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Tree-crop synergies enhance soil nutrient content and yield in semi-arid agroecosystems

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Abstract

Declining soil fertility and reduced crop yields in semi-arid regions necessitate the adoption of sustainable alternatives to conventional monocropping systems. Among these, agroforestry presents a promising and ecologically sound approach for restoring soil health and enhancing long-term agricultural productivity by integrating trees with crops to improve nutrient cycling, soil structure, and overall ecosystem resilience. This study, therefore, investigates how tree growth characteristics, in interaction with different cropping arrangements, influence key soil fertility parameters and the productivity of staple crops. A field experiment was conducted using a randomized complete block design (RCBD) with four treatments. The treatments included tree-row spacing of 75 cm with 15 cm plant-to-plant distance (30R6P), 150 × 15 cm (60R6P), and 225 × 15 cm (90R6P), which is also known as wider spacing, along with sole cropping of wheat and maize without trees as the control, and sole trees without crops as an additional reference for assessing tree physiology. The results showed that soil nitrate-nitrogen increased significantly (48.4%) with wider spacing, while phosphorus (24.4%) and potassium (5.6%) levels also increased across treatments. Tree growth was strongly influenced by spacing, with tree height and diameter increasing by 24.10% and 40.76%, respectively, compared with narrow spacing. Similar trends were observed in crops, grain weight and grains per spike improved progressively with wider tree spacing. Physiological traits such as photosynthesis rate, stomatal conductance, and transpiration were markedly higher in wider spacing, while intercellular CO_2 concentration declined (28.80%), indicating more efficient carbon fixation (22.89%) in maize and (21.57%) in wheat. Overall, the findings demonstrated that integrated tree farming with wider spacing balances the dual goals of maintaining tree growth and ensuring competitive crop yields, while enhancing soil fertility. The study highlights integrated tree farming as a viable pathway to sustainable intensification in semi-arid agroecosystems, with important implications for food security, soil conservation, and climate resilience.

Keywords: Agroforestry systems, Cropping systems, Crop productivity, Nutrient cycling, Semi-arid environment, Soil fertility

Introduction

Globally, the decline in soil fertility has become a major concern due to the combined impacts of intensive agricultural practices, industrialization, and deforestation. Soil degradation, loss of biodiversity, and excessive reliance on chemical fertilizers and pesticides are largely consequences of conventional farming systems dominated by monoculture practices (Belete and Yadete, 2023). The excessive use of synthetic inputs drives up production expenses and produces environmental challenges, including soil degradation, water pollution and reduced ecosystem vitality. Climate change makes farmers more vulnerable by reducing crop yields and creating serious challenges for sustainable agriculture (Habib-ur-Rahman *et al.,* 2022).

The concept of integrated tree farming is a sustainable agricultural system that can replace existing cropping patterns like monocropping and intensive chemical inputs, which can decrease soil fertility, reduce biodiversity, and increase vulnerability to climate change. Agroforestry

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systems benefit from trees that enrich soil by improving nutrient availability and enhancing water capture abilities while providing shading benefits as well as biological pest and disease protection (Dissanayaka *et al.,* 2024). Integrated tree farming improves profitability and resilience against natural and economic events by promoting crop diversity and minimizing input dependence. Researchers are investigating the ways to integrate tree farming and boost output and reduce operational expenses through lowered resource consumption remain sparse (Monckton and Mendham 2022). The present research targets this information gap by studying yield enhancement combined with input decrease and the economic gain potential of tree-integrated farming with crops. Agroforestry emerged as a standard land-utilization approach, yet modern research concentrated on it during the 20th and early 21st centuries because it would counter the adverse outcomes of modern farming methods, particularly soil destruction and reduced biodiversity.

The adoption of agroforestry faces main barriers due to economic limitations. Farmers must bear considerable expenses when installing their agroforestry systems, as tree planting requires substantial investments along with irrigation systems and upkeep costs (Chenyang *et al.,* 2021). Agroforestry systems produce valuable goods from timber to non-timber forest products, but still these products become available only after multiple years pass, which might scare off investors looking for quick returns. Lower cash flow and restricted credit access prevent smallholder farmers in developing nations from adopting agroforestry systems, as they lack sufficient funding and market support (Bojang and Emang 2025).

Agroforestry systems boost land productivity through tree management that enhances soil quality, sustains water availability, and controls nutrient distribution. The increasing global threat of climate change and food insecurity has brought forward agroforestry as a solution for resolving these urgent problems. agroforestry demonstrates a practical solution for farmers because it enables them to tackle climate change and regain soil fertility. Unsustainable agricultural methods cause extreme soil damage to land across the world because of high chemical fertilizer use combined with deforestation and poor water management. Multiple studies demonstrate that agroforestry is an effective solution to counter these trends by improving soil structure, boosting moisture retention, and reducing erosion (Fahad *et al.,* 2022).

Despite these well-documented ecological benefits, adoption of agroforestry practices remains constrained, especially among smallholder farmers in developing countries. The high initial costs of tree establishment, irrigation, and management, combined with delayed economic returns from timber and non-timber products, discourage investment. Limited access to credit and markets further exacerbates these challenges. Nevertheless, evidence suggests that well-designed agroforestry systems can improve land productivity by up to 30% compared to

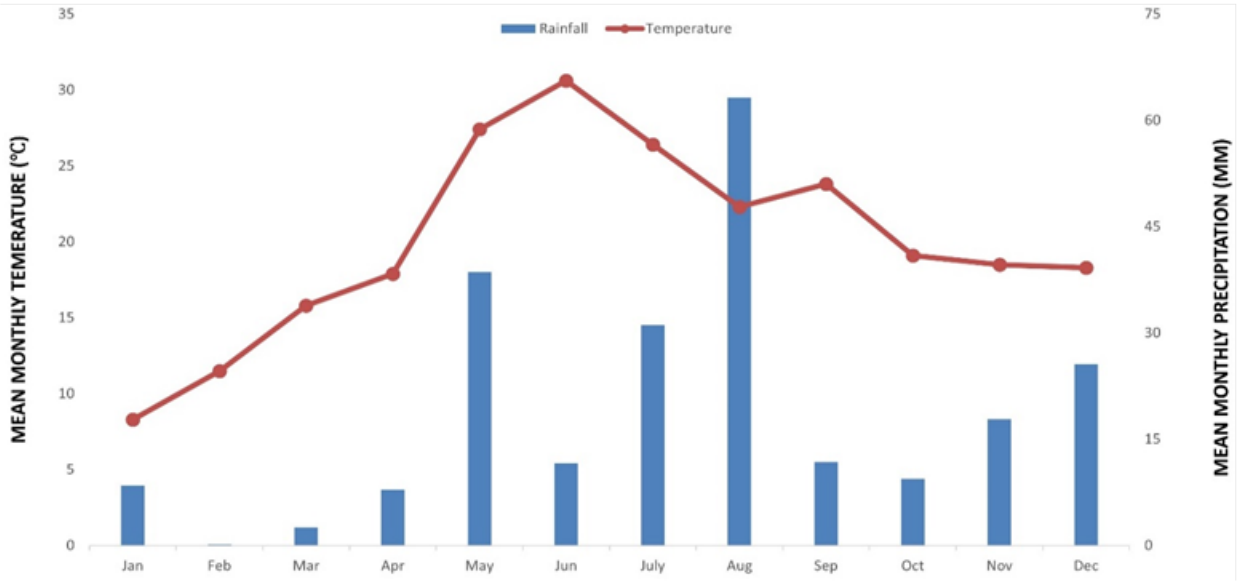


Figure 1: Mean monthly temperature and precipitation data of the weather for three years from the research site

conventional systems, offering both ecological restoration and economic opportunities (Sahoo *et al.,* 2020). Agroforestry systems in semi-arid regions have proven successful at improving soil fertility and boosting crop production while enabling sustainable land practices. The implementation of trees in agroforestry systems combats semi-arid condition threats by enhancing both soil microclimate and natural soil fertility. Agroforestry systems that integrate trees deliver protective shade and wind barriers to crops, which decrease evaporation levels and prevent temperature fluctuations. The advantages of trees contribute to improved soil water conservation while producing beneficial planting conditions, specifically in times of drought (Kumar *et al.,* 2020).

In semi-arid regions, where agriculture significantly contributes to the economy, the need for exploring innovative and sustainable farming practices (agroforestry) becomes imperative. This study delves into the collective impact of integrated tree farming with crops, enhancing both agricultural productivity and soil fertility in this region. Therefore, the current study adopts a strategy and examines two agroforestry systems (wheat-simal agroforestry systems and maize-simal agroforestry systems) and four sole cropping systems (sole-wheat, sole-maize, and sole-simal) with different spacing. The investigation focused to evaluate the potential of integrated tree farming (agroforestry systems) for the restoration of soil fertility, enhance crop productivity, reduce input requirements, and improve economic sustainability in semi-arid areas.

Table 1: Physico-chemical properties of the experimental soil

Parameter	Unit	Value
pH	-	7.85
EC	dS m^{-1}	0.65
NO_3-N	mg kg^{-1}	5.2
P	mg kg^{-1}	4.3
K	mg kg^{-1}	85

Materials and Methods

Site description

The field experiment was conducted during 2022-2024 at the National Research Center of Intercropping (NRCI), The Islamia University of Bahawalpur (IUB), located in South Punjab, Pakistan (29.37°N, 72.75°E; altitude 130 m). The area represents a semi-arid climate, receiving approximately 145 mm of annual precipitation, primarily from end-June to end-August (Figure 1). The mean annual temperature was recorded as 25.7°C. The soil physico-chemical parameters of the research site were also evaluated (Table 1).

Experimental layout and study treatments

A randomized complete block design (RCBD) with three replications was employed to evaluate the effect of tree-crop integration on soil fertility, tree physiology, and crop productivity (Figure 2). The simal (*Bombax ceiba*) was integrated with wheat (*Triticum aestivum* L.) during the Rabi season (WSAS) and maize (*Zea mays* L.) during the Kharif season (MSAS). The treatments included T1: tree-row spacing of 75 cm with 15 cm plant-to-plant distance (30R6P), T2: 150 × 15 cm (60R6P), T3: 225 × 15 cm (90R6P), which is also known as wider spacing, T4: sole cropping of wheat and maize without trees as the control, and T5: sole trees without crops as an additional reference for assessing tree physiology. Within each block, treatments were randomly assigned, with each experimental unit consisting of parallel *Bombax* rows 75 cm, 150 cm, and 225 cm at the designated row spacing and 15 cm plant-to-plant spacing within rows. At the same time, alleys were cultivated with wheat or maize according to the season. All plots were managed under irrigated conditions with uniform tillage, residue handling, and recommended fertilizer applications. Standard buffer zones were maintained between treatments to minimize border effects, and planting and harvesting were conducted using conventional equipment. Data on soil, crops, and tree parameters were recorded from the central portion of each plot to ensure accuracy and avoid edge effects.

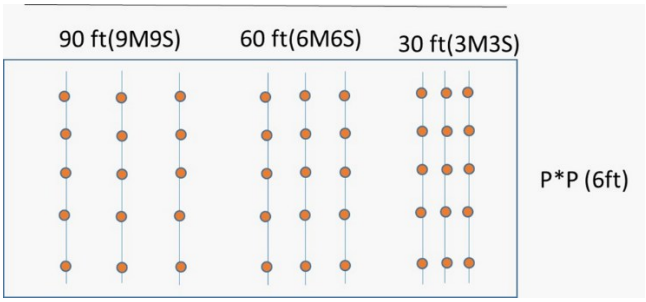


Figure 2: Layout of the study with different treatments, combining tree plantations with crops to evaluate their performance under agroforestry systems

Determining the soil properties before and after the experiment

Soil samples were collected from the plantation of *Bombax ceiba* on the chronological scale (aged 1-8 years) at depths of 0-15 cm and 15-30 cm. Five samples were collected 10 cm away from the trees at each site before and after the experiment. A composite sample was made from

these five collected samples. Twenty-four samples were collected at 0-15 cm and 15-30 cm, respectively. A total of 48 samples were collected, and these were packed in plastic bags and stored at 4 °C for physicochemical analysis. Bulk density, nitrogen, phosphorus, and potassium were analyzed in the Soil Science lab, Faculty of Agriculture and Environment, the Islamia University of Bahawalpur, according to the standard protocols.

Soil nutrients analysis (NPK)

Soil nitrate-nitrogen was determined by extracting 10 g of air-dried soil with 50 mL of 2 M KCl solution, followed by shaking for 30 minutes. The suspension was filtered, and the nitrate concentration in the extract was measured using a UV–visible spectrophotometer. The nitrate-N concentration was calculated based on standard calibration curves and expressed as mg NO_3^--N per kg of soil (Yang *et al*., 2004). Available phosphorus (P) was determined by Olsen's method (Watanabe & Olsen, 1965), where 5 g of soil was extracted with 0.5 M $NaHCO_3$ (pH 8.5). A 5 mL aliquot reacted with a color-developing reagent, and absorbance was recorded at 410 nm using a spectrophotometer, with concentrations obtained from a standard curve. Exchangeable potassium (K) was determined using a flame photometer (Richards, 1954). Standard K solutions were prepared, and emission intensities were plotted to form a calibration curve, against which soil sample readings were compared.

Tree simal (*Bombax ceiba*)

Plant height

At the termination of the experiment, plants were harvested. Plant height/shoot length was measured by using a measuring tape, right from the tip of the shoot to the collar of the plant. Average plant height was calculated for different replications and treatments.

Girth/Diameter of plant

As the stem thickness of the plants was much less, it was not possible to measure directly the girth or diameter by using a diameter tape or a simple measuring tape. So, plant diameter was measured with the help of a digital caliper at the termination of the experiment (Perez-Harguindeguy *et al.,* 2013). The average diameter was calculated for different replications and treatments.

Selection of crops

Wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) were selected for intercropping in the simal (*Bombax ceiba*)-based agroforestry system due to their different growth habits, complementary resource utilization, and local economic importance. Both crops are cereals widely cultivated in subtropical regions and have distinct seasonal growth patterns: maize as a kharif (summer) and wheat as a rabi (winter) crop, respectively, allowing efficient use of land, light, and soil nutrients throughout the year.

Plant height (cm)

At the termination of the experiment, plants were harvested. Plant height/shoot length was measured by using a measuring tape, right from the tip of the shoot to the collar of the plant. Average plant height was calculated for different replications and treatments.

1000-grain weight (g)

From the cleaned grain sample, 1000 kernels were manually counted and weighed using a digital balance. Weights were adjusted to 14% moisture. This reflects kernel development and sink capacity (Gomez *et al.,* 2022).

Photosynthetic rate

Photosynthetic rate is the total rate of photosynthetic Carbon dioxide fixation minus the rate of loss of Carbon dioxide during respiration. As CO_2 is found in the atmosphere at very low concentrations (about 0.04%), any increase in its concentration causes a rapid rise in the photosynthetic rate. This was measured by using Infrared Gas Analyzer (IRGA), LCA-4 Portable Photosynthesis System, Analytical Development Company, Hoddesdon, England.

Transpiration rate

The process in which plants absorb water through their roots and lose it from their aerial parts, such as the stem, branches, leaves, and flowers, etc. This was measured by using Infrared Gas Analyzer (IRGA), LCA-4 Portable Photosynthesis System, Analytical Development Company, Hoddesdon, England.

Stomatal conductance

Stomatal conductance estimates the rate of gas exchange and transpiration through the leaf stomata as determined by the degree of stomatal 41 apertures. This was also measured by using Infrared Gas Analyzer (IRGA), LCA-4 Portable Photosynthesis System, Analytical Development Company, Hoddesdon, England.

Intercellular CO_2 concentration

An increase in carbon dioxide concentration directly increases the process of photosynthesis, but this increase

depends on the plant species and other physiological conditions of the plant. Such changes will not only affect photosynthetic rate but can also affect other mechanisms as well. This was also measured by using an Infrared Gas Analyzer (IRGA), LCA-4 Portable Photosynthesis System, Analytical Development Company, Hoddesdon, England.

Statistical analysis

Significant differences among treatments were assessed using analysis of variance (ANOVA). Treatment means were compared using the Least Significant Difference (LSD) test, following the procedure of Gomez and Gomez (1984), using Statistix 8.1 software.

Results

Tree-crop synergies and soil nutrient contents

Soil nutrient (NPK) availability showed consistent improvement from 2022 to 2024 with wider tree spacing, and the maximum values were generally observed under sole cropping (Figure 3). For soil nitrate-nitrogen (NO_3^--N), the close spacing system (T1) always recorded the lowest values, while the sole cropping system (T4) recorded the highest. Compared to T1, T2 and T3 showed moderate increases ranging between 17-33%, whereas T4 showed the greatest rise of around 46-48%. Over the three years, the soil NO_3^--N concentration increased from 4.38 (T1, 2022) to 7.32 (T4, 2024). Soil phosphorus (P) content displayed a similar trend. Incremental gains were seen with wider spacing, with T2 and T3 showing increases of about 16-21% compared to T1 (Figure 4). The sole cropping treatment consistently produced the highest phosphorus levels, which were 24-32% greater than T1. Across the years, phosphorus values improved from 3.56 (T1, 2022) to 5.37 (T4, 2024), indicating a steady rise in soil fertility with reduced tree competition. Soil potassium (K) levels also increased across all treatments (Figure 5), though the magnitude of change was smaller compared to nitrate-nitrogen and phosphorus. T2 consistently recorded the highest increases of about 9-11% over T1, followed by modest gains in T3 (3-5%) and

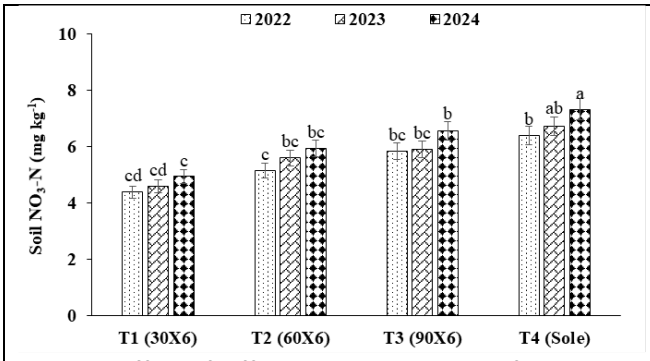


Figure 3: Effect of different simal-based agroforestry systems on Soil NO_3-N content in three years (2022-2024)

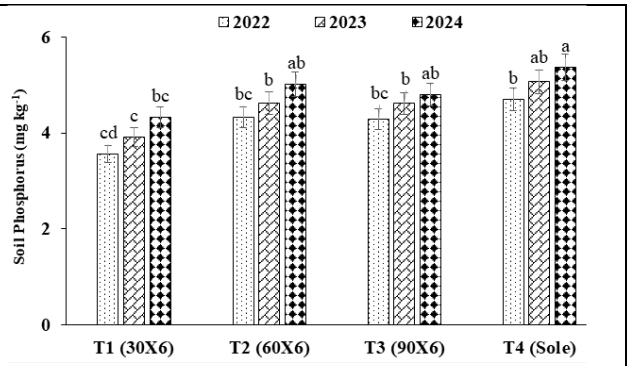


Figure 4: Effect of different simal-based agroforestry systems on Soil phosphorus (P) content in three years (2022-2024)

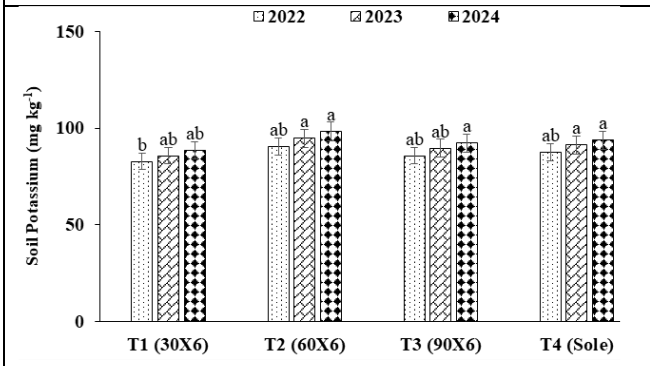


Figure 5: Effect of different simal-based agroforestry systems on Soil potassium (K) content in three years (2022-2024)

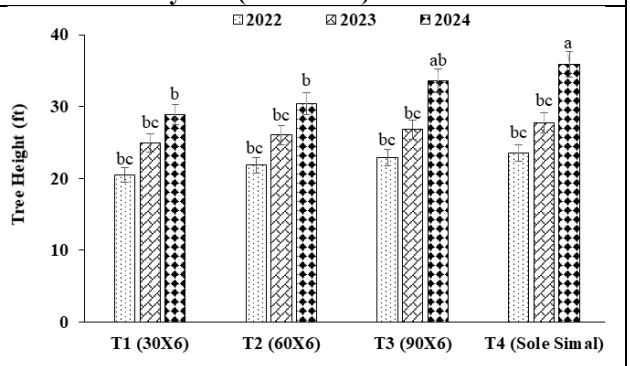


Figure 6: Effect of different simal-based agroforestry systems on Tree height of simal from 2022 to 2024

T4 (about 6%). The potassium content rose from 82.67 (T1, 2022) to 97.33 (T2, 2024), highlighting that moderate spacing was more favorable for potassium retention than sole cropping.

Impact of tree-crop synergies on tree growth

In 2022, simal mean height at T1 was 51.25 cm, the lowest across all treatments (Figure 6), indicating the constraints on growth caused by close spacing and intercropping of wheat and maize. T2 and T3 were observed to have mean heights of 54.6 cm and 57.33 cm, meaning that they had increased by 6.51% and 11.83% relative to T1. Treatment T4 which comprised only simal treatment, led to the tallest trees at 58.73 cm, which made 14.57 % advancement to T1. In 2023, simal height was recorded in T1 whose mean height was 62.33 cm. T2 and T3 recorded 65.03 cm and 67.05 cm, which were 4.31 % and 7.58 % higher than that of T1. Sole cropping (T4) had a mean height of 69.38 cm, equivalent to 11.30% taller than trees in T1. In 2024, T1 trees also had a steady level of growth. The T2 and T3 trees had a height of 75.85 cm and 83.88 cm, respectively, where T3 expressed a 16.18% increase over T1. The sole simal trees showed the maximum rate of growth once more to be high, 89.58 cm, which is a 24.10 % increase compared to T1.

In 2022, T1 mean was 16.56 cm. T2, T3 as well as T4 documented (Figure 7) mean diameters of 17.88 cm, 18.67 cm, and 18.33 cm respective. In 2023, T1 mean was 18.85 cm, T2 grew to 21.07 cm with a growth advantage of 11.76% compared to T1 and T3 and T4 had more significant mean diameters of 22.18 cm and 23.43 cm that had a comparative growth advantage by 17.63 and 24.28% in respect to T1 and T2 respectively. In 2024, average diameter in T1 trees was 22.57 cm, whereas the corresponding diameter in T2 and T3 was found to be 25.50 cm and 29.39 cm with increase of 12.98% and 30.19% respectively. Sole simal trees (T4) had the highest diameter value of 31.77 cm representing an incredible 40.76% gain compared to the baseline T1.

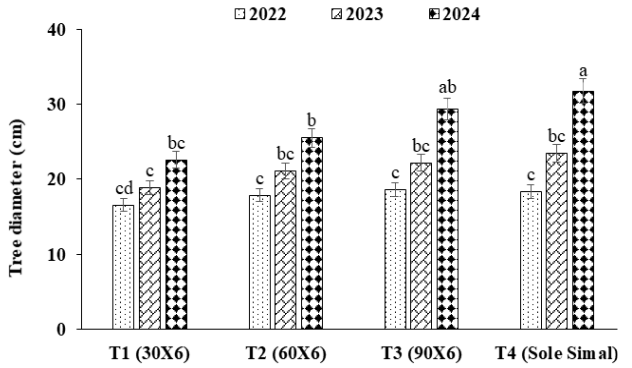


Figure 7: Effect of different simal-based agroforestry systems on Tree diameter from 2022 to 2024

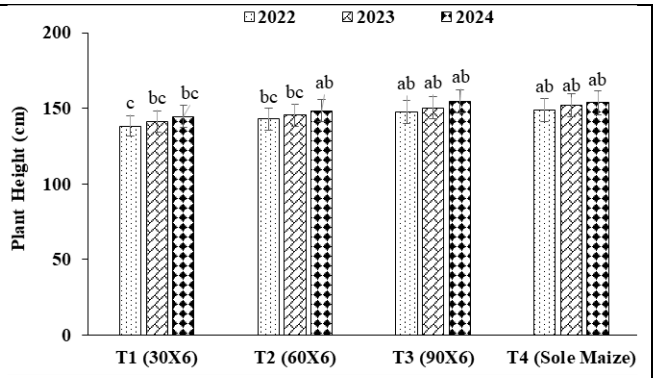


Figure 8: Effect of different simal-based agroforestry systems on maize plant height (2022-2024)

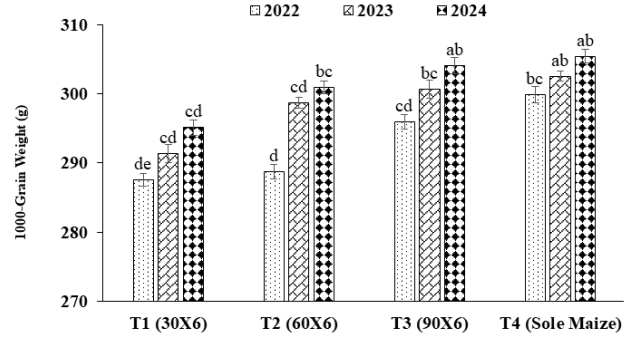


Figure 9: Effect of different simal-based agroforestry systems on maize 1000-grain weight from 2022 to 2024

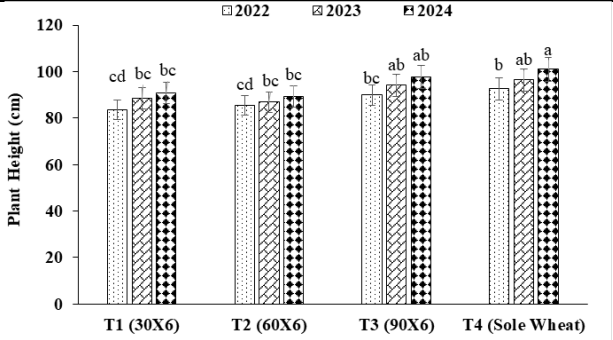


Figure 10: Effect of different simal-based agroforestry systems on wheat plant height from 2022 to 2024

Impact of tree-crop synergies on crop growth

Over all years, plant height and grain weight of maize and wheat increased with wider spacing and in sole cropping systems, indicating reduced competition under lower tree densities.

For maize, mean height improved progressively with increased spacing (Figure 8). In 2022, the lowest height was 138.25 cm occurred in T1, while T2, T3, and T4 reached 142.83 cm, 147.55 cm, and 148.75 cm, showing 3.31%, 6.73%, and 7.6% increases over T1, respectively. Similar trends continued in 2023 and 2024. Maize grain weight followed the same pattern (Figure 9). In 2022, T1 averaged 287.59 g, increasing marginally through T2 (288.73 g) and T3 (295.94 g), and peaking in T4 (299.91 g). The differences persisted in 2023 and 2024, though they narrowed with time. In 2024, grain weight ranged from 295.13 g (T1) to 305.43 g (T4), a modest 3.49% increased that the effect of spacing stabilized as trees matured.

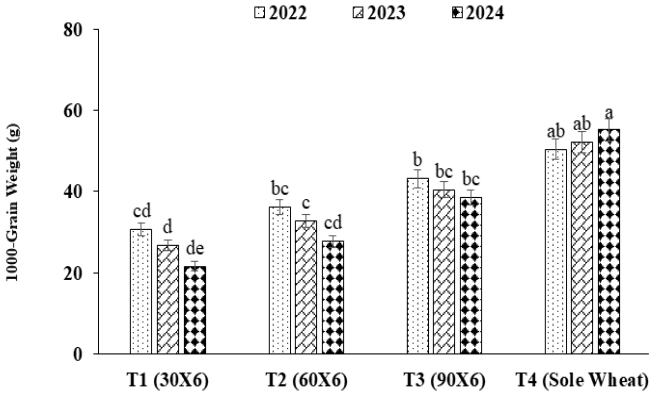


Figure 11: Effect of different simal-based agroforestry systems on wheat 1000-grain weight from 2022 to 2024

For wheat, similar responses were observed (Figure 10). In 2022, plant height ranged from 83.6 cm (T1) to 92.53 cm (T4)10.69% increase with sole cropping. Though a minor reduction appeared in T2 in 2023, wider spacing (T3 and T4) continued to enhance height. In 2024, the sole crop was recorded in T4 (100.93 cm), 11.24% higher than T1. The 1000-grain weight of wheat (Figure 11) exhibited a sharp rise with wider spacing and absence of tree competition. In 2022, it increased from 30.63 g (T1) to 50.41 g (T4) 64.58% improvement. Similar patterns in 2023 and 2024, with T4 maintaining the highest grain mass (55.19 g), equivalent to a 154.94% increase over T1.

Impact of tree-crop synergies on crop physiology

The physiological performance of maize and wheat showed consistent improvement with wider spacing and sole cropping, while closer spacing with simal (*Bombax ceiba*) significantly reduced photosynthesis, transpiration, and stomatal conductance.

For maize, photosynthetic rates increased from 22.62 µmol CO_2 m^{-2} s^{-1} (T1) in 2022 to 28.92 µmol CO_2 m^{-2} s^{-1} (T4), marking a 27.87% rise under sole cropping (Table 2). Similar patterns persisted through 2023-2024, where T4 consistently outperformed T1 by 25-31%. Transpiration and stomatal conductance followed the same trend, increasing proportionally with wider spacing transpiration rose from 1.27 to 3.78 µmol H_2O $m^{-2}s^{-1}$, while conductance improved from 0.065 to 0.121 mmol $m^{-2}s^{-1}$ across T1-T4. Conversely, intercellular CO_2 concentration (Ci) decreased as spacing widened, reflecting more efficient CO_2 fixation in widely spaced and sole maize plots, with up to 30% lower Ci in T4 compared to T1.

In the wheat, wider tree spacing and sole cropping likewise enhanced physiological traits (Table 3). Photosynthesis rose from 20.62 µmol CO_2 m^{-2} s^{-1} (T1) to 26.92 µmol CO_2 m^{-2} s^{-1} (T4) in 2022, with a consistent 25-34% advantage for sole wheat across years. Transpiration increased moderately from 1.04 to 1.86 µmol H_2O $m^{-2}s^{-1}$, and stomatal conductance improved from 0.056 to 0.096 mol H_2O $m^{-2}s^{-1}$, indicating better gas exchange in less competitive environments. Ci values declined progressively in wider and sole plots, demonstrating more efficient CO_2 utilization under reduced shading and competition.

Discussion

The results have provided strong evidence in support of the study that agroforestry systems are not only impacted by immediate competition for nutrients but also by long-term nutrient cycling processes. This increase in nitrate-nitrogen content in agroforestry systems over time may be due to the gradual accumulation of nitrogen from various sources, such as nitrogen fixation by leguminous plants or nitrogen leaching from the decomposition of organic matter. These results might be due to the fact that wider spacing treatments provide balanced nutrition, where tree biomass and root turnover contributed to a steady release of nitrogen into the soil (Baidoo *et al.,* 2025). Agroforestry systems experience progressive benefits over time, especially as the trees mature and establish more extensive root systems. Additionally, soil organic matter, which is closely linked to

Table 2: Effect of simal plantation on photosynthetic parameters of maize under different simal-based agroforestry systems and sole cropping (2022-2024)

Year	Treatment	Photosynthesis	Transpiration rate	Stomatal conductance	Intercellular CO_2 concentration
		($\mu mol\ CO_2\ m^{-2}\ s^{-1}$)			
2022	30R6P	22.62 ab	1.27 b	0.06 bc	143.43 ab
	60R6P	25.11 a	2.31 ab	0.07 b	133.79 b
	90R6P	27.51 a	3.27 a	0.08 ab	114.89 bc
	Sole	28.92 a	3.67 a	0.09 ab	100.38 cd
2023	30R6P	21.63 ab	1.37 b	0.07 b	151.11 a
	60R6P	23.47 ab	2.54 ab	0.08 ab	138.22 ab
	90R6P	24.36 ab	3.32 a	0.09 ab	120.93 bc
	Sole	27.27 a	3.67 a	0.11 a	105.06 c
2024	30R6P	19.53 b	1.55 b	0.03 c	156.61 a
	60R6P	22.17 ab	2.76 ab	0.08 ab	147.33 a
	90R6P	23.33 ab	3.33 a	0.09 ab	128.97 b
	Sole	25.53 a	3.78 a	0.12 a	111.51 bc

Table 3: Effect of simal plantation on photosynthetic parameters of wheat under different simal-based agroforestry systems and sole cropping (2022-2024)

Year	Treatment	Photosynthesis	Transpiration rate	Stomatal conductance	Intercellular CO_2 concentration
		($\mu mol\ CO_2\ m^{-2}\ s^{-1}$)			
2022	30R6P	20.62 b	1.04 de	0.05 c	121.14 b
	60R6P	23.13 ab	1.31 cd	0.06 bc	122.16 b
	90R6P	25.51 a	1.21 d	0.07 b	114.14 bc
	Sole	26.92 a	1.49 ab	0.09 ab	94.79 d
2023	30R6P	19.82 b	1.37 c	0.06 bc	128.61 ab
	60R6P	21.67 b	1.54 a	0.07 b	128.09 ab
	90R6P	22.36 ab	1.32 c	0.08 ab	119.87 bc
	Sole	25.27 a	1.67 a	0.10 a	101.43 cd
2024	30R6P	17.53 bc	1.48 ab	0.07 b	135.21 a
	60R6P	20.17 b	1.74 a	0.08 ab	137.75 a
	90R6P	21.33 b	1.78 a	0.09 ab	127.22 ab
	Sole	23.53 ab	1.87 a	0.13 a	109.03 c

nitrogen content, may have increased in the agroforestry systems with wider tree spacings, which could have contributed to enhanced nitrogen availability it was might be due to the agroforestry systems which often promote organic matter accumulation in the soil, which in turn supports the cycling of nitrogen and other essential nutrients (Schroder *et al.,* 2016).

Soil fertility can improve by increasing the organic matter content and promoting nutrient cycling, especially with the right spacing. However, monoculture systems often show superior nutrient availability, as they are managed with more direct nutrient inputs and are not subject to the complexities of agroforestry. Agroforestry systems show promising improvements in soil phosphorus over time, the sole cropping system remains the most effective in maintaining high phosphorus levels (Fahad *et al.,* 2022). The differences observed between agroforestry and sole cropping systems highlight the importance of nutrient management in determining soil fertility. The plants have more space to expand their root systems, leading to better nutrient uptake and more efficient phosphorus cycling in the soil (Nair *et al.,* 2022). The intercropping nature of agroforestry systems may also improve microbial activity, particularly mycorrhizal fungi, which are known to enhance phosphorus uptake by plants. Additionally, tree species in

agroforestry systems can contribute organic matter to the soil, which can increase the solubility of phosphorus, thereby making it more available to plants. It was emphasized from the earlier studies that proper spacing in agroforestry systems is essential for optimizing nutrient cycling and maintaining soil fertility (Fahad *et al.,* 2022).

Potassium is a critical nutrient for plant growth, affecting various physiological processes such as photosynthesis, water regulation, and disease resistance. Wider spacing in agroforestry systems can enhance crop productivity by ensuring that plants have adequate access to potassium throughout their growing cycle (Hasanuzzaman *et al.,*2018). Studies have shown that adequate potassium availability leads to better plant health and higher yield. Therefore, the results of this study imply that agroforestry systems, particularly those with optimal spacing, can not only maintain soil fertility but also improve crop productivity over time. Spacing plays a crucial role in nutrient availability in agroforestry systems. Wider spacing allows for better root growth and reduces competition, leading to more efficient potassium uptake by plants. While agroforestry systems with optimized spacing can outperform sole crops in maintaining or improving potassium content over time. This finding aligns with broader research on agroforestry systems, which suggest that these systems can enhance soil fertility and nutrient cycling (Goulart *et al.,* 2020). The increased competition for potassium, due to the high plant density, likely led to the depletion of available potassium in the soil. This is in line with findings from previous studies that report that high plant density in agroforestry systems can increase nutrient depletion. In contrast, the wider spacing allowed for a more balanced nutrient uptake by reducing root overlap, facilitating better access to potassium, and mitigating nutrient competition (Sardans and Peñuelas 2021).

Growth of simal (*Bombax ceiba*) is strongly affected by tree spacing and agroforestry systems. Closely spaced tree shows reduced height due to competition with crops for light, water and nutrients. While wider spacing or sole planting promotes better growth but reduces crops yield. This demonstrates a trade-off between maximizing tree performance and maintaining crop productivity. Proper spacing not only mitigates competition but also enhances overall system productivity, biodiversity and ecosystem resilience (Fahad *et al.,* 2022). The study demonstrates that tree spacing significantly mitigates competition in agroforestry systems, directly influencing grain weight over time. Lower grain weights under closer spacing confirm intense tree–crop competition for light, water, and nutrients (Nair *et al.,* 2022), consistent with observations in semi-arid systems where dense tree stands reduced crop yield. As spacing widened, grain weight improved, indicating reduced competitive stress and enhanced resource availability (Pardon *et al.,* 2025). These results support the notion that moderate tree densities can balance tree growth with crop productivity, optimizing ecosystem services. Furthermore, the progressive improvement in grain weight suggests that wider spacing facilitates long-term adjustments in root and canopy architecture, minimizing interspecific competition (Dissanayaka *et al.,* 2024).

The findings underscore that agroforestry systems in semi-arid regions can sustain crop yields when tree spacing is properly optimized. The minimal grain weight differences under wider spacing indicate that trees can be integrated into cropping systems without major yield penalties, while contributing to long-term benefits such as improved soil fertility, nutrient cycling, and microclimate regulation (Tadesse *et al.,* 2021). Wider spacing not only maintains yield competitiveness with sole cropping but also supports multifunctional ecosystem services, including soil conservation, carbon sequestration, and resilience to climate variability (Fahad *et al.,* 2022). Tree spacing also significantly affected the number of grains per spike, a key determinant of maize yield potential (Lee and Tollenaar, 2007). Closer spacing produced the lowest values, reflecting intense competition for light, nutrients, and moisture (Nyaga *et al.,* 2019), whereas wider spacing enhanced spikelet initiation and fertilization due to improved resource availability and reduced stress (Zhu *et al.,* 2019). These trends suggest that moderate tree densities can preserve crop reproductive performance while retaining ecological advantages. Properly managed spacing allows intercropped maize and wheat to perform comparably to sole cropping in terms of reproductive output, stabilizing tree-crop interactions over time (Kuyah *et al.,* 2021). Overall, the results affirm that optimized tree spacing is central to sustainable intensification in semi-arid agroforestry, balancing productivity with ecosystem resilience (Morales *et al.,* 2020).

Photosynthesis, the key physiological process driving tree growth and productivity, is strongly influenced by tree spacing and planting systems. Simal (*Bombax ceiba*) trees grown under wider spacing or in monoculture systems exhibit higher photosynthetic rates than those in dense agroforestry arrangements, largely due to reduced competition for light, carbon dioxide, and nutrients (Rangappa *et al.,* 2025). Similarly, transpiration rates increase with greater spacing, as wider distances allow

better water uptake and canopy cooling, while dense stands restrict transpiration through intensified water competition (Adewumi *et al.,* 2020). Stomatal conductance crucial for gas exchange and water regulation also rises under wider spacing and monoculture conditions, supporting enhanced photosynthesis and growth by facilitating efficient CO_2 uptake (Luo *et al.,* 2021). Furthermore, intercellular CO_2 concentration (Ci) levels reflect improved carboxylation efficiency in widely spaced trees, where unrestricted light and nutrient access promote greater carbon assimilation (Silveira and Marenco, 2023). These physiological responses collectively demonstrate that optimizing tree spacing in agroforestry systems enhances photosynthetic performance, water-use efficiency, and overall productivity (Bhushan *et al.,* 2025).

Conclusion

The findings indicate that the wider spacing treatment (T3: 9R6P) provided the optimal balance between tree growth, maize yield, and soil nutrient improvement. While wider spacing (T3: 9R6P) favoured tree performance, it reduced maize productivity due to lower canopy interaction. Conversely, closer spacing (T1 and T2) led to greater competition for light and nutrients, limiting both. Therefore, the 9R6P configuration is recommended as the most effective spacing for achieving sustained productivity and soil health improvement under simal-based agroforestry systems in semi-arid conditions. Long-term monitoring of soil fertility, carbon dynamics, and water-use efficiency is further encouraged to consolidate the role of simal-based agroforestry in climate-smart agriculture.

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