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RESEARCH ARTICLE

Wheat varietal response to organic fertilization under Casuarina (*Casuarina junghuhniana* Miq.) based agrisilviculture system in trans-Gangetic Plains

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Abstract

The study examined wheat varieties under a Casuarina (*Casuarina junghuhniana* Miq.) - based agrisilviculture system (CASs) with organic fertilizer at the Department of Forestry, CCS Haryana Agricultural University, Hisar, during the rabi season of 2022-23. Casuarina trees (spaced at 5 × 3 m) showed growth increments of 0.4 m in height, 1.85 cm in girth and 0.2 m in crown spread during the study. Organic fertilizer treatments significantly enhanced soil organic carbon, available nitrogen (N), phosphorus (P), potassium (K) and Diethylenetriaminepentaacetic acid (DTPA)-extractable micronutrients, including zinc (Zn), iron (Fe), copper (Cu) and manganese (Mn), compared with the control (open field). However, lower soil moisture and reduced light availability (by 54.5–59.3 %) were observed under the agroforestry system. Air temperature was slightly lower and relative humidity was higher under the Casuarina canopy. Growth, physiological and yield parameters of wheat were generally superior in the sole crop compared to the agroforestry system, except for relative stress injury (RSI) (%), N balance index (NBI), chlorophyll index (CHI) and canopy temperature depression (CTD). Among the varieties tested, WH 1270 recorded the highest test weight, dry matter accumulation, grain yield (GY) and harvest index (HI) under Casuarina. WH 1142 showed the greatest yield reduction (35.31 %) under tree shade, indicating high shade sensitivity. Wheat responded best to T1 (150 kg ha^{-1} Recommended Dose of Nitrogen (RDN) via inorganic fertilizers), with higher NBI, CHI and yield parameters, highlighting its effectiveness even under CASs. The result indicates nutrient content was consistently higher under the agroforestry system than under sole cropping, reinforcing its relevance for developing climate-resilient production systems that enhance soil conservation, diversify income and lessen environmental pressures.

Keywords: agrisilviculture; casuarina; grain yield; organic fertilizers; soil nutrients; wheat varieties

Introduction

Sustainable agriculture, a cornerstone of modern farming, seeks to enhance productivity (1) while minimizing environmental impact (2), ensuring food security (3, 4) and ecosystem health (5, 6) for future generations. Agroforestry, the integration of trees and crops (7), offers a sustainable land-use strategy by enhancing soil fertility (8) and providing essential ecosystem services such as carbon sequestration and water regulation (9–14). In addition to environmental benefits, agroforestry supports livelihoods by diversifying income and improving food security, thereby contributing to human well-being (15–18).

The agrisilviculture system offers multiple benefits, including improved soil fertility and hydrological properties, enhanced land use efficiency through vertical expansion, resilience against crop failures from extreme climate events and diverse livelihood resources such as fuel, fodder, fiber and food. Introducing nitrogen-fixing tree species (NFTs), such as Casuarina based agrisilviculture systems (CASs) can be economically attractive and ecologically sound (19). This approach reduces external nitrogen (N) inputs while improving soil health, carbon storage (20, 21), water retention (22, 23) and agricultural productivity (24–26).

Wheat (*Triticum aestivum* L.) (Golden grain) is a crucial staple crop, feeding around 35 % of the world's population and playing a significant role in India's food basket (27, 28). Rich in nutrients such as protein, carbohydrates and fiber, wheat production relies on efficient fertilizer management. Integrated nutrient management, combining organic and inorganic inputs, can improve soil health, nutrient use efficiency and wheat productivity (29–31). This study aims to enhance wheat cultivation in CASs by evaluating the impact of organic fertilizers on wheat growth, yield, physiological traits and soil health. The findings seek to promote sustainable agricultural practices, contributing to food security and environmental sustainability.

Materials and Methods

The study was conducted at the Department of Forestry, CCS Haryana Agricultural University, Hisar, India ($29^0 10'$ N, $75^0 43'$ E, 215.2 m above mean sea level). The region has a subtropical monsoonal climate with annual rainfall: 350–400 mm (mostly July–September), Temperature range: 0 °C (winter) to 45 °C (summer), coldest months: December–January and hottest months: May–June. Mean monthly values of temperature, relative humidity, evaporation and rainfall during the experimental period are presented (Fig. 1).

Experimental site and design

The plantation consists of 2-year-old *Casuarina junghuhniana* Miq. with a 5 × 3 m spacing on the research farm of the Department of Forestry, CCS HAU, Hisar. The four wheat varieties, WH-1270, WH-1184, WH-1142 and WH-1124, were cultivated with three replications under a Casuarina-based Agrisilviculture system. The three fertilizer treatments are T_1: Recommended dose of nitrogen (RDN) - 150 kg inorganic fertilizers; T_2: Farm Yard Manure (FYM) - 17.5 t ha^{-1}; and T_3: Vermicompost - 8.0 t ha^{-1}.

Observation recorded

Light intensity measurement

Light intensity was monitored weekly at 12:00 noon using a MT30 Digital Lux Meter in intercropping and open areas throughout the experimental period.

Morphological parameters

Plant height (PH) was measured from the base of the stem to the tip of the fully expanded leaf in five randomly selected plants per plot at harvest. The average PH was calculated for each plot. Crop maturity was visually assessed when 75 % of the plants exhibited yellowing and the maturity date was recorded for each variety. Dry matter accumulation (DMA) was evaluated by harvesting one-meter row lengths from three different locations in each plot at harvest. The samples were first sun-dried and then oven-dried at 72 °C for 48 hr to obtain a constant weight.

Physiological and biochemical parameters

Leaf area was measured using a CI-202 Portable Laser Leaf Area Meter in a one-meter square sampling area at 60, 90 and 120 days after sowing (DAS). Leaf blades were separated from the stalks for measurement. Canopy temperature (CT) was measured using an Everest Inter-science hand-held infrared thermometer (IRT), model 6210L. Three measurements were taken per plot at a height of 0.5 m above the canopy and at a distance of 0.5 m from the plot edge, at angles ranging from 30° to 60° from the ground. CT measurements were recorded between 12:00 and 14:00 on clear, sunny days, along with corresponding ambient temperature (AT) readings.

CTD °C = Ambient Temperature (AT) °C - Canopy Temperature (CT) °C (Eqn. 1)

Relative Stress Injury (RSI) and Membrane Permeability Index (MPI)

The membrane permeability index (%) was determined as the ratio of ion leakage to total ion concentration. The procedure entailed immersing 200 mg of leaves in 10 mL of deionized water maintained at 27 °C (90 days after sowing), followed by measurement of the initial electrical conductivity (EC1).

Total ion extraction

The same leaf sample was autoclaved for 30 min in 10 mL of deionized water to release all ions. EC2 was measured after removing the leaf.

The membrane permeability index (%) was calculated as : (EC1 / EC2) × 100 (Eqn. 2)

$$\text{Relative stress injury \%} = \left[1 - \left(\frac{1-T1/T2}{1-C1/C2}\right)\right] \times 100 \quad \text{(Eqn. 3)}$$

Here, T1 and T2 represent EC with treatment before and after autoclaving and C1 and C2 represent EC of control plants (32).

Measurement of anthocyanin, flavonoid, Nitrogen Balance Index (NBI) and Chlorophyll Index (CHI)

At 90 DAS, anthocyanin, flavonoid, NBI (33) and CHI were measured using a Dualex leaf-clip optical sensor (34). The measurements were taken on three randomly selected plants per plot at 12:00 noon, using a non-destructive method in which wheat leaves were inserted

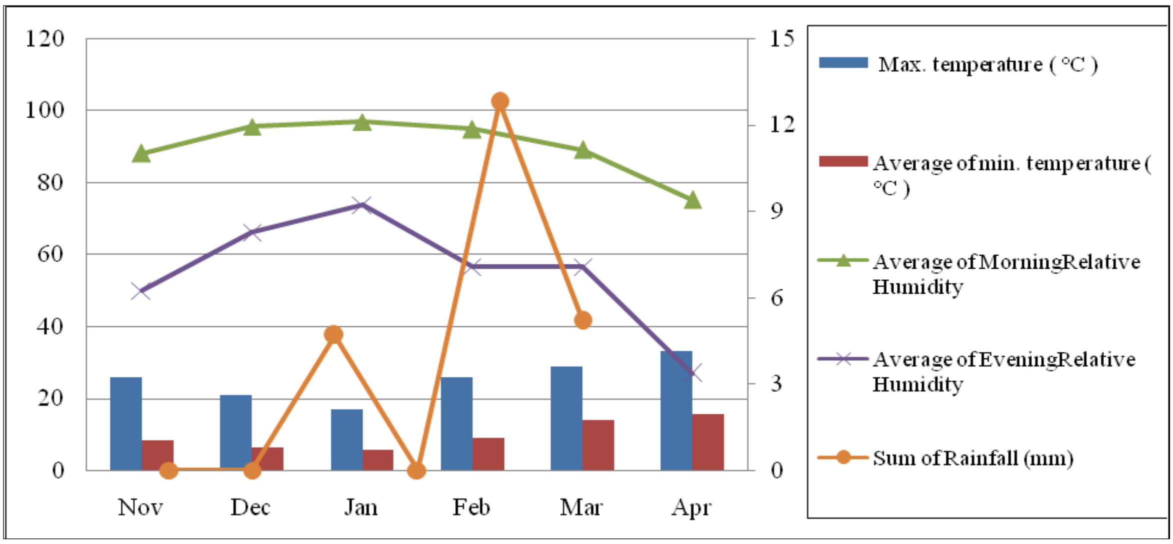

Fig. 1. Mean monthly weather data of the experimental site from November 2022 to April 2023.

into the leaf clip for data collection.

Yield and yield characteristics

The following parameters were measured

- **Effective tillers:** Counted per square meter in each plot, with averages calculated from three random locations.
- **Spike length:** Measured from peduncle base to awn tip for five spikes per replication.
- **Test weight:** Determined by counting 1000 grains from each variety and recording their weight in grams.
- **Grain yield:** Calculated per square meter and converted to t ha^{-1}.
- **Straw yield (SY):** Calculated by subtracting grain weight from biological yield (BY) (total dry weight of harvested plants per plot).

The Harvest Index (HI), a ratio of GY to BY, was calculated using the following formula (35):

$$\text{Harvest index (\%)} = \frac{\text{Grain yield}}{\text{Biological Yield}} \times 100 \quad \text{(Eqn. 4)}$$

The attraction index, a ratio of GY to SY, was calculated using the following formula:

$$\text{Attraction index (\%)} = \frac{\text{Grain yield}}{\text{Straw yield}} \times 100 \quad \text{(Eqn. 5)}$$

Nutrient content of plant samples (wheat grain and straw)

The nitrogen (N) content was measured by colorimetric method using Nessler's reagent (36), Phosphorus (P) content was estimated according to standardized procedure (37), Potassium (K) content was measured by Flame Photometry (38) and DTPA-extractable micronutrients was estimated through Atomic Absorption Spectrophotometry (39).

Statistical analysis

The collected data were analyzed statistically using R Studio software, with a *p*-value threshold of < 0.05 indicating statistical significance. Tukey's Honestly Significant Difference (HSD) test was used to identify significant differences among treatment groups. Furthermore, Spearman's rank correlation analysis was performed in OriginPro 2024b to evaluate relationships among variables.

Results and Discussions

Weekly light-intensity measurements conducted at 12:00 noon from November 2022 to April 2023 revealed consistently lower light levels under the CASs (5 × 3 m spacing) compared to open-field conditions. This reduction in light, particularly in photosynthetically active radiation (PAR), negatively affected net assimilation (NA) and overall wheat productivity, aligning with findings by other researchers (40–44). The maximum light reduction of 40.7 % was recorded in week 49 (December 5, 2022), while the minimum reduction of 14.5 % occurred in week 47 (November 23, 2022) (Table 1). These results highlight the significant shading effect of Casuarina trees on wheat growth compared to sole cropping systems.

Morphological parameters of the wheat crop 1

Plant height

The study demonstrated significant differences in PH influenced by planting geometry (45), fertilizer treatment and wheat variety (46). Sole cropping conditions produced taller plants than the CASs due to greater light availability (Table 2). Among the treatments, T1 (Recommended Dietary Allowance - RDA) promoted the tallest growth across both systems. Variety WH 1270 recorded the highest PH, followed by WH 1184 and WH 1142. Previous studies have linked reduced PH under agroforestry to lower radiation interception (42, 47, 48). Organic fertilizers enhanced nutrient availability,

Table 1. Light intensity (100 Lux) of wheat under the casuarina-based agrisilviculture system (CASs) from November 2022 to April 2023 at 12:00 noon

Weeks	Light Intensity (100 Lux)		Percent light available to the crop	Percent light reduction under an agroforestry system
	CASs	Sole crop		
Week 46	201.1	460.6	43.7	56.3
Week 47	187.5	412.2	45.5	54.5
Week 48	153.6	340.6	45.1	54.9
Week 49	152.6	374.7	40.7	59.3
Week 50	159.5	366.5	43.5	56.5
Week 51	144.4	326.8	44.2	55.8
Week 52	126.1	295.5	42.7	57.3
Week 1	120.7	289.4	41.7	58.3
Week 2	90.5	214.7	42.1	57.9
Week 3	116.6	276.6	42.1	57.9
Week 4	124.8	287.5	43.4	56.6
Week 5	102.0	236.8	43.1	56.9
Week 6	167.3	390.6	42.8	57.2
Week 7	210.5	487.0	43.2	56.8
Week 8	236.7	542.6	43.6	56.4
Week 9	260.6	593.3	43.9	56.1
Week 10	237.6	560.5	42.4	57.6
Week 11	248.8	579.8	42.9	57.1
Week 12	197.7	455.6	43.4	56.6
Week 13	230.8	536.1	43.0	57.0
Week 14	283.5	650.8	43.6	56.4
Week 15	276.5	629.6	43.9	56.1
Week 16	289.8	667.8	43.4	56.6

Table 2. Morphological and yield-related parameters of wheat plant under different treatment regimes

Variable	Test weight (g)	Spike length (cm)	No. of tillers/m^2	Plant height (cm)	Dry matter accumulation (g/mrl)	Days to maturity	Biological yield (t ha^{-1})	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Harvest index %	Attraction index %	Leaf area	CTD	NBI	CHI	Anthocynin	Flavonoids	RSI
Planting geometry																		
5 X 3 (S1)	36.3^{b}	8.741^{b}	349.167^{b}	86.836^{b}	218.93^{b}	152.806^{a}	8.28^{b}	3.27^{b}	5.01^{b}	39.19^{b}	64.62^{b}	35867^{b}	-4.475^{b}	164.519^{a}	31.058^{a}	0.134^{b}	0.153^{b}	35.276^{a}
Control (S2)	38.526^{a}	9.651^{a}	416.972^{a}	94.447^{a}	271.646^{a}	143.056^{b}	12.43^{a}	5.0^{a}	7.43^{a}	40.11^{a}	67.09^{a}	42112^{a}	-2.819^{a}	37.475^{b}	25.769^{b}	0.177^{a}	0.55^{a}	32.848^{b}
LSD (p = 0.05)	0.235	0.121	5.528	0.825	3.335	1.366	0.04	0.06	0.06	0.51	1.41	396.4	0.087	2.8	0.4	0.002	0.008	0.4
Treatments																		
T1	40.189^{a}	9.926^{a}	419^{a}	95.842^{a}	279.357^{a}	151.167^{a}	12.01^{a}	5.01^{a}	7.0^{a}	41.67^{a}	71.5^{a}	44813^{a}	-2.438^{a}	135.958^{a}	30.775^{a}	0.138^{b}	0.386^{a}	35.405^{a}
T2	35.487^{c}	8.724^{c}	360.292^{c}	86.708^{c}	221.823^{c}	145.083^{c}	9.06^{c}	3.48^{c}	5.58^{c}	38.29^{c}	62.1^{c}	36124^{b}	-3.942^{b}	106.283^{b}	28.596^{b}	0.163^{a}	0.357^{b}	33.987^{b}
T3	36.563^{b}	8.938^{b}	369.917^{b}	89.375^{b}	234.684^{b}	147.542^{b}	10.0^{b}	3.92^{b}	6.09^{b}	39.0^{b}	63.98^{b}	36031^{b}	-4.563^{c}	60.75^{c}	25.871^{c}	0.165^{a}	0.312^{c}	32.794^{c}
LSD (p = 0.05)	0.288	0.148	6.771	1.011	4.085	1.673	0.05	0.07	0.07	0.62	1.73	485.5	0.106	3.4	0.4	0.003	0.009	0.5
Varieties																		
WH 1270 (V1)	37.484^{ab}	9.283^{a}	385.333	91.339^{a}	247.634	150^{a}	10.46^{a}	4.21^{a}	6.25	40	66.80	39124^{b}	-3.672^{b}	111.944^{b}	32.417^{a}	0.164^{a}	0.367^{b}	34.2
WH 1184 (V2)	37.199^{b}	9.234^{a}	383.611	90.928^{a}	244.901	149.111^{a}	10.36^{b}	4.15^{a}	6.22	39.78	66.19	38222^{c}	-4.022^{c}	104.522^{c}	31.483^{b}	0.152^{c}	0.396^{a}	34.3
WH 1142 (V3)	37.234^{b}	9.283^{a}	385.833	91.072^{a}	244.643	143.889^{b}	10.37^{b}	4.15^{a}	6.22	39.67	65.93	40079^{a}	-3.444^{a}	119.211^{a}	24.678^{c}	0.158^{b}	0.349^{c}	33.8
WH 1124 (V4)	37.733^{a}	8.983^{b}	377.5	89.228^{b}	243.974	148.722^{a}	10.28^{c}	4.03^{b}	6.2	39.17	64.51	38532^{c}	-3.450^{a}	68.311^{d}	25.078^{c}	0.148^{c}	0.295^{d}	33.9
LSD (p = 0.05)	0.332	0.171	N.S.	1.167	N.S.	1.932	0.06	0.08	N.S.	N.S.	N.S.	560.6	0.122	3.9	0.5	0.003	0.011	N.S.
Interactions																		
SXT LSD (p = 0.05)	0.407	N.S.	9.575	1.43	5.777	N.S.	0.07	0.10	0.10	N.S.	65.54	686.6	0.15	4.8	0.6	0.004	0.013	N.S.
SXV LSD (p = 0.05)	N.S.	N.S.	N.S.	1.651	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	792.9	0.173	5.6	0.7	0.005	0.015	N.S.
TXV LSD (p = 0.05)	N.S.	N.S.	13.541	2.022	N.S.	N.S.	0.103	N.S.	N.S.	N.S.	N.S.	971.1	0.212	6.8	0.9	0.006	0.019	N.S.
S X T X V (LSD, p = 0.05)	N.S.	N.S.	N.S.	2.859	N.S.	N.S.	0.146	N.S.	N.S.	N.S.	N.S.	1373.3	N.S.	9.7	1.2	0.009	0.027	N.S.

Test weight (g), spike length (cm), number of effective tillers /m2, plant height (cm), dry matter accumulation (g/mrl), day to maturity, biological yield (t ha^{-1}), grain yield (t ha^{-1}), straw yield (t ha^{-1}), harvest index %, attraction index %, leaf area (cm^2/m^2 at 90 days), canopy temperature depression (ctd at 90 days), nitrogen balance index (nbi), chlorophyll index (chi), anthocyanin, flavonoids and relative stress injury (rsi) %, at harvesting of various wheat varieties.

particularly N, which is crucial for plant development (49–51).

Days to maturity

Wheat cultivars under the CASs took longer to mature than those under sole cropping, mainly due to reduced light interception and delayed photosynthetic activity. The T_1 (RDN) treatment further extended the maturity period, likely due to enhanced vegetative growth (Table 2). Varieties WH 1270, WH 1184 and WH 1124 exhibited the longest maturity durations. Similar trends were reported by many scientists (52, 53). While inorganic N prolongs vegetative phases, organic sources like FYM and vermicompost provide gradual nutrient release, potentially resulting in earlier maturity (54, 55).

Dry matter accumulation

Sole cropping systems accumulated more dry matter than the CASs. Treatment T_1 (RDN) consistently resulted in the highest accumulation, irrespective of cropping condition. No significant differences were observed among wheat varieties. These findings are consistent with previous studies (56, 57) that reported reduced biomass in agroforestry systems due to limited radiation. Treatments T_2 (FYM) and T_3 (Vermicompost) produced lower dry matter, likely due to reduced N availability (Table 2). This emphasizes N's role in enhancing photosynthesis, growth and biomass production (58–60).

Physiological and biochemical parameters of wheat crop 2

The study assessed key physiological and biochemical parameters of wheat crops under different system.

Leaf Area Index (LAI)

Sole cropping conditions and T_1 (RDN) treatment resulted in significantly higher LAI, with variety WH 1142 exhibiting the largest leaf area. The study revealed that planting geometry, fertilizer treatments and wheat varieties significantly influenced LAI at 90 and 120 DAS, although varietal differences were non-significant at 60 DAS (Table 2). Consistent with previous findings, adequate N availability during active growth stages is essential for optimal leaf area development (29, 61). The superior LAI under T_1 (RDN) was attributed to the rapid N release from inorganic fertilizers, which promoted cell division, elongation and tillering. This expansion in leaf area improved light interception and photosynthetic efficiency, thereby enhancing DMA and ultimately increasing crop yield.

Canopy Temperature Depression (CTD)

The CASs exhibited greater CTD compared to sole cropping, indicating cooler canopy microclimates under tree cover. Among treatments, T_3 (Vermicompost) recorded the highest CTD, while variety WH 1142 showed the most pronounced temperature depression (Table 2). Canopy temperature measurements at 60, 90 and 120 DAS were significantly influenced by planting geometry, fertilizer treatments and water use, as lower CTs have been associated with improved drought tolerance and favorable microclimatic conditions (62, 63).

Relative Stress Injury (RSI)

Higher RSI was observed under the CASs compared to sole cropping, likely due to reduced photosynthetically active radiation (PAR) caused by tree shading. Treatment T_1 (RDN) exhibited the highest RSI, possibly due to increased vegetative growth under high N availability, which may exacerbate sensitivity to stress under suboptimal light conditions (Table 2). No significant differences in RSI were recorded among wheat varieties, including a uniform varietal response to agroforestry included stress. To increased stress under lower PAR conditions, emphasizing the importance of managing both light and N inputs in shaded environments (64, 65).

Nitrogen Balance Index (NBI) and Chlorophyll Index (CHI)

The CASs consistently recorded higher NBI and CHI values than sole cropping, indicating improved N use and chlorophyll content under shaded conditions. Among the treatment, T_1 (RDN) resulted in the highest NBI and CHI across all growth stages. Variety WH 1270 exhibited superior performance for both indices (Table 2). These trends suggest that adequate N availability, particularly from inorganic sources, enhances chlorophyll synthesis and N balance, even under reduced light conditions. The NBI and CHI are strongly influenced by nutrient status and are indicative of a plants N use efficiency and physiological resilience under stress conditions such as salinity or light limitation (66, 67).

Flavonoid and anthocyanin content

Sole cropping conditions resulted in higher flavonoid and anthocyanin content compared to the CASs. Among treatments, T_1 (RDN) promoted the highest accumulation of both compounds, while variety 1184 recorded the highest flavonoid content and WH 1270 exhibited the highest anthocyanin content (Table 2). The reduced levels of flavonoids and anthocyanins under the agroforestry system may be attributed to lower soil salt concentrations, as these secondary metabolites are often synthesized in response to abiotic stress, particularly salinity. The flavonoid and anthocyanin production is closely linked to stress conditions and nutrient availability (68, 69). The enhanced accumulation of these compounds under T_1 (RDN) suggests that optimal N availability may also play a role in promoting secondary metabolite synthesis under favorable growing conditions.

Yield and yield-related parameters of wheat crop 3

Wheat grown under sole cropping conditions recorded significantly higher yields and yield components than the CASs. This can be attributed to greater light availability and reduced competition for essential resources. Among fertilizer treatments, T_1 (RDN) consistently outperformed others across all yield parameters (Fig. 2). Varietal evaluation showed that WH 1270 produced the highest GY, BY and spike length (SL), while WH 1124 recorded the highest test weight (Table 2). However, no significant varietal differences were observed for SY, HI, attraction index, or the number of effective tillers per square meter.

Effective tillers and spike length

Sole cropping systems recorded more effective tiller and SL than agroforestry systems due to better light availability and reduced competition, whereas tree presence in agroforestry suppressed tiller formation (Table 2) (70–74); Conversely, the T_1 (RDN) treatment produced longer spikes, attributed to better nutrient supply and enhanced translocation of photosynthates to reproductive organs, N application further tillering as well as SL by promoting cytokinin synthesis and efficient carbohydrate metabolism (75, 76).

Test weight

The 1000-grain weight was significantly lower under the CASs compared to sole cropping. This reduction is primarily attributed to decreased nutrient and light availability in the agroforestry system,

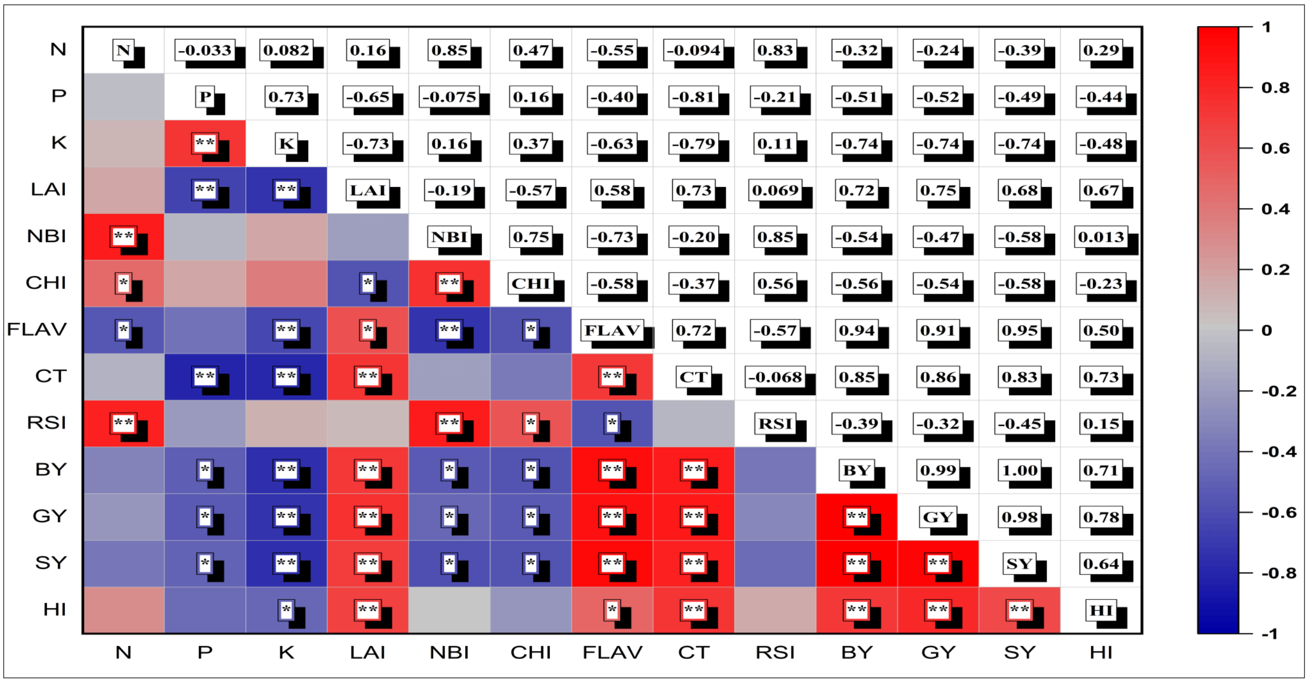

Fig. 2. Correlations among nutrient content and other parameters of the casuarina-based agrisilviculture system (CASs).

LAI: leaf area index; NBI: nitrogen balance index; CHI: chlorophyll index; FLAV: flavonoids; CT: canopy temperature depression; RSI:relative stress injury; BY: biological yield; GY: grain yield; SY: straw yield; HI: harvest index.

which adversely affects grain development and filling (77–79). Among the varieties, WH 1124 recorded the highest test weight, followed closely by WH 1270, indicating their better adaptation and potential for grain development under variable conditions (Table 2). Treatment T_1 (RDN) consistently produced the highest test weight, reflecting enhanced nutrient availability and prolonged vegetative activity (Fig. 2). This extended greenery supports improved photosynthetic efficiency and grain filling (80).

Grain and straw yields

Grain and SYs were significantly lower under the CASs, primarily due to reduced light interception and photosynthetic activity resulting from tree shading. These factors limit growth and reproductive development, resulting in yield losses. In contrast, T_1 (RDN) produced the highest grain and SYs across both systems, owing to improved nutrient uptake and photosynthetic efficiency (Table 2; Fig. 2). Enhanced nutrient supply facilitates better development of reproductive organs and increases assimilate translocation to grains, thereby boosting overall productivity (52, 81, 82).

Biological yield and yield indices

Biological yield was significantly higher in sole cropping compared to the CASs. The lower biomass production under agroforestry conditions is attributed to limited light, moisture and nutrient availability, factors which directly affect yield components (Table 2). Inorganic fertilization through T_1 (RDN) resulted in higher BY due to the immediate availability of N, which promotes vegetative growth and biomass accumulation (83, 84).

Harvest and attraction indices

Both the harvest and attraction indices were significantly lower under the CASs than under sole cropping (Table 2; Fig. 2), primarily due to reduced biomass production and limited resource availability (47, 53, 85). In contrast T_1 (RDN) consistently recorded higher values for both indices, reflecting enhanced GY, efficient assimilate partitioning and improved nutrient uptake. The role of adequate N fertilization in maximizing yield potential and physiological efficiency (23, 86).

Nutrient content of plant samples (wheat grain and straw) 4

Nutrient content and uptake

The study revealed significant differences in nutrient content and uptake between the CASs and the sole cropping system. Overall, nutrient concentrations (N, P, K, Zn, Fe, Cu, Mn) in both grain and straw were generally higher under the agroforestry system, though total nutrient uptake was slightly greater under sole cropping due to higher biomass accumulation (Table 3).

Nitrogen content in both grain and straw was significantly higher under CASs, with T1 (RDN) recording the highest levels due to the rapid availability and efficient uptake of inorganic N, while no significant varietal differences were noted. Phosphorus and K concentrations were highest in T3 (vermicompost), likely due to the slow, sustained nutrient release, which enhanced uptake (Table 3). Micronutrient (Zn, Fe, Cu, Mn) concentrations were also higher under CASs and T3, attributed to increased microbial activity and improved soil organic matter, with no significant varietal variation observed.

Nutrient uptake

Despite higher nutrient content under agroforestry, total nutrient uptake (macro and micronutrients) was slightly greater in sole cropping due to higher biomass production. Among treatments, T_1 (RDN) resulted in the highest uptake of N, K and micronutrients, except for P in straw, which was higher under T_3 (Table 3). The improved uptake under T_1 is due to increased N availability, promoting root activity and translocation efficiency (87–89).

The study found significant correlations between nutrient content and various parameters, such as N Content, which was significantly correlated with NBI, CHI, Flavonoids and RSI. Phosphorus content significantly correlated with K content, LAI, CT,

Table 3. N, P, K (%), Zn, Fe, Cu and Mn (mg kg^{-1}) content in grain and straw of wheat varieties under Casuarinas-based agrisilviculture system (CASs)

Variable	N %		P %		K %		Zn (mg kg^{-1})		Fe (mg kg^{-1})		Cu (mg kg^{-1})		Mn (mg kg^{-1})	
	Grain	Straw	Grain	Grain	Straw	Grain	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
Planting geometry														
5 X 3 (S1)	1.956[a]	0.443[a]	0.24[a]	0.119[a]	0.434[a]	1.688[a]	28.315[a]	58.264[a]	93.142[a]	180.994[a]	7.105[a]	5.515[a]	25.033[a]	52.076[a]
Control (S2)	1.774[b]	0.433[b]	0.232[b]	0.116[b]	0.422[b]	1.645[b]	26.129[b]	56.065[b]	90.726[b]	172.766[b]	6.88[b]	5.372[b]	24.374[b]	48.344[b]
LSD (p=0.05)	0.011	0.005	0.002	0.002	0.004	0.015	0.62	1.43	2.15	2.25	0.08	0.08	0.62	1.04
Treatments														
T1	1.961[a]	0.461[a]	0.226[c]	0.103[c]	0.415[c]	1.633[c]	25.714[c]	55.813[b]	89.939[b]	173.386[b]	6.844[b]	5.32[b]	23.948[b]	48.656[b]
T2	1.804[c]	0.421[c]	0.233[b]	0.118[b]	0.432[b]	1.671[b]	27.516[b]	57.454[ab]	92.452[ab]	177.767[a]	7.035[a]	5.475[a]	24.977[a]	50.784[a]
T3	1.829[b]	0.431[b]	0.248[a]	0.13[a]	0.438[a]	1.695[a]	28.437[a]	58.228[a]	93.412[a]	179.487[a]	7.098[a]	5.536[a]	25.186[a]	51.19[a]
LSD (p = 0.05)	0.013	0.006	0.003	0.002	0.005	0.018	0.76	1.75	2.63	2.75	0.1	0.09	0.76	1.27
Varieties														
WH 1270 (V1)	1.866	0.437	0.236	0.117	0.429	1.666	27.21	57.15	91.9	176.87	6.99	5.44	24.7	50.21
WH 1184 (V2)	1.863	0.439	0.237	0.118	0.427	1.664	27.21	57.16	91.9	176.88	6.99	5.44	24.71	50.21
WH 1142 (V3)	1.865	0.437	0.236	0.117	0.428	1.669	27.12	57.17	92.03	176.88	6.99	5.44	24.7	50.2
WH 1124 (V4)	1.864	0.438	0.236	0.117	0.429	1.667	27.36	57.18	91.91	176.89	7	5.45	24.71	50.22
LSD (p = 0.05)	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
Interactions														
SXT LSD (p = 0.05)	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	3.89	0.14	0.13	1.08	1.79
SXV LSD (p = 0.05)	0.022	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
TXV LSD (p = 0.05)	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
S X T X V (LSD, p = 0.05)	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

BY, GY and SY. Potassium content significantly correlated with LAI, flavonoids, CT, BY, GY, SY and HI (90, 91).

Conclusion

The study concluded that wheat growth and yield were generally superior under sole cropping compared with the Casuarina-based agrisilviculture system due to reduced light and soil moisture. However, variety WH 1270 and the T1 (150 kg ha^{-1} RDN) treatment performed best under both systems, showing higher yield, dry matter accumulation and physiological resilience. WH 1142 was most sensitive to shade. Organic fertilization improved soil health, while inorganic RDN enhanced wheat performance, indicating the potential of optimized nutrient management and variety selection to sustain wheat productivity in agroforestry systems.

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Authors' contributions

S and SA conceived, planned and conducted the experiment on Casuarina based agrisilviculture system. CS and VJ recorded the experimental data. AT, HK and SBSP statistically analyzed the data. SKV, RKA and VK prepared the manuscript in journal format and cross-checked the statistical analysis. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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