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Residual effect of carbon-equivalent organic supplements on leaf area index of wheat (*Triticum aestivum* L.)

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ABSTRACT

Leaf area index (LAI) governs radiation interception and dry-matter production in wheat and is highly sensitive to soil nutrient supply. A field experiment was conducted during the rabi seasons of 2023-24 and 2024-25 at the Agricultural Research Farm, Banaras Hindu University, Varanasi, to evaluate the residual effect of carbon-equivalent organic supplements on the LAI of wheat (*Triticum aestivum* L.) cv. HD 2967 in a rice-wheat cropping system. Eight treatments, viz. control, 100% recommended dose of fertilizer (RDF), and 2 Mg organic C ha⁻¹ through paddy straw biochar, bagasse biochar, sewage sludge, farmyard manure (FYM), decomposed crop residue and ex-situ green manuring, were evaluated in a randomized block design with three replications. LAI at 90 days after sowing (DAS) was significantly influenced by the treatments in both years. Bagasse biochar recorded the highest LAI (2.59 and 2.99 during 2023-24 and 2024-25, respectively), which was statistically at par with paddy straw biochar (2.58 and 2.96) and sewage sludge (2.54 and 2.94) in both years and with FYM (2.87) in the second year. Relative to the control (1.44 and 1.78), bagasse biochar increased LAI by 79.9% and 68.0%, and relative to 100% RDF (2.25 and 2.67) by 15.1% and 12.0%. Decomposed crop residue recorded the lowest LAI among the organic supplements and did not differ significantly from 100% RDF in 2024-25. LAI was higher in the second season under every treatment, with the largest seasonal gain in the control. The study concludes that biochar-based supplements, particularly bagasse biochar, and sewage sludge supplied on an equivalent carbon basis were the most effective in improving canopy development of wheat in the rice-wheat system.

Keywords: Bagasse biochar, Leaf area index, Organic carbon, Rice-wheat cropping system, Sewage sludge, Wheat

Introduction

Wheat (*Triticum aestivum* L.) grown after rice constitutes the rice-wheat cropping system, the principal food production system of the Indo-Gangetic Plains of India. Continuous intensive cultivation with predominantly mineral fertilization has led to declining soil organic carbon, imbalanced nutrient supply and stagnating or declining yields in several long-term rice-wheat experiments across Asia (Ladha *et al.*, 2003) [1]. Long-term studies in the region have shown that organic inputs such as FYM, green manure and crop residues sustain wheat productivity and improve soil fertility through their carry-over effects in the rice-wheat sequence (Yadvinder-Singh *et al.*, 2004; Urkurkar *et al.*, 2010) [3, 2]. The development of organic nutrient management strategies that restore soil carbon while sustaining crop growth has therefore become an important research priority.

Leaf area index (LAI), defined as the leaf area per unit ground area, is a key physiological indicator of crop growth (Watson, 1947) [4]. It determines the fraction of incident solar radiation intercepted by the canopy, and crop dry-matter production is closely proportional to the radiation intercepted (Monteith, 1977) [5]. In cereals, the fraction of radiation intercepted rises steeply as LAI increases towards about 3 (Gallagher *et al.*, 1978) [6]. Because leaf expansion is highly sensitive to the supply of nitrogen and other nutrients, LAI integrates the effects of soil fertility, nutrient availability and crop vigour before the final yield is formed, and thus provides an early and sensitive assessment of the response of wheat to nutrient management practices.

Organic manures such as FYM, green manure and crop residues supply macro- and micronutrients and improve soil physical, chemical and biological properties. Application of organic manures has been reported to increase dry-matter accumulation, LAI, photosynthetic pigments and yield of wheat (Nehra *et al.*, 2001) [7]. Sewage sludge is a nutrient-rich organic waste that can substitute part of the fertilizer requirement of crops, although its accumulation of heavy metals is a recognised constraint (Singh *et al.*, 2008) [8]. At Varanasi, one-time application of sewage sludge improved soil fertility, microbial population and enzyme activities under the rice-wheat system (Latere *et al.*, 2018) [9]. However, the effectiveness of these materials depends on their composition and decomposition behaviour. Crop residues with a wide C:N ratio may immobilize soil nitrogen during decomposition and temporarily reduce its availability to the following crop (Yadvinder-Singh *et al.*, 2005) [10].

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Biochar, the carbon-rich product of the pyrolysis of biomass under limited oxygen, has received considerable attention as a soil amendment because of its stable aromatic structure, high porosity and capacity to retain nutrients (Glaser *et al.*, 2002; Lehmann *et al.*, 2015) [11, 12]. Meta-analyses have shown that biochar increases crop productivity by about 10-11% on average, with considerable variation depending on soil type, climate and feedstock (Jeffery *et al.*, 2011; Liu *et al.*, 2013) [13, 14], and with larger responses in tropical than in temperate soils (Jeffery *et al.*, 2017) [15]. In wheat, biochar application has been reported to increase yield, particularly in combination with mineral fertilization (Alburquerque *et al.*, 2013) [16], and nitrogen-enriched biochar has been shown to increase crop growth rate and LAI, resulting in greater radiation interception and radiation use efficiency (Khan *et al.*, 2021) [17]. Crop residues such as paddy straw and sugarcane bagasse, which are otherwise burnt or underutilized, are abundant feedstocks for biochar production in India.

Most previous studies have compared organic sources on a nutrient-equivalent or fixed-mass basis, which confounds the effect of the source with the quantity of carbon added. Information on the relative effectiveness of biochars and conventional organic supplements applied on an equivalent organic-carbon basis, and on their residual influence on the canopy development of the succeeding wheat crop, remains limited, particularly under the conditions of the middle Indo-Gangetic Plains. Hence, the present study was undertaken to evaluate the residual effect of different organic supplements, applied at an equivalent rate of 2 Mg organic C ha⁻¹, on the leaf area index of wheat in a rice-wheat cropping system.

Materials and methods

A field experiment was carried out at the Agricultural Research Farm, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh, India, during the *rabi* seasons of 2023-24 and

2024-25. The site is situated at 25°16'17" N latitude and 82°57'25" E longitude, at an elevation of 74.6 m above mean sea level in the North-Gangetic Alluvial Plain. The climate is subtropical, with hot summers and cool winters, and the mean annual rainfall is about 1,122 mm, most of which is received from July to September. The soil of the experimental field was neutral to slightly alkaline in reaction (pH about 7.5), with a bulk density of 1.34 g cm⁻³ and a clay content of about 28%. The experiment was laid out in a randomized block design with eight treatments and three replications. The treatments were T₁, control (no fertilizer or organic supplement); T₂, 100% RDF; T₃, 2 Mg organic C ha⁻¹ through paddy straw converted biochar; T₄, 2 Mg organic C ha⁻¹ through bagasse converted biochar; T₅, 2 Mg organic C ha⁻¹ through sewage sludge obtained from the BHU sewage treatment plant; T₆, 2 Mg organic C ha⁻¹ through FYM; T₇, 2 Mg organic C ha⁻¹ through decomposed crop residue; and T₈, 2 Mg organic C ha⁻¹ through *ex-situ* green manuring on a dry-weight basis. The quantity of each organic supplement was calculated from its organic carbon content so that every organic treatment supplied an equal amount of organic carbon. The organic supplements were applied before transplanting of the preceding rice crop, and the wheat crop was grown on the residual effect of the supplements within the rice-wheat sequence. Wheat cultivar HD 2967 was sown on 13 December 2023 and harvested on 20 April 2024 in the first season, and sown on 13 November 2024 and harvested on 3 April 2025 in the second season, after the harvest of rice (cv. *Rajendra* Kasturi).

Leaf area index

LAI was determined at 90 days after sowing (DAS). Sample plants from a 0.5 m row length in each plot were uprooted, and leaves were separated and their area measured with a leaf area meter. LAI was calculated as the ratio of total leaf area to the ground area occupied by the plants (Watson, 1947) [4]:

$$LAI = \frac{\text{Total leaf area of plants (cm}^2\text{)}}{\text{Ground area occupied by the plants (cm}^2\text{)}}$$

The data were subjected to analysis of variance (ANOVA) for a randomized block design as described by Gomez and Gomez (1984) [18]. The significance of treatment effects was tested by the *F*-test at the 5% level of probability, and treatment means were compared using the critical difference (CD) at *p* = 0.05. The data of the two years were analysed separately.

Results and discussion

The leaf area index of wheat at 90 DAS was significantly influenced by the organic supplements in both years (Table 1, Fig. 1). All treatments recorded significantly higher LAI than the unamended control, which registered the lowest values of 1.44 and 1.78 during 2023-24 and 2024-25, respectively. Bagasse converted biochar (T₄) recorded the highest LAI of 2.59 and 2.99 in the first and second seasons, respectively. It was closely followed by paddy straw converted biochar (T₃; 2.58 and 2.96) and sewage sludge (T₅; 2.54 and 2.94), both of which were statistically at par with T₄ in both years. FYM (T₆) recorded LAI of 2.48 and 2.87; it was significantly lower than T₄ in 2023-24 but at par with it in 2024-25. *Ex-situ* green manuring (T₈;

2.45 and 2.82) and decomposed crop residue (T₇; 2.32 and 2.78) were significantly inferior to T₄ in both years.

Relative to the control, bagasse biochar increased LAI by 79.9% and 68.0% during 2023-24 and 2024-25, respectively, while the corresponding increases were 79.2% and 66.3% under paddy straw biochar, 76.4% and 65.2% under sewage sludge and 72.2% and 61.2% under FYM. Application of 100% RDF (T₂) increased LAI by 56.3% and 50.0% over the control. Bagasse biochar exceeded 100% RDF by 15.1% and 12.0%, and all organic supplements except decomposed crop residue recorded significantly higher LAI than 100% RDF in both years. Decomposed crop residue exceeded 100% RDF by only 3.1% and 4.1%, a difference that was not significant in 2024-25. Across treatments, the numerical ranking T₄ ≥ T₃ > T₅ > T₆ > T₇ > T₂ > T₁ was identical in both years.

The mean LAI across treatments increased from 2.33 in 2023-24 to 2.73 in 2024-25. The seasonal increase was greatest in the control (23.6%), followed by decomposed crop residue (19.8%) and 100% RDF (18.7%), whereas it was smaller (14.7-15.7%) under the biochars, sewage sludge, FYM and green manuring. As a result, the relative advantage of the organic supplements over the control was consistently larger in the first season than in the second.

Table 1. Effect of organic supplements on leaf area index (LAI) of wheat at 90 DAS

Treatment	LAI at 90 DAS		Increase over control (%)	
	2023-24	2024-25	2023-24	2024-25
T ₁ Control	1.44	1.78	-	-
T ₂ 100% RDF	2.25	2.67	56.3	50.0

(continued on next page)

Treatment		LAI at 90 DAS		Increase over control (%)	
		2023-24	2024-25	2023-24	2024-25
T ₃	2 Mg organic C ha ⁻¹ through paddy straw converted biochar	2.58	2.96	79.2	66.3
T ₄	2 Mg organic C ha ⁻¹ through bagasse converted biochar	2.59	2.99	79.9	68.0
T ₅	2 Mg organic C ha ⁻¹ through sewage sludge (BHU plant)	2.54	2.94	76.4	65.2
T ₆	2 Mg organic C ha ⁻¹ through farmyard manure	2.48	2.87	72.2	61.2
T ₇	2 Mg organic C ha ⁻¹ through decomposed crop residue	2.32	2.78	61.1	56.2
T ₈	2 Mg organic C ha ⁻¹ through <i>ex-situ</i> green manuring (dry-weight basis)	2.45	2.82	70.1	58.4
SEm±		0.02	0.04	-	-
CD (<i>p</i> = 0.05)		0.07	0.12	-	-

RDF, recommended dose of fertilizer; DAS, days after sowing; SEm, standard error of mean; CD, critical difference.

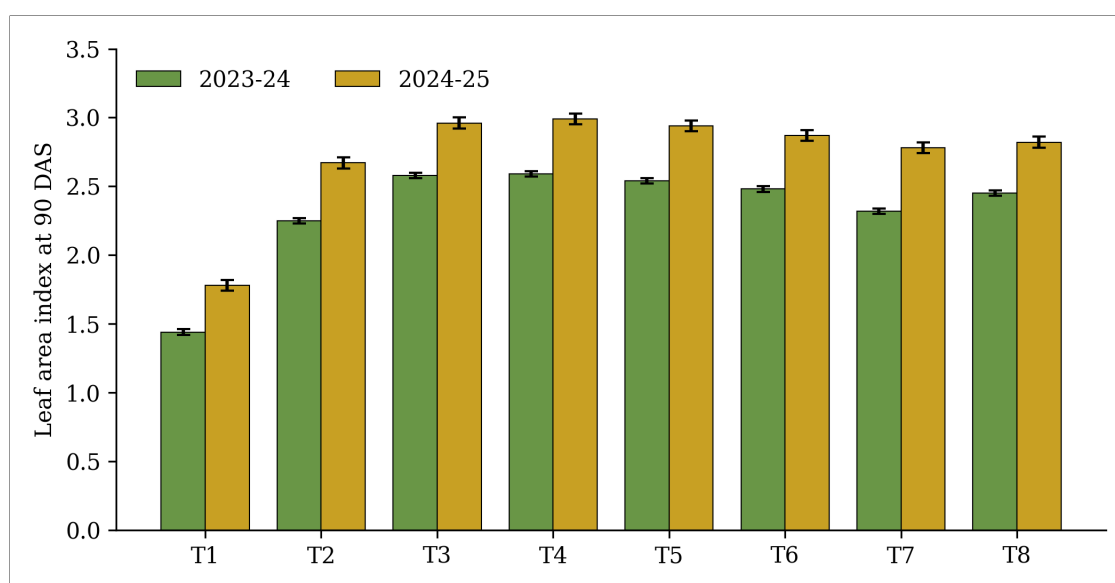


Figure 1. Leaf area index of wheat at 90 DAS under different organic supplements during 2023-24 and 2024-25 (error bars represent SEm±; treatment details as in Table 1)

The large response of LAI to all nutrient treatments over the control reflects the strong dependence of leaf expansion in wheat on nutrient supply, particularly nitrogen. Under the control, LAI remained below 2 in both seasons, indicating a canopy that could intercept only part of the incident radiation. In cereals, the fraction of radiation intercepted rises steeply until LAI approaches about 3 (Gallagher *et al.*, 1978) [6], and dry-matter production is proportional to the radiation intercepted (Monteith, 1977) [5]. The organic supplements raised LAI to between 2.3 and 3.0, the range within which the canopy captures most incident radiation. The increase in LAI under the treatments is therefore of direct agronomic significance, because it would be expected to translate into greater radiation interception, crop growth rate and biomass. A similar sequence from improved canopy development to higher radiation interception, radiation use efficiency and yield has been reported for wheat receiving nitrogen-enriched biochar (Khan *et al.*, 2021) [17]. The superior LAI under bagasse and paddy straw biochar is notable because the biochars were not applied directly to the wheat crop, and the effect observed is therefore a residual one. Biochar itself contains little readily mineralizable nitrogen, and its effect on leaf expansion is more plausibly related to improved retention and availability of nutrients in the root zone. Oxidized functional groups on biochar surfaces increase the cation exchange capacity of soil (Liang *et al.*, 2006) [19], and these surfaces continue to oxidize and acquire charge as biochar ages in soil (Cheng *et al.*, 2008) [20], which would strengthen nutrient retention over successive crops. Biochar has also been shown to re-

duce nitrate leaching (Haider *et al.*, 2017) [21] and to favour soil microbial activity and root-associated biota (Lehmann *et al.*, 2011) [22]. Residual effects of biochar on the growth and physiology of a subsequent wheat crop have been reported earlier (Akhtar *et al.*, 2015) [23]. Increases in wheat yield after biochar application, particularly in combination with fertilization, have been documented in field studies (Vaccari *et al.*, 2011; Alburquerque *et al.*, 2013) [24, 16]. The meta-analyses of Jeffery *et al.* (2011) [13] and Liu *et al.* (2013) [14] showed that the largest biochar responses occur in acidic and coarse-textured soils, where the liming effect and improved water retention of biochar are most influential. The soil of the present study was neutral to slightly alkaline with about 30% clay, so a liming effect can be excluded and the contribution of improved water retention is likely to have been modest. The response is thus more plausibly attributable to nutrient retention and the favourable root-zone environment created by biochar (Atkinson *et al.*, 2010) [25]. The near-identical performance of the two biochars (difference ≤ 0.03 LAI units) suggests that the property common to both, a stable porous carbon matrix, was more important than differences in feedstock. Bagasse-derived biochars can develop a large surface area and exchange capacity (Inyang *et al.*, 2010) [26], while rice straw biochar is rich in silicon whose solubility depends on the pyrolysis temperature (Xiao *et al.*, 2014) [27]; wheat, a silicon-accumulating species, may have benefited from the latter.

Sewage sludge performed statistically on par with the biochars. Sludge supplies readily mineralizable nitrogen and phosphorus together with micronutrients and organic matter (Singh *et al.*, 2008) [8], which explains its strong effect on leaf expansion. At the same farm, sewage sludge application improved soil fertility, microbial population and enzyme activities in the rice-wheat system (Latere *et al.*, 2018) [9]. Nevertheless, sewage sludge also carries heavy metals, and increased accumulation of metals in crop plants with rising sludge application has been reported (Singh *et al.*, 2010) [28]. The favourable canopy response to sewage sludge in the present study should therefore be weighed against metal loading in soil and grain before it is recommended for repeated use.

FYM produced an intermediate response in the first season and became statistically comparable with bagasse biochar in the second season, which is consistent with the slower and more sustained mineralization of well-decomposed manure. Improvement in LAI and other growth attributes of wheat with organic manures has been reported by Nehra *et al.* (2001) [7], and long-term experiments in the rice-wheat system have shown that FYM and green manure sustain crop productivity and improve soil fertility (Yadvinder-Singh *et al.*, 2004; Urkurkar *et al.*, 2010) [3, 2]. The relatively lower LAI under *ex-situ* green manuring may be related to the rapid mineralization of this narrow C:N material, much of whose nitrogen is likely to have been released during the preceding rice season, leaving a smaller residual pool for wheat. Decomposed crop residue was the least effective organic supplement. Cereal residues have a wide C:N ratio and their decomposition can immobilize soil mineral nitrogen and depress its availability to the following crop (Yadvinder-Singh *et al.*, 2005) [10], which would restrict leaf expansion. Earlier work on the same organic sources has also shown differences in the dry-matter partitioning of wheat (Singh *et al.*, 2025) [29].

The higher LAI of all treatments in 2024-25 is consistent with the earlier sowing of the second-season crop (13 November compared with 13 December). Delayed sowing shortens the vegetative phase and exposes wheat to higher temperatures later in the season, reducing growth and yield (Ortiz-Monasterio *et al.*, 1994) [30]. The larger seasonal gain in the control (23.6%) than under the biochars, sewage sludge and FYM (14.7-15.7%) suggests that the well-supplied treatments were less sensitive to the unfavourable conditions of the first season, whereas the nutrient-limited control benefited most from the better growing conditions of the second season. Because sowing date, weather and the cumulative effect of the supplements changed simultaneously between years, the seasonal difference cannot be attributed to a single factor, and a pooled analysis including the year $\times$ treatment interaction would help to separate these effects.

The superiority of most organic supplements over 100% RDF indicates that, in addition to carbon, the supplements supplied nutrients and improved soil conditions for leaf growth. This comparison should be interpreted in relation to the total nutrient supply of each treatment. The present results were obtained at one location over two seasons, and LAI was recorded at a single growth stage. Measurement of LAI at successive growth stages, together with leaf area duration, radiation interception, grain yield and soil properties, would help to confirm whether the canopy advantages of biochar and sewage sludge are sustained and translated into higher grain yield.

Conclusion

All organic supplements applied at 2 Mg organic C ha⁻¹ significantly increased the leaf area index of wheat at 90 DAS over the unamended control, and all except decomposed crop residue were also superior to 100% RDF. Bagasse converted biochar recorded the highest LAI (2.59 and 2.99), which was statistically at par with paddy straw converted biochar and sewage sludge in both years and with FYM in the second year. The consistent ranking of treatments across seasons indicates that stable carbon sources, particularly bagasse and paddy straw biochar, most effectively sustained canopy development of wheat in

the rice-wheat system. Long-term, multi-location studies including grain yield, soil properties and heavy-metal monitoring for sewage sludge are required before a general recommendation can be made.

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