

Comparative Evaluation of Conventional Inorganic Fertilization and *Sesbania rostrata* Green Manuring on Soil Properties and the Growth and Development of *Oryza sativa* L. 'Pant Basmati 1'

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Abstract

To assess the impacts of conventional and organic nutrient management techniques on growth, productivity, sustainability, and soil health in the Basmati rice (*Oryza sativa* L.) cultivar *Pant Basmati 1*, a two-year field experiment was carried out during the Kharif seasons of 2023 and 2024. Crop duration remained stable across management methods, as illustrated by phenological variables such as panicle initiation (58-62 days), blooming (84–88 days), and maturity (106-111 days) that were not significantly affected by fertilizer source. Conventional fertilizer supported superior growth at later stages, while organic management produced greater plant height at early growth phases. While the leaf area index and dry matter accumulation were consistently higher under conventional management because of the quick availability of nutrients, tiller density remained similar across treatments (363-411 m⁻²). Despite statistically significant variations, chlorophyll a and b quantities peaked under organic inputs at 60 DAT. Higher biological and grain yields were obtained with conventional fertilization; however, yield variations between systems were generally insignificant over time. As soil fertility stabilized, organic management notably increased the harvest index in the second year, indicating improved assimilate partitioning. The findings show that organic nutrient management can provide benefits in terms of resource efficiency and environmental sustainability while maintaining yield parity with conventional systems during the early conversion phase. Organic management techniques improve soil quality. Compared with to conventional methods, organic management practices were found to have higher soil macro and micronutrient status, water-holding capacity, aggregate stability, and soil enzyme activity (DHA and acid & alkaline phosphatase). These results show that organic Basmati rice cultivation is a feasible and sustainable alternative to traditional nutrient management, even though it may take longer to reach maximum yield.

Keywords: Basmati Rice; Nutrient Management; Conventional; Organic; Yield, soil health

Introduction

Soil health and quality determine environmental quality (Pierzynski et al., 1994), the sustainability of agriculture (Acton and Gregorich, 1995), and, consequently, human, animal, and plant health

(Habern, 1992). The concept of "soil quality" has been used in agriculture to describe a soil's ability to sustain crop growth without degradation. It is an essential part of sustainable agriculture and comprises the physical, chemical, and biological properties that enable soil to perform various functions. Productivity, diversity, and soil biological activity are crucial soil functions (Karlen et al., 1997). Karlen et al. (1997), soil biological activity, productivity, and diversity are essential soil functions. The quantity and quality of organic carbon, which determine biological traits substantially more than chemical and physical factors, are the primary factors influencing soil quality. Soil quality indicators are strongly influenced by various agricultural and plant systems and management methods (Tolanur & Badanur, 2003; Ali et al., 2025a; Shagun et al., 2024).

Despite stimulating and sustaining root growth, maintaining soil biotic habitat, and minimizing soil deterioration, healthy soil ensures adequate retention and release of water and nutrients. Therefore, maintaining soil health is essential to agriculture to improve crop health, ensure food and nutrition, cope with biotic and abiotic environmental stressors, e.g., UV-B and high light, and enhance agricultural productivity and profitability. In addition to storing and cycling nutrients, high-quality soil also filters and buffers organic and inorganic substances, producing drinkable groundwater. Therefore, managing it must be a key component of strategy to handle plant health, coping with stress, population growth, and development pressures (Yadav et al., 2019a; Yadav et al., 2019b; Lingwan et al., 2024a; Job et al., 2025; Saini. et al.,2020; Koley et al.,2025).

This study provides a comparative overview of the growth, yield, and soil health of organic and conventional *Pant Basmati-1* systems, conducted in the northwestern plains (the rice-growing region of the Tarai) of India. Basmati rice is essential from an agronomic and economic point of view, as high-quality scented varieties like Pant Basmati-1 offer strong aroma and long grain length and fetch a high market price both within the country and abroad. Given the new generation consumers' preference for quality, healthy sustainability, and environmental concern, and considering that the global organic food market is set to reach USD 380 billion by 2025 (Statista, 2024, Lingwan et al., 2016; Kushwaha et al., 2022), an analysis of organic viability for high-value crops becomes imperative. Various conventional management schemes have led to diminished soil fertility and are contrary to sustainable agricultural practices. Literature findings and data gaps in studies may contribute to the understanding of the growth parameters, yield components, and soil health of certain Basmati types such as *Pant Basmati-1*. In order to address the issue, this study determines the agronomic and biochemical characteristics in connection to different nutrient management strategies.

Compost and green manure (*Sesbania aculeata*, *Crotalaria juncea*) are examples of organic nutrient sources that do more than nourish the soil; they also maintain nutrient cycling and increase microbial diversity. That is based on current research, not merely theory (Texas A&M AgriLife Organic, 2024; FiBL, 2023). Recently, bio-augmentation-the addition of beneficial bacteria like *Pseudomonas fluorescens* and *Trichoderma harzianum*-has become popular. This increases microbial activity and accelerates decomposition (Singh et al., 2023). Conversely, traditional systems rely significantly on artificial inputs. Yes, you may immediately observe higher yields, but there is a cost: the variety of soil bacteria declines, heavy metals begin to accumulate, and the soil becomes worn out (Rahman et al., 2021; Sharma & Arora, 2023). This study examines crop growth, plant responses, yield, and soil health indicators. We are contrasting conventional synthetic fertilizers with organic methods based on green manuring. The objective is to provide

policymakers, researchers, and farmers with reliable data to inform decisions on sustainable rice production.

Crucially, as demonstrated by long-term experiments such as the DOK experiment, our work confirms that organic systems need a transition period-typically more than two years-for soil biological equilibrium to establish (Mäder et al., 2002). However, organic plots showed encouraging long-term productivity indicators, including improved sustainability indices and potential economic viability. Furthermore, Pant Basmati-1's aromatic characteristic, which results from the presence of 2-acetyl-1-pyrroline, remains a crucial marketing attribute (Kumar et al., 2023). For regions where consumer demand for residue-free rice is growing, our region-specific insights into organically managing this type are especially pertinent. With an emphasis on the true advantages and disadvantages of each rice variety, this study explores how organic rice farming functions in various geographical areas. It illustrates the difficult decisions between using conventional methods to increase harvests and switching to organic farming for environmental reasons. All of this contributes something tangible to the discussion about how to transition to more environmentally friendly agricultural practices and maximize inputs, particularly for important commodities like Basmati rice. Several studies have investigated how organic farming varies from conventional farming with respect to SOC content or stock. However, the results are difficult to generalize because they rely on variables like climate, the length of organic farming, and the precise management of both farming systems. However, most research has shown that organic farming increases the overall SOC concentration in top soils (Gattinger et al., 2012, Giannini et al., 2023). It is argued that the elevated SOC contents result from a high, or even disproportionately high, application of external OM inputs, which cannot be sustained with large-scale expansion of organic farming and only lead to carbon re-allocation rather than sequestration (Kirchmann et al., 2016, Gaudaré et al., 2023; Lingwan, & Yadav 2025).

The novelty of this work lies in its two-year, field-based comparative evaluation of organic and conventional nutrient management systems on a released Basmati rice variety (Pant Basmati 1) under subtropical Kharif conditions. Unlike many short-term or yield-only studies, this research integrates phenological stability, physiological responses, biomass partitioning, and soil quality indicators to assess system performance during the early phase of organic conversion. A key novel finding is the yield parity between organic and conventional systems despite consistently higher biomass production under inorganic fertilization, demonstrating that organic management can maintain productivity even during the initial years of transition. The study uniquely reports a significant increase in harvest index under organic management in the second year, indicating improved assimilate partitioning as soil fertility begins to stabilize, an aspect rarely quantified in Basmati rice under organic systems. Additionally, the work provides new insights into temporal shifts in growth dynamics (year- and stage-specific responses in plant height, LAI, chlorophyll content, and dry matter accumulation) rather than relying on single-stage observations organic management practices improves the soil health as compare to conventional management practices because of the Tarai soil are rich in organic matter content which improves the available macro and micronutrients and physical and biological properties. The finding that phonological traits remain unaffected by nutrient source further strengthens the understanding that nutrient management alters crop performance without disturbing crop duration in Basmati rice. Overall, this study contributes original evidence on the transition behaviour of organic nutrient management in aromatic rice, emphasizing that while organic systems may require more than two years to match conventional productivity fully, they offer environmentally sustainable yield stability with improved

soil health and nutrient use efficiency, making them a viable alternative for sustainable Basmati rice cultivation.

Material and Methods

Experimental material and Weather Conditions

The experiment is located in A₄ block of the Norman E. Borlaug Crop Research Centre of G. B. Pant University of Agriculture and Technology, Pantnagar, U. S. Nagar, Uttarakhand. (Fig. 1a) The experimental site lies in *the Tarai plains about 30 km southward of the foothill of the Shivalik range of the Himalayas at 29° N latitude, 79° 29' E longitude*, and an altitude of 243.8 m above the mean sea level. The study was conducted using *Pant Basmati-1*, a premium aromatic rice variety, with seeds obtained from the Department of Genetics and Plant Breeding, G.B. Pant University of Agriculture and Technology, Pantnagar. The Soil type is sandy loam with moderate fertility. A randomised block design (RBD) with three replications per treatment was employed.

The experiment was carried out over two consecutive *Kharif* seasons (2023 and 2024) in two adjacent experimental plots, each measuring 450 m². One plot followed conventional (inorganic) management, receiving a fertilizer dose of 120:60:40 kg N:P₂O₅:K₂O per hectare, while the other was managed under organic practices, with *Sesbania rostrata* sown as green manure and incorporated at 55 days after sowing (DAS), 1 day before transplanting. Seedlings were raised in a dry bed nursery and transplanted at 21 days old with a spacing of 20 cm × 10 cm (row × plant). All standard agronomic practices recommended for the region were followed. The crop was harvested manually at 90% panicle maturity, followed by threshing and sun drying. Grain yield was determined as weight per plot and converted into tonnes per hectare (t/ha).

Seasonal weather conditions during 2023 and 2024 were recorded, including total rainfall, average daily temperature, relative humidity, number of rainy days, wind velocity, sunshine, and evapotranspiration (Fig.1b, 1c).

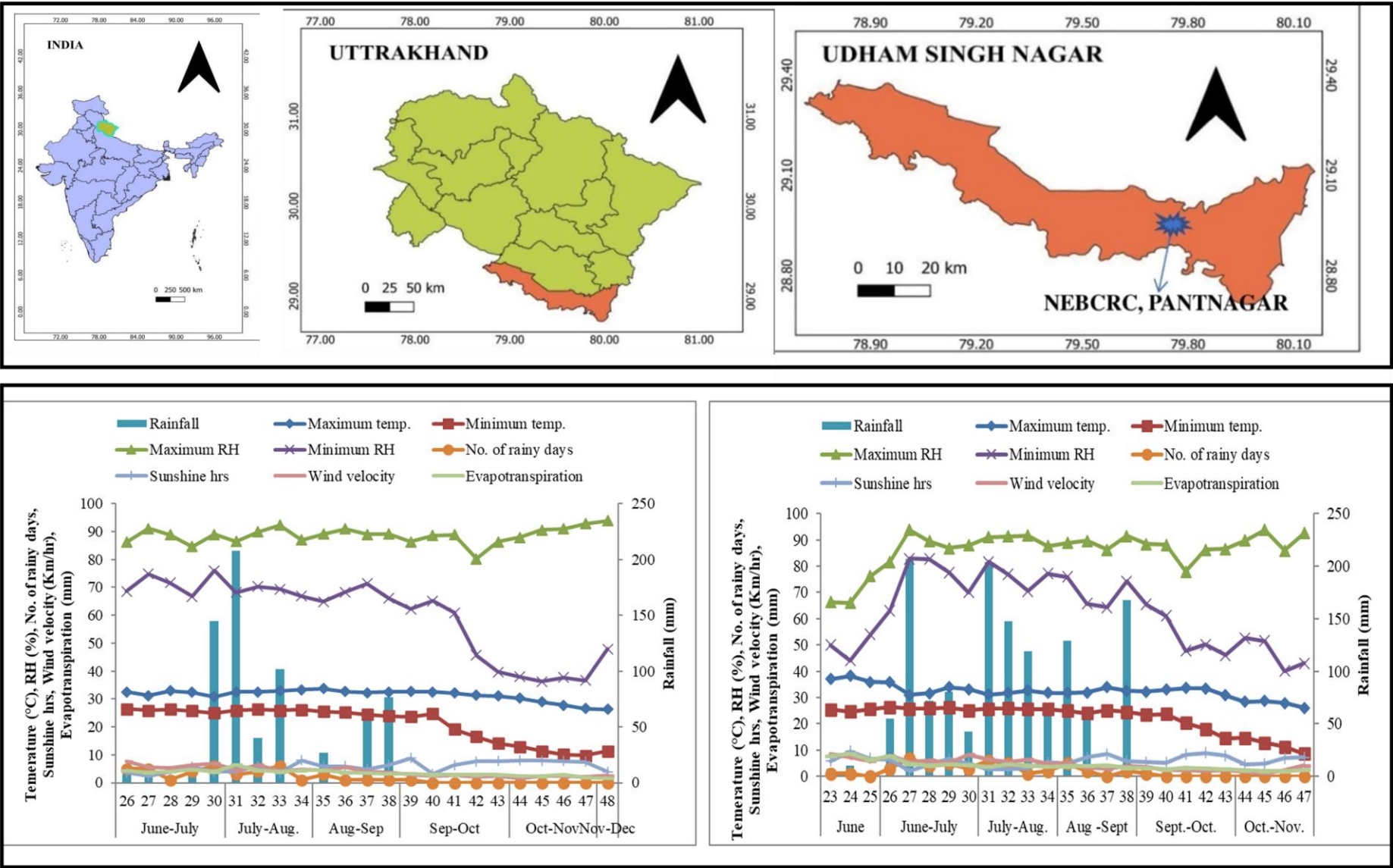


Figure 1a. Map of the location of experimental site 1b) Standard meteorological week's average weather data of season kharif, 2023, 1c) Standard meteorological week's average weather data of season kharif, 2024

Observations recorded

Parameters of plant growth

Plant height, Number of tillers and Dry matter accumulation

Measured from the soil surface to the tip of the tallest leaf on three randomly selected plants at 30, 60, and 90 days after transplanting (DAT) using a meter scale. The number of tillers was counted per square meter in each replication at 30, 60, and 90 DAT. Dry matter accumulation was analysed from Plants sampled at 30, 60, and 90 DAT, which were oven-dried at 65 ± 5°C for 48 hours, and the weight was recorded in g/m².

Leaf area index

LAI determined at the flowering stage from three hills per replication using the formula:

$$LAI = (A \times \text{Number of leaves per hill}) / 200$$

$$A = (L_1 \times W_1 \times CF) + (L_2 \times W_2 \times CF) + (L_3 \times W_3 \times CF) / 3$$

$$\text{Final LAI of genotype} = (LAI_1 + LAI_2 + LAI_3) / 3$$

Where, L₁ = Average length of 3 large leaves of hill, W₁ = Average width of 3 large leaves of hill, L₂ = Average length of 3 medium leaves of hill, W₂ = Average width of 3 medium leaves of hill, L₃ = Average length of 3 small leaves of hill, W₃ = Average width of 3 small leaves of hill, CF = Correction factor (0.75)

Phonological studies

Days to panicle Initiation, Days to flowering and Days to maturity

Beginning at 30 DAT, tillers were sampled every three days. Panicle initiation was identified through microscopic dissection using a sewing needle and noted upon the appearance of white hairs on the young panicle. Days to flowering were recorded when 50% of the panicles had fully emerged, and spikelets began anthesis, with visible stigma and anther extrusion. Days to maturity were defined when 90% of the grains on selected panicles turned straw-coloured, and the biting test confirmed grain hardness.

Chlorophyll content of leaves

Chlorophyll a, b, and total chlorophyll contents were estimated following Arnon's method (1949) (Pant et al., 2023). At flowering, 50 mg of fresh leaf tissue was incubated in 7 mL DMSO at 65°C for 3 hours. After cooling, an additional 3 mL DMSO was added, and absorbance was recorded at 663 nm and 645 nm using a spectrophotometer. Concentrations were calculated using the following equations:

$$\text{Chl a} = (12.47 \times A_{663} - 2.69 \times A_{645}) \times V / \text{wt. of sample (g)} \times 1000$$

$$\text{Chl b} = (22.9 \times A_{645} - 4.68 \times A_{663}) \times V / \text{wt. of sample (g)} \times 1000$$

$$\text{Total} = (20.2 \times A_{645}) + (8.02 \times A_{663}) \times V / \text{wt. of sample (g)} \times 1000$$

Where, A₆₆₃ = Absorbance at 663 nm, A₆₄₅ = Absorbance at 645 nm, V = Volume of DMSO used, W = Weight of leaves in gram

Parameters of yield at harvest

Total biological yield, Grain yield (t/ha) and Harvest index (%)

For the total biological yield biomass from a 1 m² area in each replication was uprooted, sun-dried, and weighed. Grain yield (t/ha) was calculated from Grain output from each plot, which was weighed and converted to tonnes per hectare. Harvest index (%) is calculated as the yield of the plant parts of economic interest (economic yield) as a percentage of total biological yield in terms of dry matter.

Collection of soil samples and processing

A composite soil sample from each plot was collected after harvesting of rice crop in the year 2023-2024. In each plot, soil was collected randomly from five points and combined into a single sample. The soil sample from each plot was stored at a low temperature (0-40 C) in the refrigerator for the study of biological properties. The remaining portion of the soil sample was air-dried in the shade, passed through a 2 mm sieve, and stored for estimating its chemical and physical properties.

Available nitrogen observations

Alkaline potassium permanganate method was used for the determination of available nitrogen (Subbiah and Asija, 1956). Available phosphorus in soil was estimated by using sodium bicarbonate extractant (0.5 M NaHCO₃) adjusted to pH 8.5 (Olsen *et al.*, 1954). Available K was determined by neutral ammonium acetate (1N NH₄OAc; pH 7) method described by Black, (1965). The modified Walkley and Black (1934) method was used to determine organic carbon, as described by Jackson (1967). Available Zn, Cu, Mn, and Fe were estimated by the method

developed by Lindsay and Norvell (1978) using an atomic absorption spectrophotometer. Water holding capacity was determined with the help of Hilgard apparatus (Piper, 1950). Modified Yoder's wet sieving method (Van Bavel, 1953) was used to determine Aggregate stability. The dehydrogenase activity of soil was determined using the method listed by Casida *et al.* (1964). The total phosphatase activity (acid and alkaline phosphatases) was determined according to the method of Tabatabai and Bremner (1969).

Statistical analysis

All recorded data were analysed using IBM SPSS Statistics. Initially, a paired t-test was applied to compare organic and inorganic treatments. Normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test) were verified before applying parametric tests. To assess treatment effects over time, a two-way factorial ANOVA was also employed, with year (2023, 2024) and treatment (organic, inorganic) as fixed factors (Shree et al., 2019). The significance of main effects and interaction terms (year $\times$ treatment) was tested to account for inter-annual variability and enhance statistical robustness. Significance was determined at $p \leq 0.05$.

Results

Phonological Parameters

Phonological traits such as days to panicle initiation, flowering, and maturity in *Pant Basmati 1* were marginally influenced by nutrient management. Across both Kharif seasons (2023 and 2024), differences in days to panicle initiation and flowering between organic and conventional systems were statistically insignificant. On average, panicle initiation occurred between 58-62 days, and flowering between 84-88 days after transplanting. Similarly, maturity ranged from 106 to 111 days, with no consistent trend favouring either system (Fig. 2a). These results suggest that nutrient source did not significantly alter the phenological timing of the crop.

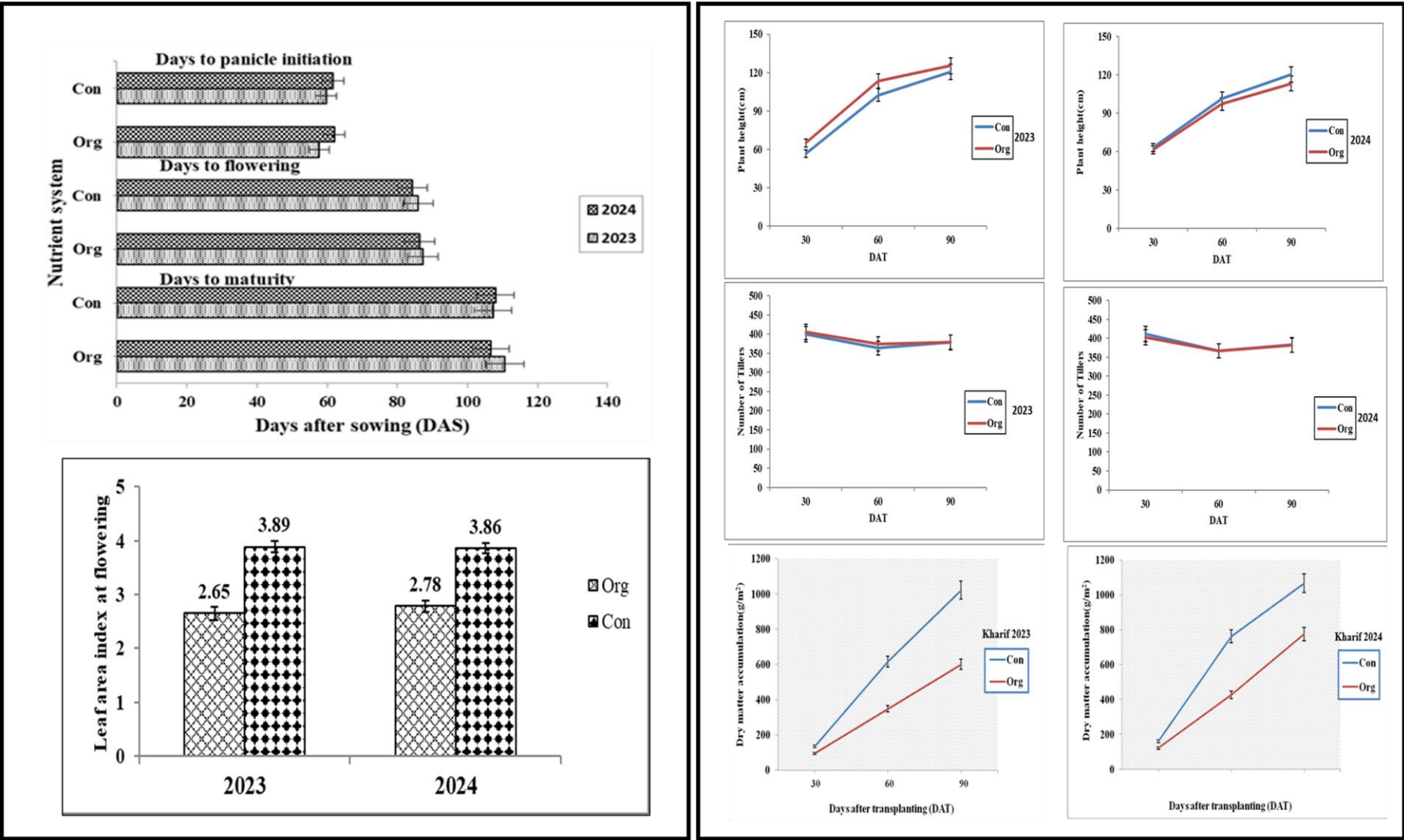


Figure 2a) Effect of inorganic and organic sources of nutrients on days to Panicle initiation, days to flowering, and days to maturity in rice variety Pant Basmati 1 during Kharif 2023 and 2024. (2b). Effect of inorganic and organic sources of nutrients on plant height of rice variety Pant Basmati 1 at 30, 60, and 90 DAT during Kharif, 2023 & 2024. (2c). Effect of inorganic and organic sources of nutrients on the number of tillers of rice variety Pant Basmati 1 at 30, 60, and 90 DAT during Kharif, 2023 & 2024. 2d). Effect of inorganic and organic sources of nutrients on leaf area index at flowering in rice variety Pant Basmati 1 (Kharif 2023 and 2024). 2e) Effect of inorganic and organic sources of nutrients on dry matter accumulation of rice variety Pant Basmati 1 at 30, 60, and 90 DAT, Kharif 2023& 2024.

Morphological Parameters

The influence of different nutrient sources on key morphological parameters, including plant height, number of tillers per plant, and leaf area index (LAI), was systematically assessed to evaluate the impact of organic and inorganic nutrient applications on rice plant growth. These metrics are important markers of overall crop development, biomass accumulation, and plant vigor. The study aims to shed light on how well organic and inorganic fertilization optimize rice growth and productivity by examining differences in these characteristics across various nutrient regimes. Plant height differed across seasons and growth stages (Fig. 2b). In 2023, organic plots exhibited significantly taller plants at 30 DAT, although differences evened out by 60 and 90 DAT. Conversely, in 2024, inorganic treatments led to significantly taller plants at 90 DAT, suggesting sustained nutrient release from mineral fertilizers at later stages.

Tiller counts remained statistically similar across both systems and years (Fig. 2c). Tillers ranged from 363 to 411 m², indicating that both nutrient sources supported adequate vegetative proliferation, with organic inputs performing comparably to conventional fertilizers. LAI was consistently higher in the inorganic system across both years (Fig. 2d), reaching 3.86-3.89, compared to 2.65-2.78 under organic management. This highlights the immediate nutrient availability under inorganic regimes, promoting greater canopy expansion. Dry matter accumulation (Fig. 2 and 4) was significantly greater in the inorganic system at all observed stages. The trend was consistent across years, underlining the role of mineral fertilizers in promoting continuous biomass development.

Physiological and Biochemical Parameters

Chlorophyll 'a', 'b', and Total Chlorophyll

While not statistically significant, chlorophyll 'a' and 'b' contents peaked at 60 DAT in the organic system (Fig. 3a, 3b, 3c), suggesting a possible benefit of organic inputs in maintaining photosynthetic pigments during critical growth phases. Biological yield was higher in the inorganic system (11.60 t/ha in 2023; 10.63 t/ha in 2024), although differences were not statistically significant (Fig. 11). Grain yield also showed no significant variation across treatments (Fig. 4a), pointing to the potential of organic systems to maintain yield parity with conventional methods over time. Harvest index remained unaffected in the first year. However, it increased significantly under organic management in the second year (Fig. 4b). This may indicate improved partitioning efficiency in organic systems as soil fertility stabilizes.

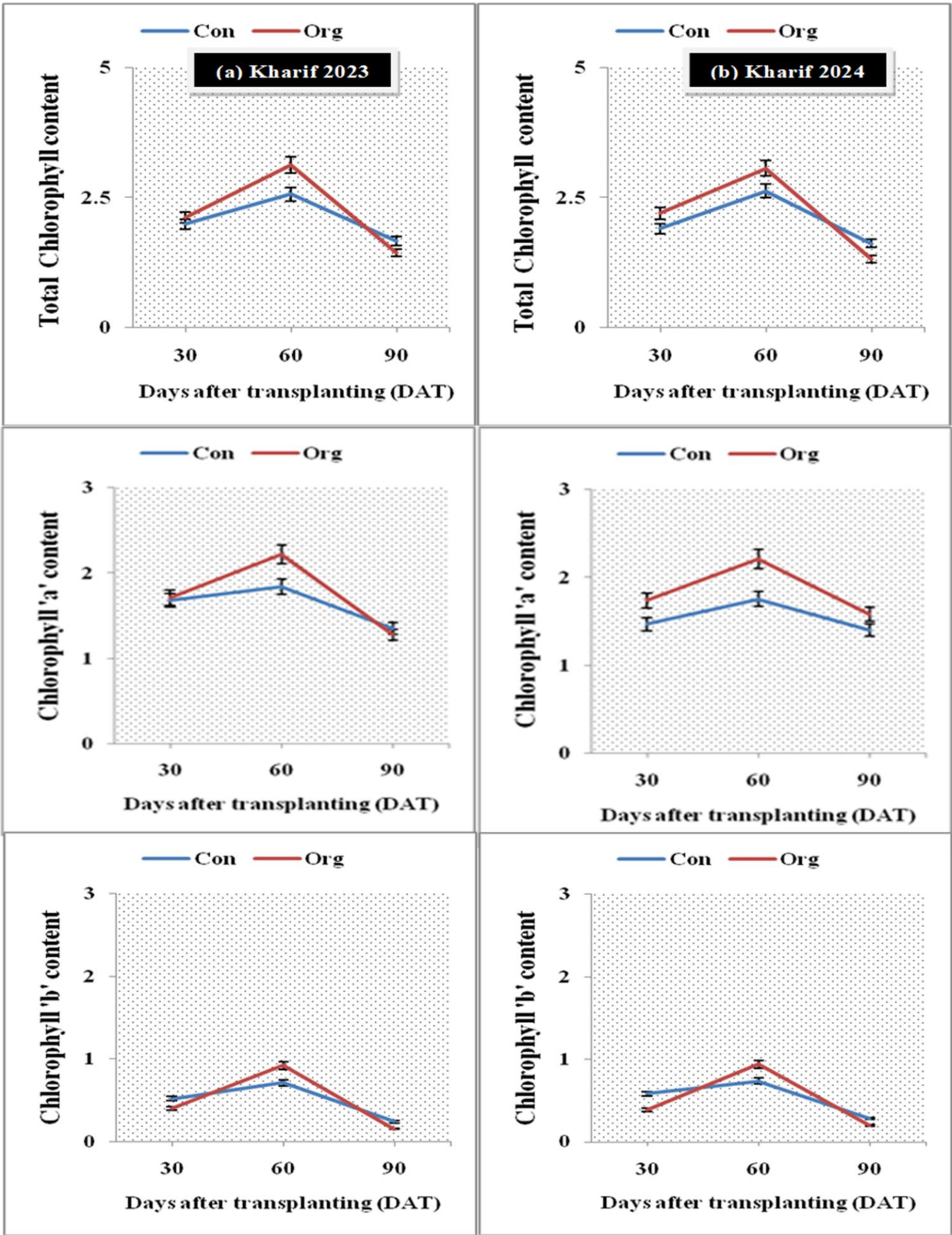


Fig. 3a) Effect of inorganic and organic sources of nutrients on total chlorophyll content (mg/g fresh wt.) of rice variety Pant Basmati 1 at 30, 60 and 90 DAT, Kharif 2023 (a) and 2024 (b), 3b) Effect of inorganic and organic sources of nutrients on chlorophyll 'a' content (mg/g fresh wt.) of rice variety Pant Basmati 1 at 30, 60 and 90 DAT, Kharif 2023 (a) and 2024 (b) 3c). Effect of inorganic and organic sources of nutrients on chlorophyll 'b' content (mg/g fresh wt.) of rice variety Pant Basmati 1 at 30, 60, and 90 DAT, Kharif 2023 (a) and 2024 (b)

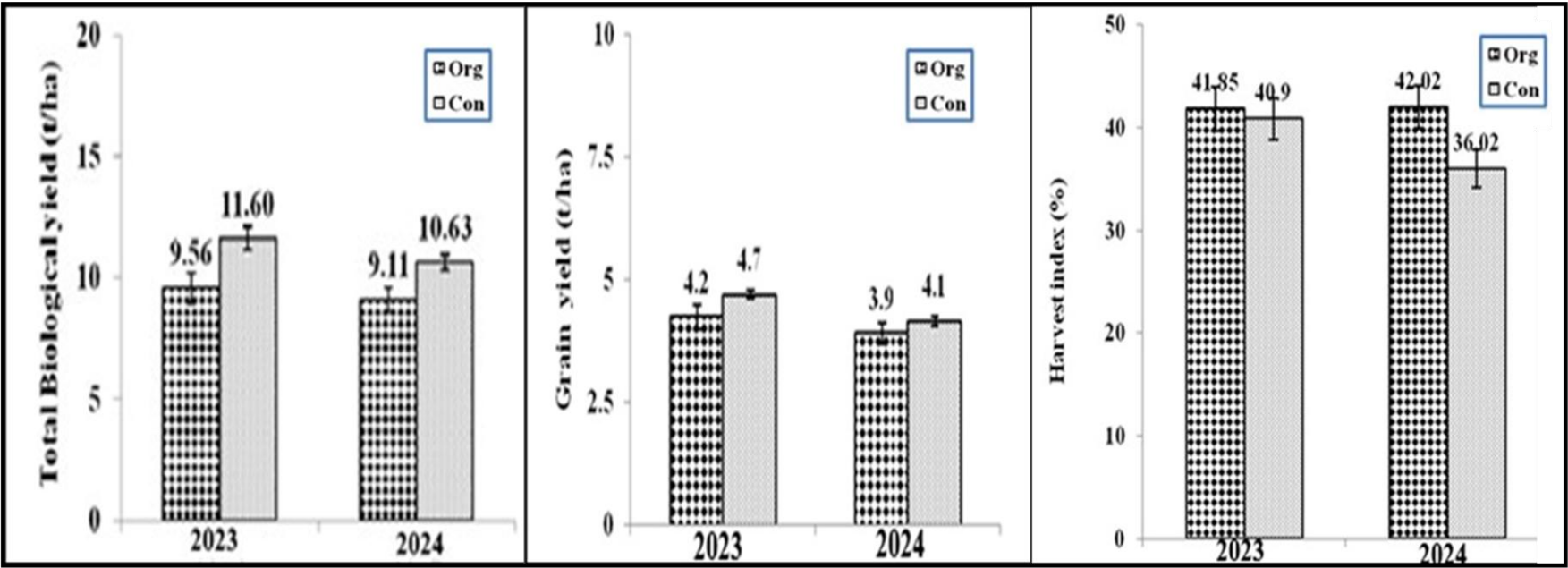


Fig. 4a. Effect of inorganic and organic sources of nutrients on total biological yield (t/ha) of rice variety Pant Basmati 1, Kharif 2023 and 2024. 4b). Effect of inorganic and organic sources of nutrients on grain yield (t/ha) of rice variety Pant Basmati 1, Kharif 2023 and 2024. 4c). Effect of inorganic and organic sources of nutrients on harvest index (%) in rice variety Pant Basmati 1(Kharif 2023 and 2024)

Available Macronutrient (Nitrogen, Phosphorous and Potassium)

The available macronutrients, i.e. nitrogen, phosphorus, and potassium, were observed highest under the organically treated plot as compared to the conventional plot (**Table 1**). In 2023, organic management supplied a greater amount of available nitrogen ($159.20 \text{ kg ha}^{-1}$) than conventional management ($152.46 \text{ kg ha}^{-1}$). Similar outcomes were observed in 2024. In 2023, organic plots had higher available P (16.84 kg ha^{-1}) compared to conventional plots (14.94 kg ha^{-1}). In 2024, the trend continued, with 17.51 kg ha^{-1} in organic plots and 15.60 kg ha^{-1} in conventional plots. Organically treated plots had higher available K levels (153.20 and $155.20 \text{ kg ha}^{-1}$, respectively) than conventional plots (148.80 and $149.46 \text{ kg ha}^{-1}$, respectively) for both years.

Table 1 Effect of organic and conventional management practices on soil macronutrients and organic carbon during *kharif* season of 2023 and 2024

Soil Properties	Year	Treatment Means ($\pm$ SD)	t-value	p-value	Significance
Available N (kg ha ⁻¹)	2023	Org 159.20 $\pm$ 3.48 Con 152.46 $\pm$ 2.59	4.06	0.014	*
	2024	Org 161.20 $\pm$ 2.59 Con 154.46 $\pm$ 4.06	2.75	0.05	*
Available P (kg ha ⁻¹)	2023	Org 16.84 $\pm$ 1.55 Con 14.94 $\pm$ 0.66	2.82	0.047	*
	2024	Org 17.51 $\pm$ 1.51 Con 15.60 $\pm$ 0.54	2.66	0.056	NS
Available K (kg ha ⁻¹)	2023	Org 153.20 $\pm$ 5.16 Con 148.80 $\pm$ 7.70	1.55	0.19	NS

	2024	Org155.20 ± 4.96 Con149.46 ± 10.47	1.63	0.18	NS
Organic C (%)	2023	Org 0.87 ± 0.03 Con 0.81 ± 0.03	3.18	0.033	*
	2024	Org 0.93 ± 0.05 Con 0.82 ± 0.03	3.26	0.03	*

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313

314 **Organic Carbon (%) and available Micronutrients (Zinc, Iron, Manganese and Copper)**

315 In both years, the Organic carbon content was significantly higher under organically (0.87 and 0.93
316 % respectively) treated plots compared to the inorganically (0.81 and 0.82 % respectively) **(Table**
317 **1)**

318 The available micronutrients, i.e., Zinc, Iron, Manganese, and Copper, were received higher with
319 organic practices as compared to inorganic (Table 2). Zinc was slightly higher in organic plots in
320 both years. In 2023, the organically treated plot had higher Zn (1.14 mg kg⁻¹) than the
321 conventional method (0.97 mg kg⁻¹). Similar trends were also observed in 2024. Fe showed
322 consistently higher availability under organic management (19.48 mg kg⁻¹ in 2023 and 20.28 mg
323 kg⁻¹ in 2024) than under conventional management (17.21 and 18.21 mg kg⁻¹). Available Mn was
324 tuned higher under the organically treated plot (5.42 mg kg⁻¹ in 2023 and 5.86 mg kg⁻¹ in 2024) as
325 compared to the conventional (4.52 and 5.18 mg kg⁻¹). Copper was also attained at higher levels
326 under organic practices (3.53 mg kg⁻¹ and 3.98 mg kg⁻¹ respectively), as compared to
327 conventional practices (2.52 and 3.25 mg kg⁻¹ respectively).

328

329 **Table 2** Effect of organic and conventional management practices on soil micronutrients during
330 *kharif* season of 2023 and 2024

Soil Properties	Year	Treatment Means (±SD)	t-value	p-value	Significance
Zn (mg kg ⁻¹)	2023	Org 1.14 ± 0.05 Con 0.97 ± 0.15	3.08	0.036	*
	2024	Org 1.18 ± 0.06 Con 1.03 ± 0.10	2.5	0.067	NS
Fe (mg kg ⁻¹)	2023	Org 19.48 ± 2.08 Con 17.21 ± 0.94	4.21	0.013	*
	2024	Org 20.28 ± 1.04 Con 18.21 ± 0.07	2.83	0.047	*
Mn (mg kg ⁻¹)	2023	Org 5.42 ± 1.01 Con 4.52 ± 0.51	3.45	0.025	*
	2024	Org 5.86 ± 0.85 Con 5.18 ± 0.72	2.61	0.059	NS
Cu (mg kg ⁻¹)	2023	Org 3.53 ± 0.49 Con 2.52 ± 0.85	3.09	0.035	*
	2024	Org 3.98 ± 0.58 Con 3.25 ± 0.42	2.71	0.053	NS

Water-Holding Capacity (%) and Aggregate Stability (%)

Organic treatment significantly enhanced WHC, with results of 59.80% in 2023 and 61.13% in 2024, compared to 53.15% and 54.49% with conventional treatment (Table 3). Improved WHC is associated with increased organic matter, aggregation, and stability of pore space. Aggregate stability improved significantly in organic plots (19.72% in 2023 and 20.44% in 2024) compared to conventional plots (17.09% and 18.87%).

Alkaline, acid Phosphatase and Dehydrogenase Activity (DHA)

During the year 2023, the organically treated plots had higher alkaline and acid phosphatase activity (42.46 and 48.13 µg PNP g⁻¹ soil h⁻¹) than conventional plots (38.15 and 39.15 PNP g⁻¹ soil h⁻¹). However, the difference was not statistically significant (**Table 3**). A similar pattern was observed in 2024, but it had a significant effect. During both years, the DHA levels were higher under organic management techniques compared to conventional methods (**Table 3**). In 2023, organic and conventional practices exhibited no significant effect on DHA (231.82 vs 226.19 µg TPF g⁻¹ day⁻¹), whereas, in 2024 (235.48 vs 228.19 µg TPF g⁻¹ day⁻¹), the organic and conventional methods showed a significant impact. This pattern suggests rising microbial oxidative activity and respiration under organic management.

Table 3. Effect of organic and conventional management practices on soil physical and biological properties during the *kharif* season of 2023 and 2024

Soil Properties	Year	Treatment Means (±SD)	t-value	p-value	Significance
WHC (%)	2023	Org 59.80 ± 0.55 Con 53.15 ± 2.60	9.05	0.001	**
	2024	Org 61.13 ± 1.01 Con 54.49 ± 2.06	6.13	0.003	**
Aggregate stability (%)	2023	Org 19.72 ± 0.61 Con 17.09 ± 1.09	7.12	0.002	**
	2024	Org 20.44 ± 0.48 Con 18.87 ± 2.07	3.41	0.025	*
Alkaline phosphatase (µg PNP g ⁻¹ h ⁻¹)	2023	Org 42.46 ± 2.52 Con 38.15 ± 2.53	2.71	0.053	NS
	2024	Org 43.45 ± 1.72 Con 39.15 ± 2.87	2.95	0.042	*
Acid phosphatase (µg PNP g ⁻¹ h ⁻¹)	2023	Org 48.13 ± 2.55 Con 40.79 ± 1.49	5.44	0.006	**
	2024	Org 50.80 ± 1.05 Con 42.45 ± 2.19	4.02	0.015	*

Dehydrogenase (µg TPF g ⁻¹ day ⁻¹)	2023	Org 231.82 ± 2.94 Con 226.19 ± 1.69	2.66	0.057	NS
	2024	Org 235.48 ± 3.54 Con 228.18 ± 1.64	3.07	0.036	*

Discussion

The differential response of *Pant Basmati 1* to organic and inorganic nutrient sources highlights key physiological and agronomic dynamics. Plant height and leaf area index (LAI)-both vital to crop productivity-were consistently higher under inorganic management, especially during later growth stages. Gebrekidan and Seyoum (2006) also noted that mineral fertilizers significantly shape canopy growth and help plants accumulate more biomass. The increased LAI is evident in the inorganic system (Fig. 2), improving photosynthetic efficiency by allowing the crop to receive more sunlight. It is not surprising that the inorganic plots had a higher biological yield (Fig. 3, 4) because LAI and dry matter both closely correlate with grain production (Oo et al., 2010; Yadav et al., 2020). The harvest index (Fig.4) increased with the organic treatment during the second year, which is an intriguing turn of events. This suggests that the plant will be more efficient in allocating its resources and utilizing nutrients, particularly once the soil settles into its new organic groove-something that Mäder et al. (2002) also observed. Even more intriguingly, the organic plots' levels of chlorophyll "a" and "b" peaked at 60 DAT (Fig. 2, 3, 4). Therefore, organic crops appear to increase photosynthetic efficiency, even though they may begin more slowly. This is likely related to a continual flow of nutrients and more active soil bacteria, as detailed by Siavoshi and Laware (2013). The fact that there was no variation in grain yields between treatments (see Fig.4) goes to demonstrate that organic systems can compete with conventional ones following the changeover and can be adopted in the future to other abiotic stresses like UV-B or high light (Job et al., 2022; Lingwan et al., 2024b; Thakur et al., 2025; Lingwan et al., 2024c). This is consistent with ongoing research, such as the DOK experiment. It is not easy to get there, however. During the transition, farmers must contend with increased pest issues, unpredictable weather, and delays in nutrient supplies. These time-related hurdles make it clear why we need long-term field trials and studies that really track how benefits build up over time.

This is supported by research from developing regions. According to Zúniga-González and colleagues (2022), field schools in Nicaragua that taught sustainable practices increased technical efficiency. The bioeconomic benefits of environmental sustainability in organic systems were previously highlighted by Blanco and Zúniga-González (2013). Our findings support the same conclusion: although organic farms may initially produce lower yields, the long-term financial and environmental benefits make organic a viable choice. Looking ahead, there is room to dig deeper. Future research should examine system productivity, multi-omics, metabolic modeling integrating data envelopment analysis (Zúniga-González et al., 2024; Lingwan et al., 2025a; Ali et al., 2025b; Lingwan et al., 2025b; Koley et al., 2024; Lingwan et al., 2025c), and factor in both bioeconomic and climate resilience metrics (Zúniga-González, 2023; Mohanasundaram et al., 2021). The study's findings clearly demonstrate that organic farming methods greatly enhanced soil health indicators, confirming the initial perspective. Compared to conventional farms, organic farms exhibited more soil organic matter, higher nutrient content, higher WHC and aggregate stability, and higher enzymatic activity. These improvements can be associated with organic farming's use of natural inputs, which increase soil structure and nutrient cycling. However, because conventional agricultural methods rely on synthetic fertilizers, soil minerals are depleted more quickly. Even though these chemical inputs release nutrients quickly, they frequently cause long-term soil deterioration, decreased microbial activity, and acidification. Over time, even greater

inputs of synthetic fertilizers may be required due to the faster nutrient loss in conventional systems, which would continue the cycle of declining soil health.

The mineralization of nitrogen and increased growth of soil microorganisms, which turn organically bound nitrogen into inorganic form, may be liable for the increase in available nitrogen content in soil caused by the application of organic matter. Enhanced nitrogen availability in organic farms, as noted by (Meena et al., 2020; Bhanuvally et al., 2024; Panghate et al., 2020). As organic matter is used, an accumulation of available P may be ascribed to the release of organic acids during decomposition, which in turn facilitates the release of native phosphorus by the solubilizing activity of these acids. Additionally, organic matter binds sesquioxides, making them inactive and lowering the soil's ability to fix phosphate, which ultimately assists in the release of an adequate quantity of plant-available P. Addition of organic matter improves the available P, as also reported by (Subehia & Sepehya, 2012; Dhaliwal et al., 2015; Cullen et al., 2025). In addition to the direct supply of K to the soil, organic matter may be attributed to the decrease in K fixation and release of K resulting from the interaction of organic matter with clays (Subehia & Sepehya, 2012; Dhaliwal et al., 2015). The use of organic matter may have promoted soil organic carbon through increased root biomass and functioned as a binding agent, promoting aggregate formation. The microbial degradation of the organic residues added to the soil emits various organic products of decay, such as polysaccharides, which act as beneficial cementing agents in the formation of large, stable aggregates that enhance soil aggregate stability. Similar work was also reported by Sihi et al. (2017) and Williams et al. (2017). The higher level of soil organic carbon with the addition of organic matter may be due to enhanced root growth, resulting in more organic residue in soil, which, after decomposition, might have increased the soil organic carbon content. These results conform to the findings of Singh *et al.* (1999) in Mollisols at Pantnagar.

The release of chelating agents from the decomposition of organic matter and the accessibility of micronutrients through organic matter may have prevented their precipitation, oxidation, and leaching. The addition of micronutrients through organic matter and the release of chelating agents from organic matter decomposition have been attributed to the increase in the available Zn, Fe, Mn, and Cu status of soils in organically treated plots. These factors may have prevented micronutrients from precipitating, oxidizing, and leaching. The lack of micronutrient replenishment with chemical fertilizers is the reason for the decrease in micronutrient levels in inorganic treatments (Lingwan et al., 2022; Lingwan et al., 2023). As organic matter is added, the soil becomes more porous, and stable aggregates form due to increased microbial activity that produces polysaccharides, glomalin, etc., thereby increasing the soil's water-holding capacity. (Bhatt et al., 2019; Kumar and Singh, 2010; Kharche et al., 2013; Jaroensuk et al., 2025). These stable aggregates have greater potential to retain water, thereby increasing the soil's water-holding capacity (Suja et al., 2017; Sarkar et al., 2024). Due to the increased availability of substrate from organic manure, which leads to high microbial activity and the release of these enzymes into the soil, the population of microorganisms may be responsible for the increase in acid and alkaline phosphatase and Dehydrogenase activity in the soil. An increase in the microbial population may also be responsible for the rise in acid, alkaline, and DHA activity in organically treated plots (Jha et al., 1992; Lugato et al., 2018; Anand et al., 2015; Rathore et al., 2024)

Conclusion

According to the study, organic basmati rice farming-especially when using green manure like *Sesbania rostrata*-pays off in the long run, whereas conventional systems provide a short-term

productivity boost. The harvest index increases, the soil becomes healthier, and nutrients are delivered more steadily. Yields are roughly the same in the second year, but it takes more than 2 years for the actual advantages of becoming organic to become apparent. Consistent increases in the harvest index and chlorophyll support this trend. All of this suggests that maintaining organic practices throughout time is crucial for basmati rice. Although there are initial challenges, organic farming increases soil fertility, reduces environmental hazards, and maintains sustainable food production. Ultimately, it is a sustainable option that aligns with global sustainability objectives and serves as a good alternative to traditional farming.

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Conflict of Interest

The authors declare that there is no conflict of interest among the co-authors regarding this research work.

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HCJ: Writing – original draft, Writing – review & editing; BP, MKB, MS: Supervision, Writing – review & editing*, SK: Writing – review & editing, Supervision.

References:

- Ali A, L. I., Zulfiqar, S., Asad, R. I. A. Z., Lingwan, M., Lianping, S. U. N., & Xianjun, W. U. (2025). Molecular and Functional Roles of Tapetum Organelles: A Nursing Staff for Pollen Development. *Rice Science*, 32(5), 617-636.
- Ali, A., & Lingwan, M. (2025). PII controls ACCase assembly to co-regulate oil and protein metabolism in plants. *Plant Physiology*, kiaf649, <https://doi.org/10.1093/plphys/kiaf649>
- Anand KV, Kubavat D, Trivedi K, Agarwal PK, Wheeler C, Ghosh A. Long-term application of Jatropha press cake promotes seed yield by enhanced soil organic carbon accumulation, microbial biomass and enzymatic activities in soils of semi-arid tropical wastelands. *Eur. J. Soil Biol.* 2015; 69:57-65
- Ashfaq, M., Khan, A., Iqbal, M. A., & Ullah, R. (2021). Advances in Basmati rice aroma research: Genetic and environmental influences. *Agricultural Sciences*, 12(3), 234-249. <https://doi.org/10.4236/as.2021.123018>
- Bandyopadhyay, S., Pramanik, P., & Choudhury, A. (2022). Impact of Sesbania green manuring on soil properties and rice yield. *Journal of Soil Science and Plant Nutrition*, 22(2), 198-212. <https://doi.org/10.1007/s42729-022-00658-4>
- Bhanuvally M, Sunitha NH (2024). Effect of organic farming practices on soil chemical properties. *International Journal of Environment and Climate Change*. 2024;14(2):470-481.

485 Bhatt, M.K, Raverkar K.P, Chandra R, Pareek N, Labanya R, Kumar V, Kaushik S, Singh D.K.
 486 (2019) Effect of long-term balanced and imbalanced inorganic fertilizer and FYM application on
 487 chemical fraction of DTPA-extractable micronutrients and yields under rice-wheat cropping system
 488 in mollisols. *Soil Use and Management* 36 (2) p.261-273

489 Bhowmick, S., Das, A., & Dutta, S. (2023). Organic farming and its role in biomass utilization and
 490 energy conservation. *Renewable Agriculture & Food Systems*, 38(1), 45-56.
 491 <https://doi.org/10.1017/S1742170523000092>

492 Black, C.A. 1965. Methods of soil analysis.Part 2. *American Society of Agronomy, inc. Madison,*
 493 *Wisconsin, U. S. A.*

494 Blanco & Zúniga-González (2013). Environmental Bioeconomic Impact in Nicaragua. Adds
 495 environmental dimensions to organic/conventional comparisons.
 496 <https://doi.org/10.5296/jas.v1i2.4033>

497 Bowles, T. M., Mooshammer, M., Socolar, Y., Calderón, F. J., Cavigelli, M. A., Culman, S. W., &
 498 Grandy, A. S. (2014). Long-term evidence shows that crop rotation diversifies soil microbiota and
 499 impacts soil organic matter dynamics. *Nature Communications*, 5, 4932.
 500 <https://doi.org/10.1038/ncomms5932>

501 Casida, L.E., Jr., D.A. and Santoro, T. 1964. Soil dehydrogenase activity. *Soil Sci.*, 98:71-376.

502 Cullen, E., & Lingwan, M. (2025). Go with the flux: Modeling accurately predicts phenotypes of
 503 Arabidopsis lipid mutants.Plant Physiology, Volume 197, Issue 1, January 2025, kiae620,
 504 <https://doi.org/10.1093/plphys/kiae620>

505 Dhaliwal, M.K., Dhaliwal, S.S., Thind, H.S., and Gupta, R.K (2015). Effect of integrated nutrient
 506 management on physio-chemical paramerters of soil in rice-wheat system. *Agri. Res. J.*, 52(2):
 507 130-137.

508 Diamond Produce. (2024). Organic vs. Conventional Farming: A Comparative Study on
 509 Environmental Impacts. Retrieved from www.diamondproduce.com

510 Dubey, P., Meena, R. S., Kumar, S., & Singh, V. K. (2015). Organic nutrient sources: A sustainable
 511 way for soil health and crop productivity. *International Journal of Plant & Soil Science*, 8(6), 1-13.
 512 <https://doi.org/10.9734/IJPSS/2015/17432>

513 FiBL (Research Institute of Organic Agriculture). (2023). Organic Farming in Europe: Advances
 514 and Challenges. FiBL Report 2023. Retrieved from www.fibl.org

515 FiBL. (2023). Organic farming statistics and trends. *Research Institute of Organic Agriculture*
 516 *(FiBL) Report 2023*. Retrieved from www.fibl.org

517

518 Gattinger, A. Muller, M. Haeni, C. Skinner, A. Fliessbach, N. Buchmann, P. Mäder, M. Stolze, P. S
 519 mith, N.-E.-H. Scialabba, U. Niggli Enhanced top soil carbon stocks under organic farming Proc.
 520 Natl. Acad. Sci., 109 (2012), pp. 18226-18231

521 Gebrekidan, H., & Seyoum, M. (2006). Effect of mineral nitrogen and phosphorus fertilizers on
 522 yield and nutrient utilization of wheat on Nitisols of Central Ethiopian Highlands. *Agriculture,*
 523 *Ecosystems & Environment*, 108(3), 241-248.

524 Ghosh, S., Patel, R., & Bhattacharya, P. (2021). Green manure application and soil health: A meta-
 525 analysis. *Soil & Tillage Research*, 210, 104882. <https://doi.org/10.1016/j.still.2021.104882>

526 Giller, K. E., van Loon, M. P., & Dijkman, J. (2022). Soil microbial diversity in organic vs.
 527 conventional systems. *Global Change Biology*, 28(5), 2547-2561.
 528 <https://doi.org/10.1111/gcb.16110>

529 H. Kirchmann, T. Kätterer, L. Bergström, G. Börjesson, M.A. Bolinder Flaws and criteria for design
530 and evaluation of comparative organic and conventional cropping systems *Field Crop*
531 *Res.*, 186 (2016), pp. 99-106

532 Hannula, S. E., & van Veen, J. A. (2016). The impact of long-term conventional and organic
533 farming on soil microbial communities and their potential functions. *Applied Soil Ecology*, 108, 132-
534 142. <https://doi.org/10.1016/j.apsoil.2016.07.002>

535 Harlan, J. R., & Ruddell, D. (2011). Conventional Agriculture: Environmental and Socioeconomic
536 Impacts. *Journal of Agricultural & Environmental Ethics*, 24(2), 187-210.
537 <https://doi.org/10.1007/s10806-010-9260-x>

538 Hartmann, M., Frey, B., Mayer, J., Mäder, P., & Widmer, F. (2015). Distinct soil microbial diversity
539 under long-term organic and conventional farming. *The ISME Journal*, 9(5), 1177-1194.
540 <https://doi.org/10.1038/ismej.2014.210>

541 Jackson, M.L. 1967. *Soil chemical analysis*. Prentice Hall of India Pvt. Ltd. New Delhi. pp. 263-
542 293.

543 Jaroensuk, J., Abraham, J. P., Zuniga, B. E., Shepard, H. S., Wei, M., Williams, R., ... & Allen, D.
544 K. (2025). Disruption of acyl-acyl carrier protein (acyl-ACP) synthetase in cyanobacteria impairs
545 lipid remodeling as revealed by acyl-ACP measurements. *Metabolic Engineering*.

546 Job, N., Lingwan, M., Masakapalli, S. K., & Datta, S. (2022). Transcription factors BBX11 and HY5
547 interdependently regulate the molecular and metabolic responses to UV-B. *Plant Physiology*,
548 189(4), 2467-2480.

549 Job, N., Dwivedi, S., Lingwan, M., & Datta, S. (2025). BBX22 enhances the accumulation of
550 antioxidants to inhibit DNA damage and promotes DNA repair under high UV-B. *Physiologia*
551 *Plantarum*, 177(1), e70038.

552 Jordan, N. (2013). *Managing biodiversity for sustainable agriculture*. Cambridge University Press.
553 <https://doi.org/10.1017/CBO9781139048505>

554 Kharche, V.K., Patil, R.S., Kulkarni, A.A., Patil, V.S and Katkar R.N. 2013. Long term integrated
555 nutrient management for enchancing soil quality and crop productivity under intensive cropping
556 system on vertisols. *J. Ind. Soc. of Soil Sci.*, 61(4): 323-332.

557 Koley, S., Jyoti, P., Lingwan, M., & Allen, D. K. (2024). Isotopically nonstationary metabolic flux
558 analysis of plants: recent progress and future opportunities. *New Phytologist*, 242(5), 1911-1918.

559 Koley, S., Jyoti, P., Lingwan, M., Wei, M., Xu, C., Chu, K. L., ... & Allen, D. K. (2025). Persistent
560 fatty acid catabolism during plant oil synthesis. *Cell Reports*, 44(4).

561 Kumar, P., Joshi, D. C., & Koul, S. (2023). Advances in aroma profiling of Basmati rice: Breeding
562 and biochemical approaches. *Food Chemistry*, 400, 134033.
563 <https://doi.org/10.1016/j.foodchem.2023.134033>

564 Kumar, R., Singh, B., & Sharma, S. (2022). Soil health improvement using green manure in
565 Basmati rice. *Agronomy*, 12(6), 789-804. <https://doi.org/10.3390/agronomy12060789>

566 Kumar, V. and Singh, A.P. 2010. Long-term effect of green manuring and farmyard manure on
567 yield and soil fertility status in rice-wheat cropping system. *J. Ind. Soc. Soil Sci.*, 58: 409-412.

568 Kushwaha, A. K., Dwivedi, S., Mukherjee, A., Lingwan, M., Dar, M. A., Bhagavatula, L., & Datta, S.
569 (2022). Plant microProteins: Small but powerful modulators of plant development. *Iscience*, 25(11).

570 Lehman, R. M., Osborne, S. L., & Duke, S. E. (2015). Organic farming promotes evenness and
571 stability in soil microbial communities. *Agriculture, Ecosystems & Environment*, 211, 112-120.
572 <https://doi.org/10.1016/j.agee.2015.06.014>

573 Lindsay, W.L. and Norvell, W.A. 1978. Development of soil test for zinc, iron, manganese and
574 copper. *Soil sci. Soc. American J.*, 42: 421-428.

575 Lingwan, M. (2016). INFLUENCE OF HIGH TEMPERATURE STRESS ON MORPHO-
576 PHYSIOLOGICAL CHARACTERISTICS IN RICE GENOTYPES (*Oryza sativa* L.). Thesis

577 Lingwan, M., & Masakapalli, S. K. (2022). A robust method of extraction and GC-MS analysis of
578 Monophenols exhibited UV-B mediated accumulation in *Arabidopsis*. *Physiology and Molecular*
579 *Biology of Plants*, 28(2), 533-543.

580 Lingwan, M., Shagun, S., Pahwa, F., Kumar, A., Verma, D. K., Pant, Y., ... & Masakapalli, S. K.
581 (2023). Phytochemical rich Himalayan *Rhododendron arboreum* petals inhibit SARS-CoV-2
582 infection in vitro. *Journal of Biomolecular Structure and Dynamics*, 41(4), 1403-1413.

583 Lingwan, M., Yadav, A., Datta, S., & Masakapalli, S. K. (2024). Time course metabolomics and
584 ¹³CO₂ mapping establish BBX31/miP1b mediated metabolic readjustments conferring UV-B
585 tolerance in *Arabidopsis*. *bioRxiv*, 2024-03.

586 Lingwan, M. (2024). Damage and repair: How Poaceae plants fix DNA damaged by UV-B
587 radiation. *Plant physiology*, 195(1), 265-267.

588 Lingwan, M. (2024). Fats influencing flowering: Pistil-derived lipids affect pollen tube growth and
589 fertility in *Arabidopsis thaliana*. *Plant Physiology*, Volume 196, Issue 2, October 2024, Pages 670–
590 671, <https://doi.org/10.1093/plphys/kiae341>

591 Lingwan, M., & Yadav, A. (2025). Sorbitol signaling: Linker histone MdH1. 1 modulates malic acid
592 buildup in apple. *The Plant Cell*, Volume 37, Issue 1, January 2025, koae332,
593 <https://doi.org/10.1093/plcell/koae332>

594 Lingwan, M. (2025). Proximity-based proteomics reveals subcellular targeting sequence in
595 Cyanobacteria. *Plant Physiology*, Volume 199, Issue 1, September 2025, kiaf237,
596 <https://doi.org/10.1093/plphys/kiaf237>

597 Lingwan, M. (2025). Jasmonic acid upregulation enhances tomato tolerance to concurrent high
598 light and heat stress. *Plant Physiology*, Volume 199, Issue 3, November 2025, kiaf555,
599 <https://doi.org/10.1093/plphys/kiaf555>

600 Lingwan, M. (2025). Metabolic modeling suggested noncanonical algal carbon concentrating
601 mechanism in *Cyanidioschyzon merolae*. *Plant Physiology*, Volume 197, Issue 2, February 2025,
602 kiaf019, <https://doi.org/10.1093/plphys/kiaf019>

603 Liu, L., Zhang, F., & Zhang, S. (1984). Correlation between chlorophyll content and photosynthetic
604 rate in rice. *Journal of Plant Physiology*, 118(2), 185-192.

605 Lori, M., Symnaczik, S., Mäder, P., De Deyn, G., & Gattinger, A. (2017). Organic farming enhances
606 soil microbial abundance and activity—A meta-analysis and review. *Science Advances*, 3(7),
607 e1700291. <https://doi.org/10.1126/sciadv.1700291>

608 Lugato E, Leip A, Jones A. Mitigation potential of soil carbon management
609 overestimated by neglecting N₂O emissions. *Nat. Clim. Change*. 2018;8(3): 219-223.24.

610 Mäder, P., Fließbach, A., Dubois, D., Gunst, L., Fried, P., & Niggli, U. (2002). Soil fertility and
611 biodiversity in organic farming. *Science*, 296(5573), 1694-1697.
612 <https://doi.org/10.1126/science.1071148>

613 Mahapatra, S. C., & Sharma, R. P. (1970). Tiller mortality in rice. *Indian Journal of Agronomy*,
614 15(1), 50-55.

615 Malik, R. K., Yadav, A., & Singh, S. (2014). Sustainable agriculture through organic farming: A case
616 study. *Journal of Sustainable Agriculture*, 8(4), 110-126.

617 Matsushima, S., & Tanaka, T. (1963). Analysis of yield-determining process and its application to
618 yield-prediction and culture improvement of lowland rice: LXVI. *Proceedings of the Crop Science*
619 *Society of Japan*, 32(1), 1-8.

620 Meena, A. L., Pandey, R. N., Kumar, D., Dotaniya, M. L., Sharma, V. K., Singh, G., Meena, B. P.,
621 Kumar, A., & Bhanu, C. (2020). Impact of 12-year-long rice based organic farming on soil quality in
622 terms of soil physical properties, available micronutrients and rice yield in a typic Ustochrept soil of
623 India. *Communications in Soil Science and Plant Analysis*, 51(18), 2331–2348.
624 <https://doi.org/10.1080/00103624.2020.1822386>

625 Meena, R. S., Mishra, P. K., & Datta, S. C. (2023). The role of beneficial microbes in sustainable
626 soil management. *Applied Soil Ecology*, 184, 104775. <https://doi.org/10.1016/j.apsoil.2023.104775>

627 Mohanasundaram, B., Bhide, A. J., Palit, S., Chaturvedi, G., Lingwan, M., Masakapalli, S. K., &
628 Banerjee, A. K. (2021). The unique bryophyte-specific repeat-containing protein SHORT-LEAF
629 regulates gametophore development in moss. *Plant Physiology*, 187(1), 203-217.

630 Olsen, S.R., Cole, C.V., Watanabe, F.S. and Dean, L.A. 1954. Estimation of Available phosphorus
631 in soil by Extraction with sodium bicarbonate U.S., Washington; D. C. Circ.: 9:39-49.

632 Oo, A. Z., Shibata, M., Takahashi, Y., & Sato, T. (2010). Effect of farmyard manure application on
633 growth and yield of rice in organic farming. *Soil Science and Plant Nutrition*, 56(2), 469-476.

634 Pant, Y., Lingwan, M., & Masakapalli, S. K. (2023). Metabolic, biochemical, mineral and fatty acid
635 profiles of edible Brassicaceae microgreens establish them as promising functional food. *Food*
636 *Chemistry Advances*, 3, 100461.

637 Panghate PA, Kuchanwar OD, Pimpale AR, Kausadikar PH, Gopal KR, Nagmote RS. (2020)
638 Dynamics of organic inputs on physicochemical properties of soil under certified organic farms in
639 Nagpur district. *Journal of Pharmacognosy and Phytochemistry*. 9(3):1395-1400.

640 Piper, C.S. 1950. *Soil and Plant Analysis*, The University of Adelaide Press, Adelaide, Australia,
641 368p.

642 Rahman, M. M., Liu, Y., & Lin, Z. (2021). Heavy metal accumulation and microbial shifts in organic
643 vs. conventional rice fields. *Environmental Pollution*, 276, 116723.
644 <https://doi.org/10.1016/j.envpol.2021.116723>

645 Rathore, S. S., Babu, S., Shekhawat, K., Kumar, V., Gairola, A., Wani, O. A., & Singh, V. K. (2024).
646 Exploring sustainable agricultural production models to coordinate system productivity, soil
647 biological health and ecoefficiency in the semi-arid region. *Environmental and Sustainability*
648 *Indicators*, 24(June), 100480. <https://doi.org/10.1016/j.indic.2024.100480>

649 Reganold, J. P., & Wachter, J. M. (2016). Organic agriculture in the twenty-first century. *Nature*
650 *Plants*, 2(1), 15221. <https://doi.org/10.1038/nplants.2015.221>

651 Saini, P., Bhatia, S., Mahajan, M., Kaushik, A., Sahu, S. K., Kumar, A., ... & Yadav, R. K. (2020).
652 ELONGATED HYPOCOTYL5 negatively regulates DECREASE WAX BIOSYNTHESIS to increase
653 survival during UV-B stress. *Plant physiology*, 184(4), 2091-2106.

654 Shagun, S., Lingwan, M., & Masakapalli, S. K. (2024). Mass spectrometry and Nuclear magnetic
655 resonance spectroscopy profiles of red and pink Rhododendron flower petals establish them as
656 rich sources of bioactive secondary metabolites. *Separation Science Plus*, 7(7), e202400007.

657 Sarkar, R. K., Chakraborty, A., & Saha, A. (2004). Nitrogen management in rice with green
658 manure. *Field Crops Research*, 88(2-3), 121-134.

659 Sarkar, S., Dhar, A., Dey, S., Chatterjee, S. K., Mukherjee, S., Chakraborty, A., Chatterjee, G.,
660 Ravisankar, N., & Mainuddin, M. (2024). Natural and Organic Input-Based Integrated Nutrient-
661 Management Practices Enhance the Productivity and Soil Quality Index of Rice–Mustard–Green
662 Gram Cropping System. *Land*, 13(11). <https://doi.org/10.3390/land13111933>

663 Sepehya, S., Subehia, S.K., Rana, S.S. and Negi, S.C. 2012. Effect of integrated nutrient
664 management on Rice-Wheat yield and soil properties in a North-Western Himalayan Region. *Ind.*
665 *J. Soil Conser.*, 40(2): 135-140.

666 Seufert, V., & Ramankutty, N. (2017). Many shades of organic: Variability in agricultural
667 sustainability. *Science Advances*, 3(3), e1602638. <https://doi.org/10.1126/sciadv.1602638>

668 Sharma, P., Arora, S., & Bhardwaj, R. (2023). Role of organic amendments in soil remediation and
669 microbial activity. *Environmental Science & Pollution Research*, 30(5), 9043-9056.
670 <https://doi.org/10.1007/s11356-023-25245-8>

671 Siavoshi, M., & Laware, S. L. (2013). Effect of organic fertilizer on chlorophyll content and
672 productivity of rice under organic farming. *Journal of Organic Agriculture*, 2(1), 32-40.

673 Shree, M., Lingwan, M., & Masakapalli, S. K. (2019). Metabolite Profiling and Metabolomics of
674 Plant Systems Using ¹H NMR and GC-MS. *OMICS-Based Approaches in Plant Biotechnology*,
675 129-144.

676 Sihi, D., Dari, B., Dinesh, K., Sharma, H. P., Nain, L., Sharma, O. P. (2017): Evaluation of soil
677 health in organic vs. conventional farming of basmati rice in North India. – *Journal of Plant*
678 *Nutrition and Soil Science* 2: 1-18.

679 Singh, N.P., Sachan, R.S., Pandey, P.C. and Bisht, P.S. 1999. Effect of a decade long-term
680 fertilizer and manure application on fertility and productivity of rice-wheat system in a mollisols. *J.*
681 *Ind. Soc. Soil Sci.*, 47(1): 72-80.

682 Subbiah, B.V. and Asija, G.L. 1956. A Rapid procedure for estimation of available nitrogen in rice
683 soils. *Curr. Sci.*, 25: 259-260.

684 Suja, G., Byju, G., Jyothi, A. N., Veena, S. S., Sreekumar, J. (2017): Yield, quality and soil health
685 under organic vs. conventional farming in Taro. – *Scientia Horticulturae* 218: 334-343

686 Tabatabai, M.A. and Bremner, J.M. 1969. Use of *p*-nitrophenyl phosphate for assay of
687 phosphatase activity. *Soil Biol. Biochem.*, 1: 301-307.

688 Texas A&M AgriLife Organic. (2024). The Role of Soil Microbes in Organic Agriculture. Retrieved
689 from www.agrilife.org

690 Thakur, Y., Lingwan, M., Pant, Y., & Masakapalli, S. K. (2025). Kinetic ¹³CO₂ mapping revealed
691 distinct light-dark metabolic transition phenotypes in *Brassica napus* seedlings under visible and
692 UV-B light. *bioRxiv*, 2025-12.

693 Timsina, J., Becker, M., & Ladha, J. K. (2023). Comparative analysis of rice production under
694 organic and conventional systems. *Field Crops Research*, 299, 108435.
695 <https://doi.org/10.1016/j.fcr.2023.108435>

696 U. Gaudaré, M. Kuhnert, P. Smith, M. Martin, P. Barbieri, S. Pellerin, T. Nesme Soil organic
697 carbon stocks potentially at risk of decline with organic farming expansion *Nat. Clim.*
698 *Chang.*, 13 (2023), pp. 719-725

699 Urkurkar, J. S., Tewari, S. and Bajpai, R.K. 2010. Influence of long term use of organic and
700 inorganic manures on soil fertility and sustainable productivity of rice (*Oryza sativa*) and wheat
701 (*Triticum aestivum*) in Inceptisols. *Ind. J. Agril. Sci.*, 80(3): 208-212.

702 V. Giannini, G. Raimondi, A. Toffanin, C. Maucieri, M. Borin Agronomic management strategies to
703 increase soil organic carbon in the short-term: evidence from on-farm experimentation in the
704 Veneto region. *Plant Soil*, 491 (2023), pp. 561-574

705 Van Bavel, C.H.M. 1949. Mean weight diameter of soil aggregates as a statistical index of
706 aggregation, *Soil Sci Soc. Am.* "Proc, 14: 20-21.

707 Verma, R. C., & Srivastava, R. K. (2004). Effect of fertilizer application on yield and nutrient uptake
708 in rice-wheat cropping system. *Journal of Agronomy*, 10(3), 215-222.

709 Walkley, A. and Black, C.A. 1934. An examination of Degtjareff method for determining soil organic
710 and a proved modification of chromic acid titration method. *Soil Sci.*, 37: 29-38.

711 Willer, H., & Lernoud, J. (2017). The World of Organic Agriculture: Statistics and Emerging Trends
712 2017. Research Institute of Organic Agriculture (FiBL) and IFOAM – Organics International.
713 Retrieved from www.fibl.org

714 Willer, H., & Lernoud, J. (2023). The world of organic agriculture: Trends and statistics. *FiBL &*
715 *IFOAM Report 2023*. Retrieved from www.fibl.org

716 Williams, D. M., Canqui, H. B., Charles, A. F., Galusha, T. D. (2017): Organic farming and soil
717 physical properties: an assessment after 40 years. – *Journal of Agronomy* 109: 600-609

718 Yadav, A., Singh, D., Lingwan, M., Yadukrishnan, P., Masakapalli, S. K., & Datta, S. (2020). Light
719 signaling and UV-B-mediated plant growth regulation. *Journal of integrative plant biology*, 62(9),
720 1270-1292.

721 Yadav, A., Bakshi, S., Yadukrishnan, P., Lingwan, M., Dolde, U., Wenkel, S., ... & Datta, S. (2019).
722 The B-box-containing microprotein miP1a/BBX31 regulates photomorphogenesis and UV-B
723 protection. *Plant physiology*, 179(4), 1876-1892.

724 Yadav, A., Lingwan, M., Yadukrishnan, P., Masakapalli, S. K., & Datta, S. (2019). BBX31 promotes
725 hypocotyl growth, primary root elongation and UV-B tolerance in Arabidopsis. *Plant Signaling &*
726 *Behavior*, 14(5), e1588672.

727 Zúniga-González & Jaramillo-Villanueva (2024). Environmental inefficiency effects on livestock
728 bioeconomy. Relevant to sustainability metrics and environmental
729 externalities. <https://doi.org/10.12688/f1000research.129183.3>

730 Zúniga-González (2023). TFP Bioeconomy Impact post Covid-19 on the agricultural economy. A
731 recent perspective on sustainability and agricultural resilience.
732 <https://doi.org/10.1371/journal.pone.0288885>

733 Zúniga-González et al. (2022). Technical efficiency in farmer field schools in Nicaragua. Useful for
734 connecting agronomic practices with performance measurement.
735 <https://doi.org/10.18845/tm.v35i3.5696>

736 Zúniga-González et al. (2024). Inputs-Oriented VRS DEA in dairy farms. Methodological insights
737 for future work on comparative system productivity.
738 <https://doi.org/10.12688/f1000research.132421.2>