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Growth Dynamics of Rice: Effects of Sustainable Farming Practices on Plant Height and Plant Density under Sodic Soil Conditions

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ABSTRACT

This study investigated the effects of sustainable farming practices and cropping systems on the growth dynamics of rice, with a focus on plant height and density under sodic soil conditions in the Indo-Gangetic Plains. The experiment was conducted for two consecutive years (2023--24 and 2024--25) at Acharya Narendra Deva University of Agriculture & Technology, Ayodhya, India, following a split-split plot design with three replications. The treatments included four farming practices: 1. Biochar-based ecological farming (BBEF), 2. Climate-Resilient Organic Farming (CROF), 3. Low-Input Natural Farming (LINF), and 4. Conventional farming (CF), three cropping systems; (1. Rice–Wheat–Mungbean, 2. Rice–Mustard–Sesbania, and 3. Rice–Barley–Mentha), and two rice varieties (1. DRR Dhan-50, and 2. Kalanamak). The results indicated that farming practices significantly influenced plant height at critical stages. The greatest plant height was consistently recorded under the CF × Kalanamak treatment, which was up to 44% taller at harvest than the LINF × DRR Dhan-50 treatment. BBEF and CROF with Kalanamak exhibited competitive growth, attaining heights within 10–13% of the CF, highlighting the potential of sustainable systems to increase vegetative growth. The plant density remained statistically uniform across the treatments and stages, suggesting that establishment is governed more by sowing practices than by postsowing management. The findings underline that while conventional farming maximizes early growth in sodic soils, sustainable practices supplemented with organic amendments and resilient varieties can offer comparable establishment without compromising ecological sustainability. These insights advocate for integrative soil management approaches in sodic environments and emphasize the need for long-term assessments of yield, soil health, and resilience.

Rice (*Oryza sativa* L.) is the principal staple food crop of the Indo-Gangetic Plains (IGP), significantly contributing to food security and rural livelihoods. However, the expansion of rice cultivation into marginal and degraded lands, such as sodic soils, poses a serious challenge for sustainable production. Sodic soils, characterized by a high exchangeable sodium percentage (ESP), elevated pH (> 8.5), and poor soil structure, adversely affect plant establishment, root development, and nutrient uptake (Qadir et al., 2018; Sharma et al., 2023). The structural degradation of sodic soils leads to crust formation, reduced infiltration, and limited aeration, ultimately restricting early plant growth and stand establishment (Minhas & Sharma, 2022).

Plant height and plant density are two critical indicators of crop establishment and early growth performance in rice. Plant height reflects vegetative vigour, nutrient uptake, and general crop health, whereas plant density at various growth stages affects canopy coverage, competition, and yield potential (Islam et al., 2021; Aslam et al., 2007). In sodic environments, reduced germination, poor seedling vigour, and limited root expansion often lead to suboptimal plant height and erratic stand establishment, causing significant yield losses (Qadir et al., 2018).

Conventional farming practices, which rely heavily on chemical inputs and intensive tillage, often fail to mitigate sodicity-induced stress and may even exacerbate soil degradation (Bashir et al., 2022; Lal, 2020). This calls for the adoption of sustainable farming practices that integrate soil amendments, organic inputs, and ecological management strategies aimed at improving soil health and plant performance. Emerging approaches such as biochar-based ecological farming (BBEF), climate- resilient organic farming (CROF), and low-input natural farming (LINF) are gaining recognition for their potential to increase soil structure, nutrient availability, and biological activity, especially in degraded soils (Lehmann & Joseph, 2015; Pimentel et al., 2005).

Despite increasing interest in sustainable agronomic practices, there remains a knowledge gap regarding their impact on the early vegetative growth dynamics of rice, particularly in sodic soils. Most existing studies focus on yield and soil chemical properties, overlooking critical early-stage growth parameters such as plant height and density, which are pivotal for successful crop establishment and resource-use efficiency (Bisht et al., 2022).

Therefore, this study was undertaken to assess the influence of sustainable farming practices on the plant height and density of rice under sodic soil conditions in the Indo-Gangetic Plains. The outcomes are expected to contribute to the understanding of growth dynamics and inform the development of effective management strategies for rice cultivation in challenging sodic environments.

2. Materials and methods

2.1 Study Site and Experimental Conditions

The field experiment was conducted during the Kharif seasons of 2023–24 and 2024–25 at the Research Farm (N.S.P.–06) of Acharya Narendra Deva University of Agriculture & Technology (ANDUAT), Kumarganj, Ayodhya, Uttar Pradesh, India, in collaboration with the International Rice Research Institute–South Asia Regional Centre (IRRI-ISARC), Varanasi. The experimental site is situated at 26°53′N latitude, 81°84′E longitude, and 113 m above mean sea level. The region experiences a humid subtropical climate characterized by hot summers (up to 45°C), cool winters (as low as 5°C), and annual monsoon rainfall of approximately 1000–1200 mm, which is predominantly received between June and September. The meteorological data recorded during the crop growth period revealed considerable temperature variation, with total seasonal rainfall amounting to 2004.16 mm over the study years.

The soil of the experimental site belongs to the Eastern Plain Zone of the Indo-Gangetic Plains and is classified as sodic in nature, with high pH (ranging from 9.17–9.34), moderate electrical conductivity (1.08–1.22 dS m^{-1}), low organic carbon (0.28–0.38%), and a clay loam texture. Prior to experimentation, composite soil samples were collected from depths of 0–5 cm, 5–15 cm, and 15–30 cm and analysed for physical, chemical, and biological properties following standard methods (Jackson, 1973; Walkley & Black, 1934). The experimental field, which had remained uncultivated for several decades, was reclaimed and brought under a rice-based cropping system for this study.

2.2 Experimental Design and Treatment Details

The experiment was performed in a split-split plot design with three replications. The main plot factor comprises four farming practices—biochar-based ecological farming (BBEF), climate-resilient organic farming (CROF), low-input natural farming (LINF), and conventional farming (CF). The subplot factor included three rice-based cropping systems: Rice–Wheat–Mungbean (RWM), Rice–Mustard–Sesbania (RMS), and Rice–Barley–Mentha (RBM). The subplot factor consisted of two rice varieties, DRR Dhan-50 and Kalanamak. Each treatment combination was assigned to a plot measuring 19.25 m^2, with a net plot area of 15 m^2 for recording observations.

2.3 Crop establishment and management practices

In the BBEF, CROF, and LINF treatments, rice was established via the dry direct seeded rice (dry-DSR) method, whereas puddled transplanted rice (PTR) was followed under CF. The zero-tillage technique was adopted for wheat, mustard, barley, mungbean, sesbania, and mentha in sustainable farming systems, with conventional tillage used in CF plots. Nutrient management varied with each practice: BBEF included biochar, ecozyme, amino acids, and humic acid; CROF involved FYM, vermicompost, azolla, BGA, and vermiwash; LINF emphasized Jeevamrit, Bijamrit, mulching (Acchadana), and Whapasa; and CF applied the recommended dose of fertilizers (RDF) via conventional chemical inputs. Water management was tailored to each system, with alternate wetting and drying (AWD) practiced under sustainable methods and conventional flooding in the CF. Residue and plant protection practices were managed as per the respective treatment protocols, ensuring consistency in implementation across replications.

2.4 Observations recorded

Plant height was measured at 30, 60, and 90 days after sowing (DAS) and at harvest on ten randomly selected rice plants from each plot, and the length from the ground level to the tip of the longest leaf or panicle was recorded. The plant density was determined at the same intervals by counting the number of plants within a 1 m^2 quadrat placed randomly at two locations per plot. The average of the two counts was used to express the plant density per m^2. These parameters were selected to study the establishment and early vegetative growth dynamics of rice under different farming practices in sodic soil conditions.

2.5 Statistical analysis

All recorded data were statistically analysed via analysis of variance (ANOVA), which is suitable for a split-split plot design with XLSTAT software (Addinsoft, 2023). The treatment means were compared via the least significant difference (LSD) test at the 5% level of significance. The data were analysed separately for each year and pooled over two years to account for annual variations and treatment interactions.

3. Results

3.1 Farming Practices and Variety Interaction

The interaction between farming practices and rice varieties significantly influenced plant height at 30 DAS, 90 DAS, and harvest, whereas plant density remained statistically unaffected at all the observed stages (Table 1).

Table: 01. Interaction Effect of Farming Practices and Variety on Plant Height (cm) and Plant Density (plants m^{-2}) of Rice at Different Growth Stages under Sodic Soil Conditions.

where *Sc. 1* - BBEF (biochar-based ecological farming), *Sc. 2* – Climate-Resilient Organic Farming (CROF), *Sc. 3* – LINF (Low-Input Natural Farming), *Sc. 4* – CF (conventional farming); *Variety 1*- DRR Dhan 50, *Variety 2*- Kalanamak

	Plant Height				Plant Density			
Scenarios x Variety	**30 DAS**	**60 DAS**	**90 DAS**	**At harvest**	**30 DAS**	**60 DAS**	**90 DAS**	**At harvest**
Sc. 1 x Variety 1	24.863 bcd	56.295 a	77.208 ab	93.042 ab	34.455 a	33.963 a	33.233 a	32.743 a
Sc. 1 x Variety 2	28.288 ab	63.420 a	86.192 ab	100.661 ab	35.190 a	34.717 a	34.120 a	33.673 a
Sc. 2 x Variety 1	24.431 bcd	55.873 a	81.453 ab	92.130 ab	34.908 a	34.038 a	33.042 a	32.172 a
Sc. 2 x Variety 2	27.487 abc	62.695 a	92.570 ab	101.290 ab	35.068 a	34.192 a	33.192 a	32.315 a
Sc. 3 x Variety 1	21.177 d	47.540 a	64.125 b	79.062 b	34.353 a	33.500 a	32.527 a	31.675 a
Sc. 3 x Variety 2	23.828 cd	54.363 a	72.932 ab	84.970 b	34.103 a	33.255 a	32.292 a	31.445 a
Sc. 4 x Variety 1	26.935 bc	61.493 a	85.417 ab	102.938 ab	36.083 a	35.268 a	33.942 a	32.610 a
Sc. 4 x Variety 2	30.980 a	70.408 a	97.432 a	113.678 a	36.137 a	34.948 a	33.773 a	32.598 a
Pr > F(Model)	<0.0001	0.166	0.021	0.012	0.106	0.135	0.158	0.104
Significant	Yes	No	Yes	Yes	No	No	No	No

3.1.1 Plant Height

At 30 DAS, significant variation was observed ($P < 0.0001$). The tallest plants (30.98 cm) under the CF × Variety 2 treatment (Kalanamak) were 41.9% taller than the shortest (21.18 cm) under the LINF × Variety 1 treatment. This early advantage is attributed to nutrient availability and puddled transplanting under CF. At 60 DAS, although the differences were not significant ($P = 0.166$), CF with Kalanamak maintained a numerically greater height (70.41 cm). At 90 DAS, significant differences reappeared ($P = 0.021$), with CF × Variety 2 (97.43 cm) being 34.4% taller than LINF × Variety 1. At harvest, the CF × Variety 2 mixture reached 113.68 cm, which was 43.8% greater than that of the LINF × Variety 1 mixture (79.06 cm) ($P = 0.012$). BBEF × Variety 2 (100.66 cm) and CROF × Variety 2 (101.29 cm) differed by only ~11% from those of CF, highlighting the growth-promoting effect of organic amendments when paired with resilient varieties.

3.1.2 Plant density

The plant density remained statistically uniform across the treatments ($P > 0.05$), ranging from 31.45 to 36.14 plants/m^2. This uniformity indicates that establishment is more influenced by the sowing method and seed rate than is postsowing management.

3.1.3 Growth dynamics interpretation

CF consistently promoted greater plant height, especially in Kalanamak. BBEF and CROF also supported competitive growth (~10–13% difference from CF). LINF resulted in a shorter plant height but did not compromise establishment. These findings suggest that sustainable systems maintain plant populations but differ in terms of postestablishment growth.

3.2 Farming Practices and Cropping System Interaction

3.2.1 Plant Height

Table: 02. Effect of Farming Practices × Cropping System Interaction on Plant Height and Plant Density of Rice at Sequential Growth Stages under Sodic Soil Conditions.

Scenarios x Cropping system	Plant Height				Plant Density			
	30 DAS	**60 DAS**	**90 DAS**	**At harvest**	**30 DAS**	**60 DAS**	**90 DAS**	**At harvest**
Sc. 1 x Cs. 1	24.240 c	46.040 cd	69.040 abc	84.290 abc	34.345 a	33.855 a	33.130 a	32.640 a
Sc. 1 x Cs. 2	24.655 c	46.585 c	69.185 abc	84.325 abc	34.860 a	34.360 a	33.615 a	33.120 a
Sc. 1 x Cs. 3	24.885 c	47.670 bc	62.210 bc	77.290 abc	34.945 a	34.445 a	33.700 a	33.200 a
Sc. 2 x Cs. 1	24.955 c	47.725 bc	70.685 ab	83.930 abc	34.495 a	33.515 a	32.535 a	31.555 a
Sc. 2 x Cs. 2	25.270 c	48.130 bc	70.500 ab	84.615 abc	34.960 a	33.960 a	32.965 a	31.965 a
Sc. 2 x Cs. 3	25.470 bc	49.550 abc	73.080 a	87.075 abc	34.525 a	33.540 a	32.565 a	31.580 a
Sc. 3 x Cs. 1	22.065 d	41.125 e	59.110 c	71.860 c	35.340 a	34.580 a	33.565 a	32.810 a
Sc. 3 x Cs. 2	22.430 d	41.095 e	59.495 c	73.055 bc	32.985 a	32.295 a	31.375 a	30.690 a
Sc. 3 x Cs. 3	22.060 d	42.165 de	59.385 c	73.330 bc	33.110 a	32.415 a	31.495 a	30.800 a
Sc. 4 x Cs. 1	26.890 ab	51.265 ab	75.930 a	90.410 ab	36.380 a	35.535 a	34.190 a	32.845 a
Sc. 4 x Cs. 2	27.360 a	51.775 ab	77.780 a	91.400 a	36.845 a	36.025 a	34.660 a	33.285 a
Sc. 4 x Cs. 3	27.520 a	53.145 a	77.730 a	92.070 a	34.700 a	33.940 a	32.680 a	31.420 a
Pr > F(Model)	<0.0001	<0.0001	<0.0001	0.004	0.610	0.580	0.628	0.637
Significant	Yes	Yes	Yes	Yes	No	No	No	No

where *Sc. 1* - BBEF (biochar-based ecological farming), *Sc. 2* – Climate-Resilient Organic Farming (CROF), *Sc. 3* – LINF (Low-Input Natural Farming), *Sc. 4* – CF (conventional farming); *Cs. 1* – RWM (Rice–Wheat-Mungbean), *Cs. 2* – RMS (Rice-Mustard-Susbania), *Cs. 3* – RBM (Rice-Barley-Mentha);

Significant interaction effects were noted at all stages: 30 DAS ($P < 0.0001$), 60 DAS ($P < 0.0001$), 90 DAS ($P < 0.0001$), and at harvest ($P = 0.004$) (Table 2). The tallest plants at 30 DAS were under CF × RMS (27.36 cm) and CF × RBM (27.52 cm), outperforming LINF × RWM (22.06 cm) by 24.0%. Similar trends persisted at 60 DAS, with CF × RBM (53.15 cm) being 29% taller than LINF × RWM. At 90 DAS, CF × RMS (77.78 cm) topped the growth chart, maintaining a 31.6% advantage over LINF × RWM (59.11 cm). At harvest, CF × RMS (91.40 cm) remained superior, 27.2% higher than that of LINF × RWM (71.86 cm). BBEF × RMS (84.32 cm) and CROF × RBM (87.08 cm) performed better than LINF, affirming the benefit of integrated inputs.

3.2.2 Plant density

No significant differences in plant density ($P > 0.05$) were observed. The values ranged from 30.69 to 36.85 plants m^{-2}. The highest density was under CF × RMS, and the lowest density was under LINF × RMS. This finding reinforces that establishment is governed by the sowing method and initial conditions rather than by management intensity.

3.2.3 Growth dynamics interpretation

Conventional farming consistently promoted greater plant height, particularly under the RMS and RBM cropping systems. Sustainable systems such as BBEF and CROF performed moderately below CF but better than LINF, particularly with RBM. The absence of density differences underscores the minor role of farming practices in establishment but their significant role in postestablishment growth, which impacts biomass accumulation and yield potential.

DISCUSSION

4.1 Influence of Farming Practices and Varieties **on Plant Growth Dynamics**

The interaction effect between farming practices and rice variety was significant for plant height, particularly at the early (30 DAS), middle (90 DAS), and maturity stages. The tallest plants consistently occurred under conventional farming (CF) combined with Kalanamak, with up to 43.8% greater height at harvest than under LINF × DRR Dhan 50. This trend highlights the superior capacity of intensive input systems, involving chemical fertilizers and puddled transplanting, to increase vegetative growth under sodic conditions. These results align with those of Sharma et al. (2023), who emphasized that in degraded soils, conventional inputs can effectively mitigate stress effects by improving nutrient uptake and root zone conditions. Despite the superiority of CF, BBEF and CROF combined with Kalanamak achieved plant heights within 10–13% of the CF at harvest, demonstrating that sustainable practices can significantly support vegetative growth, particularly when coupled with a resilient variety. The competitive performance of these systems suggests that organic amendments such as biochar and vermicompost can be used as partial substitutes for chemical fertilizers by enhancing soil health and nutrient dynamics, as noted by Bisht et al. (2024) and Minhas & Sharma (2022). In contrast, LINF consistently presented the lowest plant height across all stages, reflecting the inherent limitations of low-input systems in nutrient-deficient sodic soils. While natural farming principles may offer long-term soil health benefits, their immediate impact on plant biomass accumulation appears to be constrained in high-stress environments. Interestingly, plant density remained unaffected by farming practices or variety, maintaining a narrow range of 31.45–36.14 plants m^{-2}. This uniformity across treatments underscores that stand establishment in rice is more dependent on the sowing method and seed rate than on postestablishment nutrient management, a finding supported by Islam et al. (2021).

4.2 Influence of Farming Practices and Cropping Systems on Plant Growth Dynamics

The interaction between farming practices and cropping systems significantly influenced plant height across all growth stages. The CF combined with the rice–mustard–Sesbania (RMS) and rice–Barley–Mentha (RBM) cropping systems presented the tallest plants, with heights 28–29% greater than those of the LINF combined with the RWM at harvest. This consistent advantage reinforces the role of intensive nutrient and water management in overcoming sodicity-induced growth limitations. Among sustainable practices, BBEF × RMS and CROF × RBM performed comparatively well, suggesting that integrating organic amendments within diversified cropping systems can increase vegetative growth even under sodic stress. The improved performance of these combinations may result from better nutrient cycling and improved soil structure associated with organic inputs and specific crop rotations (Sharma et al., 2023). The absence of significant differences in plant density among cropping system × farming practice combinations, despite observable numerical variations (~12%), reaffirms that initial plant establishment is more influenced by crop establishment techniques than by management inputs. This consistency implies that sustainable systems do not compromise plant stand establishment — a critical factor for maintaining yield potential in challenging soils.

4.3 Implications for Sustainable Rice Cultivation in Sodic Soils

These findings collectively highlight that conventional farming practices maximize vegetative growth due to their immediate nutrient supply and soil conditioning effects, which are particularly beneficial in sodic soils. However, the promising performance of BBEF and CROF when BBEF **is** combined with responsive varieties and suitable cropping systems suggests that sustainable practices hold significant potential for maintaining competitive growth with reduced ecological impact. The critical insight from this study is the robust establishment capacity across all systems, demonstrated by the nonsignificant differences in plant density. This finding indicates that sustainable systems, while potentially yielding slightly lower biomass, can ensure reliable stand establishment, an essential component of crop resilience in sodic environments. These outcomes support the adoption of integrated sustainable farming strategies that couple soil amendments with stress-tolerant varieties and context-specific cropping systems, offering a balance between productivity and environmental stewardship.

CONCLUSION

The study demonstrated that while conventional farming consistently increased rice plant height by up to 44% compared with that of low-input systems, sustainable practices such as BBEF and CROF narrowed this growth gap significantly, especially when paired with the tolerant Kalanamak variety. The plant density remained uniform across the treatments, confirming that establishment success is independent of farming practice intensity in sodic soils. The results suggest that sustainable practices, when integrated with resilient varieties and suitable cropping systems, can offer a viable alternative to conventional farming for rice cultivation in sodic environments**.** Although vegetative growth is relatively low in natural farming systems, their ability to maintain stable plant density without compromising stand establishment makes them promising for long-term soil health and sustainability. Overall, this study underscores the need for long-term research to evaluate how these growth dynamics translate into yield performance, soil health improvement, and cropping system resilience under sodic stress conditions. Such insights will be crucial for developing adaptive, sustainable farming models for degraded soils of the Indo-Gangetic Plains.

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