



RESEARCH ARTICLE

Integrated use of weed-derived biochar and inorganic fertilisers enhances growth, physiology and yield of wheat under rainfed subtropical conditions

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Abstract

A field experiment was conducted during the rabi season of 2023–24 at the ACRA Research Farm, Jammu, to evaluate the potential of converting invasive weeds into biochar for improving wheat (*Triticum aestivum* L.) productivity under rainfed subtropical conditions. A total of 16 treatments including *Lantana camara* L. and *Adhatoda vasica* Nees biochar at 2, 4 and 6 t ha⁻¹ combined with 50 % or 100 % recommended dose of fertilisers (RDF), farmyard manure (FYM) treatments and an absolute control were evaluated in a randomized block design (RBD). Application of *L. camara* biochar at 6 t ha⁻¹ with 100 % RDF recorded the highest grain yield (4129.81 kg ha⁻¹), statistically at par with *A. vasica* biochar at 6 t ha⁻¹ with 100 % RDF (4081.95 kg ha⁻¹) and *Lantana* biochar at 6 t ha⁻¹ with 50 % RDF (4006.63 kg ha⁻¹). High-dose biochar treatments significantly improved plant height, tiller count, leaf area index, dry matter accumulation and SPAD chlorophyll values. Weed-derived biochar at 6 t ha⁻¹ is an effective strategy to manage invasive weeds while enhancing rainfed wheat yield, enabling a 50 % reduction in inorganic fertiliser use without yield penalty.

Keywords: *Adhatoda vasica*; biochar; integrated nutrient management; *Lantana camara*; rainfed wheat

Introduction

Wheat is one of the most important cereal crops globally, serving as a primary staple food for billions of people and providing essential nutrients including carbohydrates, proteins and micronutrients. Global wheat production in 2024–25 is estimated at approximately 787 to 792.9 million tonnes, grown across 220 million hectares, reflecting its critical role in ensuring global food security (1). India ranks as the second-largest wheat producer worldwide, with production projected to reach a record 115.3 million tonnes in 2024–25 (2). In the Union Territory of Jammu & Kashmir, wheat is a major rabi crop cultivated on approximately 0.28–0.30 million hectares with annual production around 0.49 million tonnes, yet productivity remains substantially lower than the national average at approximately 2357 kg ha⁻¹ compared to the national average of 3415 kg ha⁻¹, primarily due to small landholdings, limited input availability and the predominance of rainfed cultivation conditions (3).

Productivity constraints in rainfed wheat systems are multifaceted and interconnected (4). The rainfed subtropics of Jammu are characterised by coarse-textured soils with low organic carbon

reserves (5), poor water-holding capacity and inherently limited nutrient availability, making them highly susceptible to degradation (6). Excessive and imbalanced use of inorganic fertilisers without adequate organic inputs has further depleted soil health, reducing soil structure and aggregate stability while increasing nutrient losses, particularly nitrogen through leaching (4). These conditions severely limit nutrient-use efficiency and crop response to applied fertilisers, resulting in declining productivity and environmental concerns such as groundwater contamination and greenhouse gas emissions (7). Rainfall in rainfed systems is erratic and often insufficient, compounding the effects of poor soil fertility and exacerbating moisture stress during critical growth stages (8). Under such constraints, conventional approaches using mineral fertilisers alone are often inadequate for sustaining yields, necessitating integrated soil and nutrient management strategies that simultaneously improve soil physical, chemical and biological properties while enhancing nutrient availability and water retention (4).

Biochar, a stable, carbon-rich material produced through pyrolysis of biomass under oxygen-limited conditions, has emerged as a promising soil amendment with multiple beneficial properties (9). Recent literature demonstrates that biochar can significantly

enhance soil cation exchange capacity, water-holding capacity and aggregate stability, thereby improving nutrient retention and availability (10). Application of biochar has been shown to increase soil microbial activity and promote nutrient cycling, with reported improvements in nitrogen (N), phosphorus (P) and potassium (K) availability in the root zone (11). In wheat and other cereals, biochar combined with mineral nitrogen fertilisers has been reported to increase grain yield, nitrogen acquisition efficiency and protein content, particularly in degraded or low-fertility soils (12). However, biochar responses are highly variable and context-dependent, influenced by feedstock type, pyrolysis conditions, application rate, soil properties and climate; some studies have reported yield depressions when biochars with very high carbon-to-nitrogen ratios were applied without adequate nitrogen supplementation (13). Additionally, evidence from rainfed subtropical systems remains limited and the synergistic effects of biochar and graded fertiliser doses on wheat growth physiology and yield under farmers' field-like rainfed conditions have not been thoroughly investigated in the Jammu region (14).

A significant opportunity exists to utilise locally available problematic weeds as biochar feedstock (15). Invasive weeds such as *Lantana camara* L. and *Adhatoda vasica* Nees occupy vast areas of uncultivable wasteland across the region, creating a management challenge; however, these biomass sources could be converted into biochar through pyrolysis (16). Utilising weed-derived biochars not only addresses weed management but also creates an affordable, locally produced soil amendment that could improve wheat productivity in adjacent rainfed croplands (17). Despite the potential, information remains scarce regarding (i) the nutrient composition and agronomic efficacy of weed-derived biochars in the Jammu agroecosystem, (ii) the optimum biochar application rates and their interaction with graded doses of NPK fertilisers for wheat and (iii) the effects on integrated growth dynamics, physiological indicators (SPAD chlorophyll, chlorophyll concentration), biomass accumulation, yield components and grain yield under actual rainfed field conditions of Jammu.

Therefore, this study was undertaken to address these research gaps and generate actionable information for farmers and agronomists. The specific objectives were: (1) To evaluate the effect of different levels and sources of biochar, in combination with graded doses of inorganic fertilisers, on growth, physiological traits and biomass production of wheat under rainfed subtropics of Jammu; and (2) To assess the impact of integrated biochar and inorganic fertiliser application on yield attributes and grain yield of wheat and to identify the most effective biochar-fertiliser treatment for maximising productivity under rainfed conditions.

Materials and Methods

Experimental site and climate

The field experiment on wheat (*Triticum aestivum* L.) was conducted during the rabi season of 2023–24 at the Research Farm of the Advanced Centre for Rainfed Agriculture (ACRA), Rakh Dhiyansar, Bari Brahmana, Jammu. Wheat was sown on 29th November 2023 and harvested on 10th April 2024. During the crop season (SMW 44 of 2023 to SMW 15 of 2024), weekly rainfall ranged from 0.0 mm in several weeks to a maximum of 22.9 mm, indicating low and uneven precipitation typical of rainfed subtropical conditions. Weekly mean maximum temperature varied between 10.8 and 32.3 °C, whereas

minimum temperature ranged from 4.4 to 17.5 °C. Morning relative humidity remained high (69.1–95.3 %), while evening relative humidity fluctuated between 40.9 and 77.7 %. These weather conditions together indicate that the crop experienced a cool, relatively moist winter followed by warmer and comparatively drier conditions towards grain filling and maturity.

Soil characteristics

Before laying out the experiment, composite surface soil samples (0–15 cm) were collected from the experimental area and analysed for basic physico-chemical properties. The soil was sandy loam in texture (63.51 % sand, 19.24 % silt and 17.25 % clay) as determined by the hydrometer method and textural triangle (18). Soil pH and electrical conductivity were analysed by Jackson (19) (1:2.5 soil:water) and were 6.5 and 0.22 dS m⁻¹, respectively, indicating slightly acidic, non-saline conditions. Organic carbon was low (2.9 g kg⁻¹) as estimated by the Walkley and Black wet oxidation method (20). Available N, P and K were 154.5, 14.6 and 106.1 kg ha⁻¹, respectively, determined by alkaline KMnO₄ distillation (21), NaHCO₃ extraction (22) and neutral normal ammonium acetate extraction (23). Overall, the soil represented a low-fertility sandy loam typical of rainfed subtropics of Jammu.

Production and characterisation

Biochars were prepared separately from *L. camara* and *A. vasica* biomass using a modified barrel method under limited oxygen (slow pyrolysis). Air-dried, chopped biomass of each weed was loaded into the barrel and pyrolysed at a temperature range of 350–450 °C with a heating rate of approximately 5–10 °C min⁻¹. Charring was carried out for a duration of 2–3 hr until no visible smoke was produced, indicating complete charring under oxygen-limited conditions maintained by restricting air intake to the barrel. The biochars produced were allowed to cool, then crushed and sieved before characterisation and field application.

Lantana biochar had pH 7.80, bulk density 0.93 mg m⁻³, electrical conductivity 0.27 dS m⁻¹, organic carbon 0.79 %, fixed carbon 58.53 %, volatile matter 26.20 %, moisture content 8.23 %, ash 7.03 %, yield 41.87 % and contained 2.95 % total N (determined by Kjeldahl digestion method), 0.21 % P and 2.71 % K, with total carbon 79.13 % and oxygen 10.58 %. The relatively high N content in both biochars may be attributed to the high initial N content of the weed feedstocks and the formation of thermally stable N-heterocyclic structures (e.g., pyrrolic and pyridinic N) during slow pyrolysis, which resist volatilisation and are retained in the char matrix. *Adhatoda* biochar showed pH 8.15, bulk density 1.06 mg m⁻³, electrical conductivity 0.27 dS m⁻¹, organic carbon 0.84 %, fixed carbon 66.13 %, volatile matter 19.10 %, moisture content 8.97 %, ash 5.10 %, yield 52.90 % and contained 2.52 % total N (Kjeldahl method), 0.35 % P and 1.03 % K, with total C 83.97 % and O 8.65 %.

Experimental design and treatments

The experiment was laid out in a randomized block design (RBD) with 16 treatments and 3 replications, giving a total of 48 plots. The test crop was wheat variety JAUW 672, sown at an inter-row spacing of 22.5 cm. Each plot measured 6 m × 4 m.

Treatments consisted of different levels and sources of biochar, in combination with graded doses of inorganic fertilisers, along with FYM-based treatments and an absolute control (B₀). B₀: Absolute control; B₁: 100 % recommended dose of fertilisers (RDF); B₂: *L. camara* biochar (2 t ha⁻¹) + 50 % RDF; B₃: *L. camara* biochar (2 t

ha⁻¹) + 100 % RDF; B₄: *L. camara* biochar (4 t ha⁻¹) + 50 % RDF; B₅: *L. camara* biochar (4 t ha⁻¹) + 100 % RDF; B₆: *L. camara* biochar (6 t ha⁻¹) + 50 % RDF; B₇: *L. camara* biochar (6 t ha⁻¹) + 100 % RDF; B₈: *A. vasica* biochar (2 t ha⁻¹) + 50 % RDF; B₉: *A. vasica* biochar (2 t ha⁻¹) + 100 % RDF; B₁₀: *A. vasica* biochar (4 t ha⁻¹) + 50 % RDF; B₁₁: *A. vasica* biochar (4 t ha⁻¹) + 100 % RDF; B₁₂: *A. vasica* biochar (6 t ha⁻¹) + 50 % RDF; B₁₃: *A. vasica* biochar (6 t ha⁻¹) + 100 % RDF; B₁₄: FYM (25 % N) + 75 % RDF; B₁₅: FYM (50 % N) + 50 % RDF. The recommended fertiliser dose for wheat was applied as per state recommendations using urea, diammonium phosphate and muriate of potash as sources of N, P and K, respectively. In FYM treatments, the quantity of manure was calculated based on its N content and the remaining N requirement was met through urea.

Crop establishment and management

The experimental field was prepared by conventional tillage, including ploughing, harrowing and levelling. The required quantity of each biochar treatment was uniformly broadcast on the designated plots and incorporated into the top 0–15 cm soil layer about 15 days prior to sowing. Wheat seeds of JAUW 672 were sown in rows at the recommended seed rate using a seed-cum-fertiliser drill on 29th November 2023. Fertilisers were band-placed at sowing according to the treatment plan; full P and K and basal N were applied at sowing and remaining N in those treatments receiving split application was top-dressed at standard crop stages. The crop was grown entirely under rainfed conditions. Weed management, plant protection measures and other cultural operations were carried out uniformly across all treatments in accordance with local recommendations.

Observations

Crop growth observations were recorded at 30, 60, 90 and 120 days after sowing (DAS) and at harvest. Plant height (cm) was measured from the soil surface to the tip of the spike (excluding awns) on tagged plants and averaged. Number of tillers plant⁻¹ was counted on the same tagged plants at each stage. Leaf area index (LAI) was determined from measured leaf area of sampled plants using a leaf area meter and expressed as leaf area per unit ground area. Dry matter accumulation (g m⁻²) was estimated by destructive sampling from a fixed area within each plot, oven-drying the plant material to constant weight and converting to a square-meter basis. Physiological measurements were taken at 30, 60, 90 and 120 DAS on fully expanded leaves of representative plants in each plot. SPAD meter readings were used to measure chlorophyll status with a handheld SPAD meter and expressed in SPAD units. Chlorophyll

content (mg g⁻¹ fresh weight) was determined by extracting leaf tissue in 80 % acetone and measuring absorbance with a spectrophotometer; total chlorophyll was calculated using Arnon's method (24): Total Chl (mg g⁻¹) = 20.2(A₆₄₅) + 8.02(A₆₆₃) × (volume of acetone in mL / fresh weight in g).

At physiological maturity, yield attributing characters and grain yield were recorded. Spike length (cm) was measured from the base to the tip (excluding awns) of sampled spikes. Grains spike⁻¹ were counted after threshing the sampled spikes. Test weight (g) was recorded as the weight of 1000 sound, sun-dried grains from each plot. Grain yield (kg ha⁻¹) was obtained by harvesting the net plot area, threshing and cleaning the produce and converting the recorded grain weight to kilogram per hectare at standard grain moisture.

Statistical analysis

All recorded data were subjected to analysis of variance (ANOVA) appropriate for a RBD. Treatment means were compared using critical difference (CD) at 5 % probability level. Standard error of mean (SE_m±) and CD ($p = 0.05$) were computed to assess the significance of differences among treatments. Statistical analysis was carried out using the KAU GRAPES software package.

Results

Crop growth studies

Plant height

Plant height of wheat increased steadily with crop age and was markedly influenced by the integrated application of biochar and inorganic fertilisers (Table 1). At 30 DAS, treatment B₇ (*L. camara* biochar 6 t ha⁻¹ + 100 % RDF) recorded the tallest plants (24.58 cm), which was statistically at par with B₁₃ (*A. vasica* biochar 6 t ha⁻¹ + 100 % RDF, 24.25 cm) and B₆ (*L. camara* biochar 6 t ha⁻¹ + 50 % RDF, 23.84 cm), while the minimum height (11.13 cm) was observed in the absolute control B₀. At 60 DAS, B₇ again maintained the maximum plant height (38.83 cm), being at par with B₆ (38.40 cm) and B₁₃ (38.61 cm), whereas B₀ remained significantly shortest (23.20 cm). A similar trend was evident at 90 DAS, where B₇ produced the tallest plants (87.33 cm), closely followed and statistically similar with B₁₃ (86.72 cm) and B₆ (86.57 cm) and the lowest plant height was recorded under B₀ (57.75 cm). At 120 DAS, B₇ recorded the highest plant height (93.72 cm), at par with B₁₃ (93.00 cm) and B₆ (92.84 cm), while B₀ showed the minimum value (60.81 cm). At harvest, B₇ continued to be superior (96.63 cm), at par with B₁₃ (95.68 cm) and B₆ (95.31 cm),

Table 1. Plant height (cm) of wheat as influenced by integrated application of biochar and inorganic fertilisers in rainfed subtropics of Jammu

Treatment	30 DAS	60 DAS	90 DAS	120 DAS	At harvest
B ₀	11.13	23.20	57.75	60.81	61.28
B ₁	13.41	27.01	61.00	65.00	66.13
B ₂	15.71	29.22	70.27	74.48	75.73
B ₃	16.01	29.66	70.83	75.08	76.46
B ₄	18.40	32.47	75.51	80.71	82.32
B ₅	20.88	35.24	79.74	85.19	86.91
B ₆	23.84	38.40	86.57	92.84	95.31
B ₇	24.58	38.83	87.33	93.72	96.63
B ₈	15.45	28.81	69.53	73.72	74.94
B ₉	15.86	29.45	70.81	75.06	76.35
B ₁₀	18.22	32.37	75.25	80.19	81.76
B ₁₁	20.51	35.10	79.28	84.57	86.19
B ₁₂	21.59	35.34	80.55	86.12	88.58
B ₁₃	24.25	38.61	86.72	93.00	95.68
B ₁₄	21.13	35.27	80.32	85.82	88.04
B ₁₅	18.08	32.04	74.83	79.24	80.82
SE(m)±	0.63	0.95	2.29	2.34	2.32
C.D at 5 %	1.82	2.74	6.62	6.75	6.71

with B₀ (61.28 cm) producing the shortest plants.

Number of tillers

Number of tillers per plant was markedly influenced by different biochar and fertiliser treatments at all crop stages (Table 2). At 30 DAS, the maximum number of tillers was recorded with B₇ (3.93), which was statistically at par with B₆ (3.79) and B₁₃ (3.83), whereas the absolute control B₀ (1.67) produced the lowest number of tillers. At 60 DAS, B₇ registered the highest tiller number (11.10), being at par with B₆ (10.52) and B₁₃ (10.80), while B₀ (4.29) showed the minimum. At 90 DAS, B₇ (10.92) was statistically comparable with B₆ (10.46) and B₁₃ (10.68), with B₀ (4.11) the lowest. At 120 DAS, B₇ maintained superiority with 9.81 tillers per plant, at par with B₆ (9.20) and B₁₃ (9.67), while B₀ (2.57) remained significantly inferior throughout.

Dry matter accumulation

Dry matter accumulation in wheat increased consistently with advancing growth stages and differed significantly among the treatments at all observations (Table 3). At 30 DAS, the highest dry matter was recorded under B₇ (29.74 g m⁻²), at par with B₁₃ (29.09 g m⁻²) and B₆ (28.80 g m⁻²), whereas B₀ (16.00 g m⁻²) was lowest. At 60 DAS, B₇ registered the maximum (266.03 g m⁻²), at par with B₁₃ (258.04 g m⁻²) and B₆ (242.85 g m⁻²), with B₀ (108.29 g m⁻²) the minimum. A similar trend persisted at 90 DAS, where B₇ (688.32 g m⁻²) was at par with B₆ (673.73 g m⁻²) and B₁₃ (680.49 g m⁻²), with B₀ (432.44 g m⁻²) lowest. At 120 DAS, B₇ attained the maximum (1027.39 g m⁻²), at par with B₆ (1011.31 g m⁻²) and B₁₃ (1019.87 g m⁻²), with B₀ (593.02 g m⁻²) the minimum. At harvest, B₇ maintained superiority (1041.33 g m⁻²), at par with B₆

(1025.14 g m⁻²) and B₁₃ (1033.77 g m⁻²), while B₀ (595.30 g m⁻²) consistently remained lowest.

Leaf area index

Leaf area index of wheat increased up to 90 DAS and declined thereafter and was significantly influenced by the nutrient management treatments at all stages (Table 4). At 30 DAS, the highest LAI was recorded with B₇ (0.57), at par with B₆ (0.54) and B₁₃ (0.56), while B₀ (0.25) was lowest. At 60 DAS, B₇ (1.90) was at par with B₆ (1.84) and B₁₃ (1.87), with B₀ (1.01) the minimum. At 90 DAS, B₇ (3.63) was comparable with B₆ (3.58) and B₁₃ (3.60), with B₀ (2.21) lowest. At 120 DAS, B₇ (2.34) was at par with B₆ (2.17) and B₁₃ (2.22), while B₀ (0.68) consistently recorded the lowest LAI throughout.

Physiological studies

SPAD readings

SPAD chlorophyll meter readings of wheat increased up to 90 DAS and declined to 120 DAS and were significantly influenced by biochar and fertiliser treatments at all stages (Table 5). At 30 DAS, the highest SPAD value was recorded with B₇ (43.94 units), at par with B₆ (43.09 units) and B₁₃ (43.54 units), while B₀ (27.23 units) was lowest. At 60 DAS, B₇ (58.69 units) was at par with B₆ (57.74 units) and B₁₃ (58.01 units), with B₀ (38.11 units) the minimum. At 90 DAS, B₇ (50.78 units) was comparable with B₆ (50.17 units) and B₁₃ (50.40 units), with B₀ (28.23 units) lowest. At 120 DAS, B₇ (43.30 units) was at par with B₆ (42.35 units) and B₁₃ (42.88 units), while B₀ (24.12 units) consistently registered the lowest chlorophyll status.

Table 2. Number of tillers/plant of wheat as influenced by integrated application of biochar and inorganic fertilisers in rainfed subtropics of Jammu

Treatment	30 DAS	60 DAS	90 DAS	120 DAS
B ₀	1.67	4.29	4.11	2.57
B ₁	1.80	5.75	5.59	3.88
B ₂	2.19	7.10	6.99	5.01
B ₃	2.54	7.32	7.24	6.23
B ₄	2.73	8.87	8.83	7.06
B ₅	3.20	9.09	9.06	8.13
B ₆	3.79	10.52	10.46	9.20
B ₇	3.93	11.10	10.92	9.81
B ₈	2.12	6.83	6.74	4.77
B ₉	2.43	7.07	6.96	5.54
B ₁₀	2.67	8.55	8.52	6.80
B ₁₁	3.10	8.78	8.74	7.87
B ₁₂	3.46	9.83	9.74	8.72
B ₁₃	3.83	10.80	10.68	9.67
B ₁₄	3.31	9.62	9.57	8.49
B ₁₅	2.56	8.38	8.34	6.58
SE(m)±	0.09	0.28	0.27	0.24
C.D at 5 %	0.25	0.81	0.79	0.70

Table 3. Dry matter accumulation (g m⁻²) of wheat as influenced by integrated application of biochar and inorganic fertilisers in rainfed subtropics of Jammu

Treatment	30 DAS	60 DAS	90 DAS	120 DAS	At harvest
B ₀	16.00	108.29	432.44	593.02	595.30
B ₁	19.72	136.58	510.59	698.34	703.21
B ₂	21.43	158.96	573.08	795.33	800.16
B ₃	22.17	172.43	605.67	832.46	838.43
B ₄	24.68	202.36	649.08	908.34	915.19
B ₅	26.53	232.47	672.93	963.43	970.28
B ₆	28.80	242.85	673.73	1011.31	1025.14
B ₇	29.74	266.03	688.32	1027.39	1041.33
B ₈	21.15	155.34	565.08	783.46	788.29
B ₉	21.91	169.13	598.09	820.67	826.54
B ₁₀	24.42	199.01	641.18	896.73	903.58
B ₁₁	26.22	228.52	664.13	950.68	957.53
B ₁₂	27.44	235.67	666.54	991.23	1004.76
B ₁₃	29.09	258.04	680.49	1019.87	1033.77
B ₁₄	26.91	233.56	670.41	958.37	965.22
B ₁₅	24.21	194.23	635.29	873.52	880.37
SE(m)±	0.91	7.50	18.85	26.80	27.23
C.D at 5 %	2.64	21.67	54.46	77.42	78.67

Table 4. Leaf area index of wheat is influenced by integrated application of biochar and inorganic fertilisers in rainfed subtropics of Jammu

Treatment	30 DAS	60 DAS	90 DAS	120 DAS
B ₀	0.25	1.01	2.21	0.68
B ₁	0.29	1.23	2.56	0.97
B ₂	0.35	1.43	2.83	1.18
B ₃	0.38	1.50	2.94	1.28
B ₄	0.43	1.62	3.12	1.53
B ₅	0.49	1.73	3.39	1.89
B ₆	0.54	1.84	3.58	2.17
B ₇	0.57	1.90	3.63	2.34
B ₈	0.34	1.41	2.81	1.16
B ₉	0.37	1.47	2.90	1.24
B ₁₀	0.42	1.59	3.08	1.47
B ₁₁	0.48	1.70	3.32	1.81
B ₁₂	0.52	1.78	3.47	2.04
B ₁₃	0.56	1.87	3.60	2.22
B ₁₄	0.50	1.75	3.41	1.95
B ₁₅	0.41	1.56	3.03	1.42
SE(m)±	0.02	0.06	0.10	0.07
C.D at 5 %	0.05	0.17	0.29	0.20

Table 5. SPAD chlorophyll meter readings of wheat as influenced by integrated application of biochar and inorganic fertilisers in rainfed subtropics of Jammu

Treatment	30 DAS	60 DAS	90 DAS	120 DAS
B ₀	27.23	38.11	28.23	24.12
B ₁	29.52	43.21	33.44	28.90
B ₂	31.14	46.58	37.89	32.14
B ₃	32.07	47.31	38.67	33.22
B ₄	35.79	51.24	44.28	37.19
B ₅	38.93	54.17	47.62	39.98
B ₆	43.09	57.74	50.17	42.35
B ₇	43.94	58.69	50.78	43.30
B ₈	30.68	45.33	37.01	31.47
B ₉	31.55	46.84	38.01	32.67
B ₁₀	35.43	50.62	43.54	36.78
B ₁₁	38.44	53.21	46.78	39.31
B ₁₂	39.31	52.34	46.43	39.05
B ₁₃	43.54	58.01	50.40	42.88
B ₁₄	39.22	52.07	45.33	38.79
B ₁₅	33.49	46.87	40.09	33.98
SE(m)±	1.23	1.52	1.24	1.07
C.D at 5 %	3.55	4.40	3.58	3.08

Total chlorophyll content

Total chlorophyll content in wheat leaves increased up to 90 DAS and declined thereafter and it was significantly affected by the different biochar and fertiliser treatments at all stages (Table 6). At 30 DAS, the highest total chlorophyll (1.73 mg g⁻¹) was recorded under B₇, at par with B₆ (1.64 mg g⁻¹) and B₁₃ (1.69 mg g⁻¹), while B₀ (0.48 mg g⁻¹) was lowest. At 60 DAS, B₇ (1.99 mg g⁻¹) was at par with B₆ (1.89 mg g⁻¹) and B₁₃ (1.94 mg g⁻¹), with B₀ (0.64 mg g⁻¹) the minimum. At 90 DAS, B₇ (3.42 mg g⁻¹) was comparable with B₆ (3.15 mg g⁻¹) and B₁₃ (3.35 mg g⁻¹), while B₀ (0.83 mg g⁻¹) was lowest. At 120 DAS, B₇ (1.56 mg g⁻¹) was at par with B₆ (1.43 mg g⁻¹) and B₁₃ (1.49 mg g⁻¹), while B₀ (0.40 mg g⁻¹) consistently showed the lowest chlorophyll status.

Yield and yield attributes

Grain yield and yield attributes of wheat were markedly improved by the integrated application of biochar and inorganic fertilisers (Table 7). The highest grain yield was obtained with treatment B₇ (4129.81 kg ha⁻¹), which was statistically at par with B₁₃ (4081.95 kg ha⁻¹), B₆ (4006.63 kg ha⁻¹), B₁₂ (3852.45 kg ha⁻¹) and B₁₄ (3815.49 kg ha⁻¹), whereas the absolute control B₀ (1743.11 kg ha⁻¹) recorded the lowest grain yield. Test weight was maximum under B₇ (36.40 g), at par with B₆ (35.70 g) and B₁₃ (35.97 g), with B₀ (25.55 g) minimum. Number of grains per spike was highest in B₇ (34.47), at par with B₁₃ (33.06), B₆ (32.73), B₁₂ (30.13), B₁₄ (29.50), B₅ (29.21) and B₁₁ (28.65), while B₀ (20.11) was lowest. Spike length was maximum under B₇

(13.39 cm), at par with B₁₃ (13.20 cm), B₆ (13.01 cm), B₁₂ (12.99 cm), B₁₄ (12.70 cm), B₅ (12.52 cm) and B₁₁ (12.38 cm), whereas B₀ (7.77 cm) produced the shortest spikes.

Correlation analysis

Pearson's correlation analysis (Table 8) revealed highly significant positive relationships between growth parameters and grain yield (GY) in wheat. In the present study, * denotes significance at $p \leq 0.05$ (two-tailed) and ** denotes significance at $p \leq 0.01$ (two-tailed). Plant height (PH, $r = 0.919^{**}$), tillers (TIL, $r = 0.922^{**}$), dry matter accumulation (DMA, $r = 0.913^{**}$) and LAI (LAI, $r = 0.914^{**}$) showed strong highly significant positive correlations with GY. Physiological parameters including SPAD chlorophyll meter readings ($r = 0.861^{**}$) and total chlorophyll (CHL, $r = 0.908^{**}$) were also strongly and significantly correlated with final grain yield. Yield attributes-test weight (TW, $r = 0.809^{**}$), grains per spike (GPS, $r = 0.858^{**}$) and spike length (LOS, $r = 0.905^{**}$)-demonstrated excellent inter-correlations ($>0.8^{**}$) and strong positive relationships with GY. All yield attributes were highly inter-correlated, confirming their coordinated response to biochar-fertiliser integration.

Discussion

Integrated application of weed-derived biochar with inorganic fertilisers exerted a strong and coherent influence on wheat growth, physiology and yield under rainfed subtropics of Jammu (25, 26). Biochar from *L. camara* and *A. vasica* applied at 6 t ha⁻¹ together with

Table 6. Total chlorophyll content (mg g⁻¹) of wheat as influenced by integrated application of biochar and inorganic fertilisers in rainfed subtropics of Jammu

Treatment	30 DAS	60 DAS	90 DAS	120 DAS
B ₀	0.48	0.64	0.83	0.40
B ₁	0.66	0.82	1.13	0.59
B ₂	0.81	1.00	1.40	0.78
B ₃	0.90	1.08	1.46	0.82
B ₄	1.11	1.32	1.96	1.04
B ₅	1.28	1.58	2.54	1.24
B ₆	1.64	1.89	3.15	1.43
B ₇	1.73	1.99	3.42	1.56
B ₈	0.78	0.96	1.38	0.75
B ₉	0.86	1.03	1.42	0.80
B ₁₀	1.02	1.29	1.77	1.00
B ₁₁	1.28	1.53	2.17	1.21
B ₁₂	1.44	1.68	2.86	1.28
B ₁₃	1.69	1.94	3.35	1.49
B ₁₄	1.34	1.63	2.67	1.25
B ₁₅	1.02	1.26	1.73	0.98
SE(m)±	0.03	0.05	0.07	0.04
C.D at 5 %	0.08	0.13	0.19	0.10

Table 7. Yield attributes and grain yield (kg ha⁻¹) of wheat as influenced by integrated application of biochar and inorganic fertilisers in rainfed subtropics of Jammu

Treatment	Grain yield (kg ha ⁻¹)	Test weight (g)	Grains/spike	Spike length (cm)
B ₀	1743.11	25.55	20.11	7.77
B ₁	2261.62	28.10	22.01	8.23
B ₂	2687.38	28.38	22.89	9.61
B ₃	2939.87	29.01	25.12	10.47
B ₄	3470.96	30.57	26.07	11.33
B ₅	3711.96	32.28	29.21	12.52
B ₆	4006.63	35.70	32.73	13.01
B ₇	4129.81	36.40	34.47	13.39
B ₈	2663.38	28.21	22.67	9.26
B ₉	2795.63	28.69	23.16	9.91
B ₁₀	3430.80	29.75	25.78	11.15
B ₁₁	3500.81	30.82	28.65	12.38
B ₁₂	3852.45	32.89	30.13	12.99
B ₁₃	4081.95	35.97	33.06	13.20
B ₁₄	3815.49	32.68	29.50	12.70
B ₁₅	2965.63	29.55	25.37	10.95
SE(m)±	139.09	0.92	0.94	0.36
C.D at 5 %	401.71	2.67	2.70	1.05

Table 8. Pearson's correlation coefficients (r) among growth, physiological parameters and yield attributes of wheat as influenced by weed-derived biochar and fertiliser treatments.

	PH	TIL	DMA	SPAD	CHL	LAI	GY	TW	GPS	LOS
PH	1									
TIL	0.577**	1								
DMA	0.963**	0.501**	1							
SPAD	0.010	0.741**	-0.081	1						
CHL	0.386**	0.666**	0.203*	0.672**	1					
LAI	0.763**	0.784**	0.603**	0.405**	0.743**	1				
GY	0.919**	0.922**	0.913**	0.861**	0.908**	0.914**	1			
TW	0.883**	0.880**	0.868**	0.837**	0.906**	0.864**	0.809**	1		
GPS	0.915**	0.921**	0.910**	0.884**	0.942**	0.913**	0.858**	0.874**	1	
LOS	0.919**	0.926**	0.916**	0.830**	0.918**	0.907**	0.905**	0.845**	0.865**	1

PH: Plant height; TIL: No. of tillers plant⁻¹; DMA: Dry matter accumulation; SPAD: chlorophyll meter reading; CHL: Total chlorophyll; LAI: Leaf area index; GY: Grain yield; TW: Test weight; GPS: Grains per spike; LOS: Length of spike.

** Correlation is significant at 0.01 level (two-tailed).

* Correlation is significant at 0.05 level (two-tailed).

either 100 % RDF (B₇ and B₁₃) or 50 % RDF (B₆ and B₁₂) consistently outperformed mineral fertiliser alone (B₁) and the absolute control (B₀) across most traits, indicating a clear synergism between the carbonaceous amendment and applied nutrients. This synergy can be explained by improvements in soil physical, chemical and biological environments that directly support root growth, nutrient acquisition and canopy development. Biochar is rich in stable carbon and typically possesses high surface area, porosity and cation exchange capacity, which enhance retention of ammonium, potassium and other nutrient cations, reduce leaching losses and

buffer soil pH in coarse-textured rainfed soils (27). In addition, biochar provides microsites and energy sources for soil microorganisms, which can stimulate enzymatic processes such as dehydrogenase, urease and phosphatase activities, accelerating organic matter turnover and nutrient mineralisation (28). The resulting increase in plant-available nutrients and improved rooting conditions likely underpinned the superior vegetative growth observed under B₇, B₆ and B₁₃ (29). However, these mechanistic explanations are inferred from the existing literature on biochar effects; direct post-harvest soil data such as soil organic carbon,

available NPK, CEC, bulk density and microbial biomass were not measured in the present study and should be addressed in future work to substantiate these claims.

The pronounced increases in plant height, tiller number, leaf area index and dry matter accumulation under these treatments indicate that biochar-fertiliser combinations strongly influenced wheat morphology and canopy architecture (30). In B_7 and B_{13} , a more favourable root zone environment would have supported greater root length density and root surface area, enabling enhanced uptake of nitrogen, phosphorus and potassium from the fertilised soil (31). Adequate nitrogen is particularly crucial for synthesis of amino acids and structural proteins that drive cell division and elongation in growing stems; thus, improved N supply explains the taller plants and greater tillering capacity recorded under these treatments relative to B_1 and B_0 (32). Phosphorus availability from biochar-amended soil also contributes to ATP production and energy transfer within meristematic tissues, supporting rapid cell division at tiller buds and in leaf primordia (33). Potassium, retained on biochar surfaces, regulates stomatal function and turgor, maintaining cell expansion and thereby contributing to larger leaf blades and higher LAI (34).

Physiological parameters further support the view that weed-derived biochar improved the functional status of the wheat canopy (35, 36). Higher SPAD readings and total chlorophyll content recorded in B_7 , B_6 and B_{13} indicate sustained nitrogen assimilation into chlorophyll molecules and photosynthetic proteins. Nitrogen retained in the root zone by biochar-enhanced cation exchange capacity is more readily taken up by roots and assimilated into chlorophyll via glutamine synthetase and related enzymes in chloroplasts, enhancing light-harvesting capacity (37). Elevated chlorophyll levels, together with increased LAI, expand the effective photosynthetic surface area, thereby raising canopy photosynthesis and carbohydrate production (38). Biochar may also improve soil porosity and water-holding capacity, which could moderate fluctuations in soil water potential under intermittent rainfall; however, soil moisture data and water use efficiency measurements were not recorded in this study and the extent of such effects remains to be verified in future experiments (39).

These growth and physiological advantages were effectively translated into improved yield components and grain yield. Treatments with 6 t ha⁻¹ biochar in combination with 100 % or 50 % RDF produced longer spikes, more grains per spike and higher test weight than RDF alone or FYM-based treatments, showing that biochar improved both sink size and sink filling capacity (40–47). During spike initiation and floret differentiation, adequate nitrogen, phosphorus and water are essential to support high rates of cell division, hormone balance and carbohydrate supply in the developing spikelets (48). Enhanced root uptake of nutrients likely created a favourable hormonal and metabolic environment, minimising floret abortion and increasing the number of fertile florets (49). Later, during grain filling, high chlorophyll content would maintain photosynthesis and phloem loading, ensuring a continuous supply of assimilates to the grains, explaining the higher test weight in these treatments (50). The strong linear relationship between dry matter accumulation at later stages and grain yield suggests that total biomass and its efficient partitioning to ears were the principal determinants of yield under the rainfed conditions of this study (51).

Among all treatments, *L. camara* biochar at 6 t ha⁻¹ with 100 % RDF (B_7) produced the highest grain yield, closely followed by *A. vasica* biochar at 6 t ha⁻¹ with 100 % RDF (B_{13}) and *Lantana* biochar at 6 t ha⁻¹ with 50 % RDF (B_6). Grain yield in B_7 was more than double that of B_0 , highlighting the magnitude of response to integrated nutrient management (52). The comparable performance of B_6 and B_{13} with B_7 suggests that weed-derived biochars from both species are agronomically effective and that biochar can partially substitute for mineral fertilisers by improving nutrient-use efficiency (53). This is consistent with other reports that biochar application enhances nitrogen retention and uptake, reduces leaching and can maintain yields at reduced fertiliser rates in cereal systems (54). In contrast, lower biochar doses (2 and 4 t ha⁻¹) or FYM-based treatments, despite some improvement over the control, were unable to match the yield obtained with 6 t ha⁻¹ biochar, suggesting that a threshold level of carbon input is required to significantly modify soil physical and biochemical properties under the coarse-textured rainfed soils of Jammu (55).

The integrated responses of morphology, physiology and yield observed in this study underline the central role of the soil-plant-atmosphere continuum in determining wheat performance under rainfed subtropics. Weed-derived biochar likely improved soil structure and pore connectivity, facilitating root exploration and gas exchange, while its high carbon content provided energy and habitat for microbial communities that drive key enzymatic processes governing nutrient cycling (56). Thus, the superior performance of treatments B_7 , B_6 and B_{13} represents the combined outcome of improved soil biology, nutrient dynamics, plant morphology and physiological function (57). These findings demonstrate that converting problematic weeds such as *L. camara* and *A. vasica* into biochar and integrating them with recommended fertiliser doses is a biological and agronomically sound strategy to enhance wheat productivity and resource-use efficiency in rainfed subtropical environments (15).

Conclusion

A field experiment conducted during rabi 2023–24 at ACRA Research Farm, Jammu evaluated weed-derived biochars (*Lantana camara* and *Adhatoda vasica*) at 2, 4 and 6 t ha⁻¹ combined with 50 % and 100 % RDF on wheat (*Triticum aestivum* L. var. JAUW 672) under rainfed subtropical conditions. Randomized block design (16 treatments, 3 replications) showed 6 t ha⁻¹ biochar + 100 % RDF (*Lantana* B_7 : 4129.81 kg ha⁻¹; *Adhatoda* B_{13} : 4081.95 kg ha⁻¹) produced the highest grain yield, statistically at par with *Lantana* 6 t ha⁻¹ + 50 % RDF (B_6 : 4006.63 kg ha⁻¹), all significantly outperforming the absolute control (1743.11 kg ha⁻¹) and 100 % RDF alone. Growth parameters (plant height 96.63 cm, tillers 9.81 plant⁻¹, LAI 3.63, DMA 1041.33 g m⁻²), physiological traits (SPAD 58.69, chlorophyll 3.42 mg g⁻¹) and yield attributes (spike 13.39 cm, grains/spike 34.47, test weight 36.40 g) were superior under high-dose biochar treatments. Correlation analysis confirmed strong significant relationships between growth, physiology and yield ($r = 0.809^{**}$ – 0.922^{**}). *Lantana camara* and *A. vasica* biochars at 6 t ha⁻¹ with RDF significantly improved wheat growth, physiology and yield under rainfed Jammu subtropics. The 50 % RDF substitution (B_6) achieved comparable yield to full fertilisation, demonstrating biochar's potential to reduce inorganic fertiliser dependence. Converting invasive weeds to biochar represents a sustainable, cost-effective

strategy for rainfed wheat productivity and soil health restoration in coarse-textured, low-fertility soils of the Jammu subtropics.

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Authors' contributions

S contributed to conceptualisation, data curation, formal analysis, investigation, methodology, statistical analysis, writing of the original draft, and writing - review and editing. APS, NS and BS were involved in data curation, formal analysis, investigation, methodology and preparation of the original draft. AK, MS and AP contributed to data curation, formal analysis, investigation, methodology, statistical analysis and writing - review and editing. All authors read and approved the final manuscript.

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During the preparation of this work the authors used ChatGPT to improve readability and language of the work. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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