±0.42de	7.99±0.24abcd	9.01±0.34abcd	8.5±0.29abc	295.05±7.13b	299.61±10.02bc	297.33±8.57bc
N1+S+B	38.79±0.91bc	40.13±1.73ab	39.46±1.31bc	8.07±0.29abc	9.56±0.4a	8.81±0.29ab	298.83±6.71b	305.01±9.43b	301.92±8.03cd
N2+C	30.94±0.26g	28.92±0.74e	29.93±0.5f	7.12±0.17defg	7.51±0.46def	7.31±0.31def	289.2±2.96b	291.99±3.92bc	290.59±3.44cd
N2+S	34.35±0.61ef	34.06±1.57d	34.21±1.09e	7.43±0.07cdef	7.66±0.44cd	7.54±0.2cde	293.4±5.2b	331.09±8.23a	312.25±6.38b
N2+B	36.48±0.62cde	36.74±0.39cd	36.61±0.5de	8.1±0.16ab	9.39±0.48ab	8.74±0.18ab	334.45±7.2a	336.04±6.89a	335.25±7.05a
N2+S+B	40.79±0.29ab	42.73±0.46a	41.76±0.38ab	8.17±0.21ab	9.73±0.43a	8.95±0.32ab	339.88±5.48a	341.19±5.06a	340.54±5.26a
N3+C	32.53±0.45fg	29.13±0.12e	30.83±0.28f	7.27±0.16defg	7.67±0.4de	7.47±0.28cdef	330.27±8.47a	298.55±7.92bc	314.41±8.15b
N3+S	34.67±0.59ef	35.01±1.58d	34.84±1.08e	7.84±0.31bcde	7.83±0.46bcd	7.84±0.36bcd	334.28±7.68a	335.84±7.58a	335.06±7.62a
N3+B	38.3±0.57cd	38.68±1.62bc	38.49±1.07cd	8.27±0.32a	9.57±0.37ab	8.92±0.34ab	340.54±4.29a	342.1±4.22a	341.32±4.25a
N3+S+B	41.51±1a	42.92±0.51a	42.22±0.76a	8.43±0.32a	9.85±0.36a	9.14±0.34a	343±5.06a	344.93±4.88a	343.96±4.97a

* N0%: 0; N1: 50%; N2: 75%; N3: 100% of the recommended rate of 168 kg N ha⁻¹. C: no amendment; S: seaweed extract; B: biochar; S+B: biochar combined with seaweed extract. Bars represent mean ± standard deviation. Different letters indicate significant differences according to Tukey's test at P ≤ 0.05.

Table S3: Effect of different treatments on Wheat traits and yield after harvesting in 2024 and 2025.

Treatments	Flag leaf area (cm ²)			Chlorophyll (mg g ⁻¹ f.w)			plant height (cm)			1000-grain weight (g)			Grain yield (kg ha ⁻¹)			Straw yield (kg ha ⁻¹)		
	2024	2025	combine	2024	2025	combine	2024	2025	combine	2024	2025	combine	2024	2025	combine	2024	2025	combine
N. Fertilization																		
N0	31.85±2.66d	28.85±2.52d	30.35±2.58d	25.17±2.16d	22.78±1.64d	23.97±1.9d	64.1±3.09d	61.35±2.41d	62.73±2.71d	36.03±2.89c	32.1±2.2d	34.07±2.58d	3995.67±117.31d	3766.75±59.31d	3881.21±87.28d	6775.46±129.1d	6409.2±173.57d	6592.33±145.47d
N1	45.42±2.97c	43.67±2.98c	44.54±2.95c	32±1.98c	29.65±1.82c	30.83±1.87c	87.16±3.48c	81.71±3.15c	84.44±3.31c	43.37±2.76c	41.5±3.6c	42.43±3.17c	6234.9±422.12c	5848.33±577.41c	6041.61±497.44c	9964.53±330.15c	9170.21±169.61c	9567.37±248.59c
N2	50.07±3.11b	50.58±4.44b	50.33±3.76b	36.09±2.67b	35.53±2.84b	35.81±2.74b	91.45±2.68b	91.3±3.97b	91.38±3.29b	44.44±2.87a	44.79±2.96b	44.62±2.89b	6632±311.7b	6559.75±422.16b	6595.88±362.33b	11311.2±573.35b	11023.13±662.84b	11167.17±607.9b
N3	51.91±2.49a	52.82±3.25a	52.37±2.86a	37.25±2.31a	36.71±2.66a	36.98±2.48a	92.66±2.46a	93.09±2.49a	92.88±2.47a	45.66±2.37a	46.75±2.75a	46.21±2.55a	6735.83±291.53a	6882.84±187.24a	6809.33±238.36a	11503.93±628.3a	11677.22±426.53a	11590.58±517.63a
Amendments																		
C	40.66±8.25d	39.3±9.03d	39.98±8.64d	29.46±4.98d	28.06±5.22d	28.76±5.1d	79.48±11.91d	77.24±12.31d	78.36±12.07d	38.07±4.12d	37.03±5.55d	37.55±4.8d	5504.51±985.88d	5393.78±1109.87d	5449.14±1040.01d	9269.79±1585.57d	9106.43±1894.65d	9188.11±1731.73d
S	44.55±7.12c	43.21±8.52c	43.88±7.81c	32.01±3.96c	30.6±4.85c	31.3±4.38c	83.79±11.58c	81.71±12.58c	82.75±12.03c	42.31±3.57c	40.66±5.3c	41.48±4.42c	5788.56±108.7c	5583.8±1146.98c	5686.18±1107.3c	9830.25±1877.93c	9405.98±1927.54c	9618.12±1893.11c
B	45.98±7.78b	45.37±9.92b	45.67±8.83b	33.67±4.97b	31.94±5.63b	32.81±5.29b	85.09±11.32b	83.55±12.58b	84.32±11.88b	43.88±3.32b	42.71±5.51b	43.29±4.4b	6060.26±120.21b	5893.73±1289.66b	5976.99±1241.49b	10062.46±200.688b	9740.1±2102.09b	9901.34±2049.04b
S+B	48.07±8.36a	48.04±10.14a	48.06±9.25a	35.37±5.12a	34.08±6.48a	34.72±5.8a	87.02±11.67a	84.97±13.1a	86±12.33a	45.24±4.05a	44.75±6.26a	45±5.15a	6245.06±120.235a	6186.36±1363.05a	6215.71±1287.33a	10392.62±2107.33a	10027.14±227.575a	10209.88±218.448a
Interaction																		
N0+C	27.39±0.09g	24.83±0.26i	26.11±0.18g	21.7±0.09j	20.04±0.08i	20.87±0.07j	59.48±0.5j	57.53±0.39k	58.51±0.45i	31.25±0.11i	28.48±0.23i	29.87±0.16i	3845.99±25.86i	3684.56±20.64k	3765.28±23.22i	6628.47±31.44i	6128.51±7.18j	6378.49±12.78i
N0+S	32.51±0.21f	29.24±0.28h	30.86±0.24f	25.45±0.06i	23.16±0.09k	24.31±0.07i	64±0.54i	61.18±0.15j	62.59±0.34h	36.25±0.14h	31.95±0.28h	34.1±0.2h	3960.16±27.49i	3770.93±21.67j	3865.55±20.64i	6716.24±31.8i	6411.86±7.52j	6564.05±12.82i
N0+B	33.15±0.12f	29.74±0.29h	31.42±0.2f	25.88±0.06i	23.56±0.09k	24.72±0.07i	65.69±0.78hi	63.05±0.38ij	64.37±0.57h	38.2±0.1g	33.67±0.18g	35.94±0.13gh	4011.45±16.75i	3770.93±21.67j	3891.19±18.7li	6788.48±31.29i	6510.59±7.67j	6649.54±11.81i
N0+S+B	34.33±0.11f	31.68±0.31g	33.01±0.19f	27.62±0.07hi	24.36±0.1lj	25.99±0.08hi	67.24±1.83h	63.65±0.41i	65.44±0.94h	38.43±0.1g	34.3±0.25g	36.37±0.17gh	4165.09±26.88h	3840.58±21.57i	4002.84±24.11h	6968.67±33.05h	6585.84±7.72i	6777.25±13.37h
N1+C	40.51±0.16e	39.25±0.37f	39.88±0.26e	28.77±0.14h	27.04±0.09i	27.9±0.08h	81.59±0.72g	76.71±0.58h	79.15±0.65g	38.83±0.13g	35.96±0.71f	37.4±0.42g	5688.37±43.15g	5193.16±25.07h	5440.77±33.8g	9446.94±44.27g	8923.17±3.69h	9185.06±22.79g
N1+S	46.08±0.31d	43.61±0.41e	44.84±0.35d	32.33±0.25d	29.42±0.19h	30.88±0.13g	87.57±0.78f	81.78±0.73g	84.68±0.75f	43.61±0.05ef	41.1±0.26e	42.36±0.16ef	6025.92±52.33f	5518.8±18.02g	5772.36±33.28f	9991.63±46.5f	9132.78±3.78g	9562.21±23.92fg
N1+B	46.75±0.16d	44.26±0.53e	45.51±0.3d	32.9±0.27fg	30.03±0.1h	31.47±0.16fg	89.15±1.11ef	83.48±0.4fg	86.32±0.73ef	44.97±0.17de	43.33±0.34d	44.15±0.23de	6415.58±39.66de	5947.66±3.63de	6181.62±21.45de	10067.89±19.05fg	9234.59±3.82g	9651.24±9.25fg
N1+S+B	48.36±0.2c	47.54±0.44d	47.95±0.32c	34.01±0.18ef	32.13±0.2f	33.07±0.09ef	90.35±0.8cdef	84.89±0.65f	87.62±0.72def	46.06±0.06bcd	45.61±0.38c	45.83±0.16bcd	6809.71±34.15bc	6733.7±32.31b	6771.71±30.41bc	10351.64±48.47ef	9390.29±3.88f	9870.96±24.92ef
N2+C	45.69±0.16d	44.26±0.51e	44.97±0.33d	32.57±0.12f	31.38±0.16g	31.98±0.13f	87.54±0.7f	84.94±0.53f	86.24±0.6ef	40.09±0.56f	40.89±0.48e	40.49±0.42f	6174.87±50.43e	6084.96±22.97f	6129.92±35.12e	10446.98±24.84de	10208.87±24.87ef	10327.92±24.81de
N2+S	49.6±0.22bc	49.46±0.58c	49.53±0.36bc	34.77±0.1de	34.76±0.18d	34.77±0.13de	91.13±0.68bcde	91.41±0.75de	91.27±0.68bcd	43.97±0.07de	43.74±0.08d	43.85±0.07de	6522.79±38.93de	6204.8±41.73cd	6363.79±40.3de	11220.87±50.31cd	10548.18±33.82d	10884.52±33.24cd
N2+B	50.59±0.17b	52.34±1.09b	51.47±0.63b	37.82±1.03bc	36.91±0.25c	37.36±0.62bc	92.43±0.32bcd	93.66±0.66abc	93.05±0.22abc	45.9±0.13bcd	45.54±0.24c	45.72±0.16bcd	6881.79±32.07ab	6892.69±14.86b	6887.24±23.35ab	11567.74±54.21b	11543.13±66.03c	11555.43±56.96b
N2+S+B	54.41±0.15a	56.27±0.58a	55.34±0.36a	39.2±0.84ab	39.06±0.23ab	39.13±0.52ab	94.72±0.76ab	95.2±0.71ab	94.96±0.71ab	47.81±0.13ab	49±0.42b	48.4±0.16ab	6948.56±7.06ab	7056.55±36.18ab	7002.56±21.36ab	12009.23±27.37ab	11792.35±25.25b	11900.79±5.33ab
N3+C	49.07±0.17f	48.87±0.36cd	48.97±0.26cd	34.81±0.12de	33.77±0.23e	34.29±0.16de	89.3±0.71def	89.76±0.73cde	89.53±0.69f	42.1±0.11ef	42.8±0.39d	42.45±0.25ef	6308.81±44.38cd	6612.43±34.12ef	6460.62±39.25cd	10556.79±49.47cd	11165.17±52.27e	10860.98±50.87d
N3+S	49.99±0.17e	50.56±0.52bc	50.27±0.34bc	35.47±0.13cd	35.05±0.17cd	35.26±0.13cd	92.47±0.66abc	92.47±0.66cd	92.47±0.66abc	45.42±0.05cd	45.83±0.26c	45.62±0.15cd	6645.38±52.21bc	6840.69±59.54c	6743.03±55.14c	11392.27±62.43bc	11531.1±14.67cd	11461.68±24.97bc
N3+B	53.41±0.14a	55.19±0.54a	54.3±0.34a	38.07±0.13b	37.26±0.19c	37.67±0.13b	93.07±0.6ab	94.02±0.69bc	93.55±0.61ab	46.44±0.2abc	48.3±0.17b	47.37±0.18abc	6932.24±5.01ab	6963.63±18.91ab	6947.94±11.8ab	11825.74±110.03ab	11672.53±15.84b	11749.14±60.45ab
N3+S+B	55.18±0.15a	56.67±0.58a	55.93±0.36a	40.63±0.11a	40.77±0.21a	40.74±0.12a	95.79±1.31a	96.13±1.31a	95.96±1.31a	48.68±0.1a	50.08±0.23a	49.38±0.15a	7056.88±55.38a	7114.61±5.74a	7085.75±30.5a	12240.94±65.51a	12340.09±39.3a	12290.51±30a

* N0%: 0; N1: 50%; N2: 75%; N3: 100% of the recommended rate of 168 kg N ha⁻¹. C: no amendment; S: seaweed extract; B: biochar; S+B: biochar combined with seaweed extract. Bars represent mean ± standard deviation. Different letters indicate significant differences according to Tukey's test at P ≤ 0.05.

Table S4: Effect of different treatments on total nutrient uptake by wheat plants after harvesting in 2024 and 2025.

Treatments	Total N uptake (kg ha-1)			Total P uptake (kg ha-1)			Total K uptake (kg ha-1)		
	2024	2025	combine	2024	2025	combine	2024	2025	combine
N. Fertilization									
N0	101.07±4.65d	92.69±3.56d	96.88±4.05d	22.97±1.11d	17.7±2.45d	20.34±1.73d	147.14±5.83d	117.49±7.18d	132.32±6.38d
N1	160.65±11.03c	152.17±13.55c	156.41±12.25c	37.86±2.96c	31.85±4.23c	34.86±3.57c	222.79±6.47c	198.02±18.7c	210.4±10.89c
N2	177.9±10.76b	178.34±12.77b	178.12±11.65b	42.5±2.57b	47.9±6.01b	45.2±4.2b	253.78±18.94b	271.19±24.94b	262.49±21.7b
N3	190.35±14.7a	199.67±13.54a	195.01±14.02a	46.16±3.17a	53.21±2.35a	49.68±2.68a	273.66±28.3a	290.62±18.04a	282.14±23.08a
Amendments									
C	142.92±29.1d	141.96±35.4d	142.44±32.11d	33.97±7.73d	32.42±13.53d	33.2±10.53d	203.74±37.96d	196.17±62.11d	199.96±49.15d
S	154.1±33.28c	150.22±38.05c	152.16±35.54c	36.45±8.53c	37.01±14.04c	36.73±11.12c	221.47±45.48c	211.31±64.61c	216.39±54.26c
B	162.84±36.68b	160.92±41.86b	161.88±39.2b	38.67±9.43b	39.28±14.21b	38.98±11.67b	229.85±53.17b	229.9±70.74b	229.88±61.8b
S+B	170.12±38.12a	169.77±45.55a	169.94±41.8a	40.41±9.64a	41.94±14.61a	41.17±12.02a	242.31±58.1a	239.94±75.98a	241.13±66.88a
Interaction									
N0+C	94.65±1.47k	87.26±1.13l	90.96±1.29i	21.47±0.27f	13.61±0.43j	17.54±0.35f	139.4±1.26h	106.04±2.27m	122.72±1.73h
N0+S	99.77±1.1jk	92.14±0.93kl	95.95±1hi	22.67±0.24f	18.17±0.5ij	20.42±0.36f	144.93±0.18h	117.75±1.14l	131.34±0.66h
N0+B	102.71±0.51ij	95.57±0.76k	99.14±0.61hi	23.29±0.18f	19.47±0.23hi	21.38±0.19f	148.96±0.48h	121.7±1.05kl	135.33±0.39h
N0+S+B	107.14±0.7i	95.77±0.73k	101.46±0.71h	24.47±0.18f	19.55±0.12h	22.01±0.14f	155.27±0.33h	124.47±0.9k	139.87±0.41h
N1+C	146.12±1.12h	136.3±0.98j	141.21±1.04g	33.92±0.38e	27.2±0.29g	30.56±0.32e	214.9±0.24g	173.92±2.42j	194.41±1.17g
N1+S	155.65±1.06g	144.87±0.7i	150.26±0.83g	36.53±0.36de	29.46±0.28f	33±0.31de	229.83±0.37fg	186.4±2.49i	208.12±1.12fg
N1+B	165.16±1.08ef	154.87±0.32h	160.01±0.69f	39.16±0.31de	32.26±0.26e	35.71±0.28de	217.97±0.33f	211.87±0.57h	214.92±0.4fg
N1+S+B	175.67±0.98d	172.66±0.98f	174.16±0.93d	41.83±0.28cd	38.47±0.25d	40.15±0.25cd	228.46±0.32f	219.88±0.63g	224.17±0.26ef
N2+C	162.2±1.97f	163.22±1.06g	162.71±1.47ef	38.86±0.39cd	38.91±0.35e	38.89±0.31cd	223.99±1.55d	236.95±3.21f	230.47±1.05def
N2+S	174.35±1.05d	168.65±1.19fg	171.5±1.11de	41.49±0.31bc	47.55±3.61d	44.52±1.72bc	252.52±0.49f	258.53±2.81cd	255.53±1.16cd
N2+B	185.04±0.86c	187.92±0.37d	186.48±0.6c	44.16±0.22ab	51.2±0.85c	47.68±0.5ab	263.83±0.69bc	290.49±0.85d	277.16±0.42bc
N2+S+B	190.02±0.28c	193.57±1.75cd	191.79±1.01c	45.49±0.21ab	53.95±1.44c	49.72±0.69ab	274.8±0.29ab	298.79±1.66ab	286.79±0.8ab
N3+C	168.71±1.79e	181.05±2.26e	174.88±2.02d	41.62±0.43abc	49.97±0.59d	45.8±0.51abc	236.67±0.5g	267.77±1.7d	252.22±0.66cde
N3+S	186.64±2c	195.23±4.51c	190.93±3.07c	45.11±0.7ab	52.86±0.54c	48.99±0.6ab	258.61±1.17d	282.56±1.33c	270.59±1.24bc
N3+B	198.43±0.89b	205.33±0.95b	201.88±0.82b	48.07±0.29ab	54.2±0.92b	51.14±0.45ab	288.65±3.09ab	295.54±1.82ab	292.09±2.33ab
N3+S+B	207.64±3.16a	217.08±2.27a	212.36±1.3a	49.84±0.67a	55.8±1.5a	52.82±0.53a	310.7±0.7a	316.63±2.44a	313.66±1.57a

* N0%: 0; N1: 50%; N2: 75%; N3: 100% of the recommended rate of 168 kg N ha-1. C: no amendment; S: seaweed extract; B: biochar; S+B: biochar combined with seaweed extract. Bars represent mean ± standard deviation. Different letters indicate significant differences according to Tukey's test at P ≤ 0.05.

Table S5: Effect of different treatments on nutrient use efficiency indices after harvesting in 2024 and 2025.

Treatments	RE (kg kg ⁻¹)			AE (kg kg ⁻¹)			PEP (kg kg ⁻¹)			PE (kg kg ⁻¹)			N Surplus (kg kg ⁻¹)			IE (kg kg ⁻¹)		
	2024	2025	combine	2024	2025	combine	2024	2025	combine	2024	2025	combine	2024	2025	combine	2024	2025	combine
N. Fertilization																		
N0	0	0	0	0	0	0	0	0	0	33.51	51.33	42.42	-101.07	-92.69	-96.88	106.70	109.86	108.28
N1	0.32	0.32	0.32	27.89	25.74	26.82	87.86	80.86	84.36	87.30	81.27	84.29	25.08	33.56	29.32	101.00	99.03	100.02
N2	0.28	0.31	0.29	24.75	26.23	25.49	64.40	63.11	63.76	89.85	85.32	87.59	100.70	100.26	100.48	100.93	98.67	99.80
N3	0.24	0.29	0.26	19.53	22.45	20.99	49.10	49.97	49.54	81.61	78.33	79.97	181.10	171.78	176.44	96.03	93.19	94.61
Amendments																		
C	0.180	0.197	0.189	16.09	16.97	16.53	47.03	45.59	46.31	66.97	64.51	65.74	66.03	66.99	66.51	104.19	103.52	103.85
S	0.201	0.209	0.205	17.75	17.32	17.53	49.82	47.12	48.47	76.06	81.23	78.65	54.84	58.73	56.78	102.09	101.29	101.69
B	0.222	0.237	0.229	18.83	18.96	18.89	51.69	49.52	50.61	73.58	74.13	73.85	46.11	48.02	47.07	99.80	98.62	99.21
S+B	0.234	0.273	0.254	19.51	21.17	20.34	52.83	51.71	52.27	75.68	76.38	76.03	38.83	39.18	39.00	98.59	97.32	97.95
Interaction																		
N0+C	0	0	0	0	0	0	0	0	0	0	0	0	-94.7	-87.3	-91.0	110.7	112.5	111.6
N0+S	0	0	0	0	0	0	0	0	0	39.92	76.33	58.13	-99.8	-92.1	-96.0	107.0	110.5	108.8
N0+B	0	0	0	0	0	0	0	0	0	41.01	56.69	48.85	-102.7	-95.6	-99.1	105.1	107.6	106.4
N0+S+B	0	0	0	0	0	0	0	0	0	53.10	72.32	62.71	-107.1	-95.8	-101.5	103.9	108.9	106.4
N1+C	0.277	0.264	0.271	25.09	23.17	24.13	83.05	76.00	79.53	90.56	87.75	89.16	39.61	49.43	44.52	103.59	103.57	103.58
N1+S	0.301	0.284	0.292	27.34	23.85	25.60	87.04	78.89	82.96	90.88	84.00	87.44	30.08	40.86	35.47	102.91	101.14	102.02
N1+B	0.336	0.319	0.328	28.66	25.36	27.01	90.05	81.74	85.90	85.23	79.43	82.33	20.57	30.86	25.72	99.81	98.03	98.92
N1+S+B	0.369	0.414	0.391	30.45	30.59	30.52	91.31	86.81	89.06	82.54	73.90	78.22	10.06	13.07	11.57	97.70	93.39	95.54
N2+C	0.242	0.273	0.258	22.07	23.26	22.66	59.66	58.48	59.07	91.00	85.33	88.17	116.40	115.38	115.89	102.49	99.83	101.16
N2+S	0.268	0.275	0.271	24.42	23.42	23.92	63.69	60.13	61.91	91.21	85.27	88.24	104.25	109.95	107.10	101.78	99.34	100.56
N2+B	0.296	0.331	0.313	26.07	28.40	27.24	66.22	66.17	66.20	88.23	85.67	86.95	93.56	90.68	92.12	99.71	98.11	98.91
N2+S+B	0.297	0.351	0.324	26.46	29.84	28.15	68.05	67.66	67.85	88.97	85.00	86.98	88.58	85.03	86.81	99.77	97.38	98.57
N3+C	0.199	0.252	0.226	17.21	21.44	19.32	45.40	47.86	46.63	86.30	84.94	85.62	202.74	190.40	196.57	99.98	98.21	99.09
N3+S	0.234	0.278	0.256	19.23	22.00	20.61	48.56	49.46	49.01	82.23	79.34	80.78	184.81	176.22	180.52	96.66	94.15	95.40
N3+B	0.258	0.295	0.277	20.57	22.08	21.33	50.50	50.17	50.34	79.83	74.73	77.28	173.02	166.12	169.57	94.53	90.76	92.65
N3+S+B	0.271	0.327	0.299	21.12	24.26	22.69	51.95	52.38	52.16	78.10	74.30	76.20	163.81	154.37	159.09	92.96	89.63	91.29

* Recovery efficiency (RE); agronomic efficiency (AE); partial factor productivity (PEP); physiological efficiency (PE); nitrogen surplus; internal efficiency (IE). N0%: 0; N1: 50%; N2: 75%; N3: 100% of the recommended rate of 168 kg N ha⁻¹. C: no amendment; S: seaweed extract; B: biochar; S+B: biochar combined with seaweed extract. Bars represent mean ± standard deviation.