



RESEARCH ARTICLE

Performance of millet intercrops under *Casuarina junghuhniana* Miq.-based agroforestry system and consequent changes in soil fertility

B Sivakumar¹, K Ananthi^{2*}, A Balasubramanian¹, S Radhakrishnan³, P Rajendran¹, B Muralidharan⁴,
S Navaneetha Krishnan¹, S Ashwin Kumar¹, R Adithiyan¹ & P Ravi Raja Simman¹

¹Forest College and Research Institute, Tamil Nadu Agricultural University, Mettupalayam 641 301, Tamil Nadu, India

²Agricultural College and Research Institute, Tamil Nadu Agricultural University, Tiruvannamalai 606 753, Tamil Nadu, India

³Horticulture College and Research Institute, Periyakulam 625 604, Tamil Nadu, India

⁴Horticulture College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 001, Tamil Nadu, India

*Correspondence email - ananthik@tnau.ac.in

Received: 20 June 2026; Accepted: 10 August 2026; Available online: Version 1.0: 24 September 2026

Cite this article: Sivakumar B, Ananthi K, Balasubramanian A, Radhakrishnan S, Rajendran P, Muralidharan B, Navaneetha KS, Ashwin KS, Adithiyan R, Ravi RSP. Performance of millet intercrops under *Casuarina junghuhniana* Miq.-based agroforestry system and consequent changes in soil fertility. Plant Science Today. 2026;13(sp5):01–10. <https://doi.org/10.14719/pst.16225>

Abstract

An intercropping experiment was made through three consecutive crop cycles with *Casuarina junghuhniana* Miq. Plantations of (Casuarinaceae) established between 3–18 months after tree planting to determine the most suitable millet species and to determine the effect of intercropping on soil fertility. Six millet intercrops-kodo millet (*Paspalum scrobiculatum* L.), foxtail millet (*Setaria italica* (L.) P.Beauv.), finger millet (*Eleusine coracana* (L.) Gaertn.). Invading species include Gaertn., barnyard millet (*Echinochloa frumentacea* Link) and three crop species including little millet (*Panicum sumatrense* Roth) and proso millet (*Panicum miliaceum* L.) were tested in a randomised block design (RBD) with 3 blocks at the tree spacing of 2 m × 2 m. Evaluation was done for growth attributes, dry matter production (DMP), grain yield, crop equivalent yield (CEY), tree growth parameters, soil fertility and economics. Little millet always had the highest DMP (2560–2650 kg ha⁻¹) and grain yield (770–1890 kg ha⁻¹) under intercropping and added the highest value for tree height (5.63 m at 18 months) and wood production (29.84 t ha⁻¹). *C. junghuhniana* + little millet produced the highest total land equivalent ratio (land equivalent ratio (LER) = 2.92) followed by *C. junghuhniana* + barnyard millet (LER = 2.51). Maximum net income (₹26000) and benefit to cost ratio (B : C = 3.16) was also obtained for little millet. The post-harvest soil analysis showed that the soil under all intercropping treatment was better in terms of soil electrical conductivity, soil organic carbon and available soil nutrients, namely nitrogen (N), phosphorus (P) and potassium (K) than in the tree-alone treatment. Kodo millet was least compatible intercrop in the study. Little millet is suggested as the best intercrop for *C. junghuhniana*-based short rotation plantation agroforestry, providing a viable option to the smallholder farmers to obtain short-term food and income and to promote the growth of trees and regeneration of soil fertility, thus emphasising the importance of selecting the appropriate species for agroforestry intercrop systems for better ecological and economic returns.

Keywords: agroforestry; *Casuarina junghuhniana*; dry matter production; land equivalent ratio; millet intercropping; nutrient cycling; soil fertility; soil organic carbon

Introduction

Agroforestry systems which combine trees with annual crops can have several benefits for sustainable land use such as increased productivity, soil health and benefits to the smallholder farmer's economy (1). The diversification of agroforestry systems has been recognised as an imperative for food security and to decrease rural poverty in developing countries, especially in the tropics and subtropics where land degradation is a problem (2). Fast growing multipurpose tree species play a special role as part of the agricultural system in the South and Southeast Asian agriculture context (3). The association of trees and food crops is a fundamental element of climate-smart agriculture with both mitigation and adaptation benefits under climate variability (4).

Casuarina junghuhniana Miq., a non-leguminous biological nitrogen fixing actinorhizal tree (family Casuarinaceae) is an exotic species (5). Indigenous cultivation of the species is vast in the coastal and inland regions of Tamil Nadu Andhra Pradesh and Odisha in India for pulpwood, fuelwood and land reclamation and the rotation period is 3 to 4 years (6). The nitrogen (N₂) fixation ability and the perennial deposition of leaf litter by *C. junghuhniana* will continuously increase the soil organic carbon and mineral nitrogen pools, potentially leading to improving productivity of associated intercrops (7). The enrichment effects have been also recorded for other actinorhizal tree species in agroforestry setting, thus supporting the ecological importance of using nitrogen-fixing trees in mixed land-use systems (8).

The situation with *C. junghuhniana* is somewhat different as, during the early growth phase (up to eighteen months after planting), the tree canopy is relatively open and there is less competition for light. Intercropping is therefore possible during this stage with crops for short duration. This is different in the case of *C. junghuhniana* because the tree canopy is relatively open and that there is less competition for light in the earlier growth phase (zero to eighteen months after planting) (9). The amount of light reaching the understorey is an important factor in determining the success of intercropping in a tree-based system and the timing of canopy closure needs to be considered when choosing a suitable combination of crop species (10, 11). The small millets (*Paspalum scrobiculatum* L., *Setaria italica* (L.) P.Beauv., *Eleusine coracana* (L.) Gaertn., *Elechinochloa frumentacea* Link, *Panicum sumatrense* Roth and *Panicum miliaceum* L.) are grouped together under 'nutri-cereals because they have a high micronutrient content, better dietary fibre and high tolerance for marginal soil and low rainfall (12). This makes them ideal for use in understory cropping systems in early rotation.

The land equivalent ratio (LER) is the standard indicator for performance evaluation of mixed cropping systems and is represented by the relative land area needed for sole crops to achieve the same production as does an intercrop (13). Meta-analyses published have shown that intercropping systems generally result in an LER of 1.2 to 1.8 in various agroecosystems, representing significant land use efficiency compared to monoculture (14). The LER values commonly are greater than 2.0 in tree-based agroforestry due to the complementary nature of the tree and agroforestry components in several resource dimensions (15). Market prices and input costs also have a significant impact on the economic performance of such systems and benefit to cost analysis is a widespread tool that has been used to evaluate the viability of an agroforestry enterprise (16). Although the agronomic potential of *C. junghuhniana* is well documented, systematic assessment of the performance of millet species as intercrops over multiple production cycles and their simultaneous impact on the growth of trees and soil fertility has not been reported in the literature. Uses of cereals and millets in tree-based systems have been documented to be productive (17, 18), but few of these studies have focused on species specific compatibility over several crop cycles. The present study aimed, therefore, to (i) identify the most compatible millet intercrop for the *C. junghuhniana*-based agroforestry at 3, 9 and 18 months after planting; (ii) quantify the effect of intercropping on *C. junghuhniana* growth and wood production; and (iii) characterise the changes in soil physicochemical properties caused by intercropping.

Materials and Methods

Experimental site and design

The experiment was carried out for a period of eighteen months at Forest College and Research Institute, Coimbatore, India (11.32° N, 76.94° E, 426 m above sea level). The soil used in this experiment was a sandy loam. Prior to planting the tree, pre-experimental (baseline) soil characterisation of composite samples (0–30 cm depth) showed the following values: soil organic carbon (OC) 0.43 %, soil available nitrogen (N) 168 kg ha⁻¹, soil available phosphorus (P) 8.4 kg ha⁻¹, soil available potassium (K) 121 kg ha⁻¹ and pH (near-neutral) 7.62. These baseline values indicate that the fertility level of the soils is low to

medium and are typical of soils found in the Coimbatore area and serve as a benchmark for the assessment of soil improvements after harvest. The experiment was laid out in a randomised block design (RBD) with 3 replications and 6 treatments. The *C. junghuhniana* was planted at 2 m × 2 m (2500 trees ha⁻¹) spacing with north-south tree row planting to place trees to receive uniform light. The size of each gross plot was 6 m × 6 m (36 m²) with four rows of trees and the millet intercrop sown in between the rows and the net plot was 4 m × 4 m, without border rows and trees, for growth, yield and soil sampling. Each of the 6 millets was grown in intercropped and also in sole-crop (pure-stand) design, where intercropped and sole-crop plots were planted in the same RBD and replicated 3 times with an adjacent block of the same size (6 m × 6 m) under tree-free conditions where all agronomic management was identical except for the crop configuration. To reduce inter-plot competition for light, moisture and nutrients and to avoid the lateral rooting of plots growing in the same block, a 1.5 m unplanted buffer strip was used between adjacent plots within a block and a 2 m buffer was used between the intercropped block and the sole-crop block to prevent lateral root interference between treatments. Three intercrops - 0–6 months as first crop, 6–12 months as second crop and 12–18 months as third crop - were grown after the tree planting.

Treatments

The six treatments were: T₁: *C. junghuhniana* + kodo millet; T₂: *C. junghuhniana* + foxtail millet; T₃: *C. junghuhniana* + finger millet; T₄: *C. junghuhniana* + bamyard millet; T₅: *C. junghuhniana* + little millet; and T₆: *C. junghuhniana* + proso millet. Each intercrop was also grown as a pure (sole) crop under identical conditions for comparative purposes. A tree-alone plot (control) was maintained for tree growth assessments.

Growth and yield assessments

Intercrop plant height (cm) and collar diameter (mm) were recorded at 30 days after sowing (DAS), 60 DAS and at harvest. Dry matter production (DMP, kg ha⁻¹) and grain yield (kg ha⁻¹) were measured at harvest for both intercropped and sole-cropped plots. Crop equivalent yield (CEY) was calculated by converting non-monetary yields into equivalent units of a reference crop.

The land equivalent ratio (LER) was calculated as the sum of the partial LERs for the tree and intercrop components according to Willey (13): $LER = (\text{intercrop yield} / \text{sole-crop yield}) + (\text{tree volume under intercropping} / \text{tree volume under monocropping})$. The LER calculations follow the framework established for tree-crop systems, where values greater than 1.0 confirm a productivity advantage of the mixed system over component monocultures (15).

Tree growth measurements

Tree height (m) and basal diameter (mm) of *C. junghuhniana* were recorded at 6, 12 and 18 months after planting. Current annual increment (CAI) in height and basal diameter was calculated for the 6–18-month period. Mean tree volume (m³ tree⁻¹) was estimated using standard allometric equations for the species and wood production (t ha⁻¹) was derived from tree volume and wood density (9). Allometric approaches for estimating biomass in short-rotation plantations have been validated across multiple *Casuarina* species and growing conditions (19).

Soil analysis

Composite soil samples (0–30 cm depth) were collected from each

plot after the final crop harvest. Soil pH was measured potentiometrically in a 1 : 2.5 soil-to-water suspension; electrical conductivity (EC, dS m^{-1}) in a 1:2.5 aqueous extract; soil organic carbon (OC) by the Walkley-Black wet oxidation method; available N by the alkaline permanganate method; available P by the Olsen method; and available K by flame photometry following neutral normal ammonium acetate extraction (20). These standard methods have been widely applied in agroforestry soil fertility assessments and are recognised for their reliability under tropical field conditions (21).

Economic analysis

The cost of cultivation for each treatment was computed by summing all major variable input costs, namely hired and family labor (land preparation, sowing, weeding and harvesting operations), seed/planting material, fertilisers and soil amendments, plant protection chemicals and irrigation (energy and water charges), while fixed costs associated with tree establishment were excluded from the intercrop cost estimate since they are amortised over the full plantation rotation. Gross income was computed by multiplying the grain and by-product (straw/stover) yield of each treatment by the prevailing local farm-gate market price of the respective millet during the harvest season of the corresponding crop cycle (2023–24) and net income was derived as gross income minus the cost of cultivation. The benefit-to-cost (B : C) ratio was computed as gross income divided by cost of cultivation. Because market prices are subject to seasonal and inflationary fluctuation, all price data used in the economic analysis correspond to a single harvest season to ensure internal comparability across treatments and readers applying these values to other locations or time periods should adjust for local price and inflation differences. Economic analyses of agroforestry systems often incorporate both direct marketable outputs and ecosystem service values; however, the present analysis was restricted to marketable crop and wood yields in accordance with standard farm-level economic appraisal practice (16).

Statistical analysis

All data were subjected to analysis of variance (ANOVA) appropriate for a RBD. The standard error of the difference (SEd) and critical difference (CD) at $p = 0.05$ were computed for mean separation. Multiple comparison among the 6 millet intercrop treatments was performed using Duncan's multiple range test (DMRT) at $p = 0.05$. All

statistical procedures were performed using OPSTAT statistical software (CCS Haryana Agricultural University, Hisar, India). Additionally, a principal component analysis (PCA) was performed on the normalised, treatment-variable matrix (scaled to unit variance). The resulting PCA biplot was utilised to synthesize, cross-examine and visually interpret the overarching multi-variable interactions establishing the ecological and economic compatibility of the different millet intercrops within the *C. junghuhniana* agroforestry system. Pearson correlation coefficients (r) were computed to cross-examine linear dependencies between understorey agronomic yield traits, overstorey wood production metrics, post-harvest soil nutrient variables and total economic indicators. The resulting correlation matrix was mapped into a color-coded geometric tile matrix (correlogram) using ggplot2 to visualise the structural mechanisms regulating tree-crop-soil dynamics

Results

First-cycle intercrop performance (3–6 months after tree planting)

Significant differences were recorded in plant height and collar diameter of all millet intercrops compared to their corresponding pure-crop values throughout the first crop cycle (Tables 1 and 2). At 60 DAS, little millet (T_5) recorded the greatest plant height under intercropping (46.50 cm) compared to its sole-crop value (49.4 cm), while barnyard millet (T_4) showed the highest collar diameter (9.5 mm at 60 DAS). At final harvest, plant heights ranged from 92.10 cm (Kodo millet) to 102.0 cm (Little millet) under intercropping versus 92.7 to 123.6 cm in sole cropping, indicating a moderate but significant suppression of height growth under the partial shade of tree canopy.

In the first crop cycle, the highest DMP (2560 kg ha^{-1}) and grain yield (1890 kg ha^{-1}) under intercropping were recorded for little millet (T_5), whereas kodo millet (T_1) recorded the lowest values (DMP: 1975 kg ha^{-1} ; grain yield: 720 kg ha^{-1}). The yield reduction under intercropping relative to sole cropping was most pronounced in kodo millet (55 % reduction) and least pronounced in little millet (16 % reduction). Little millet also attained the highest CEY in the first cycle (Table 3).

Table 1. Effect of intercropping with *Casuarina junghuhniana* on plant height of intercrops in the first crop cycle (cm)

Sl.No.	Intercrops	30 DAS IC	30 DAS PC	60 DAS IC	60 DAS PC	Harvest IC	Harvest PC
1.	Kodo millet	32.6	33.8	34.0	36.2	92.10	92.7
2.	Foxtail millet	36.5	38.6	42.8	44.6	96.4	97.5
3.	Finger millet	39.4	42.4	39.1	40.8	94.5	95.6
4.	Barnyard millet	32.1	33.8	40.4	44.2	99.20	100.6
5.	Little millet	30.1	32.2	46.50	49.4	102.0	123.6
6.	Proso millet	32.7	34.2	39.4	41.2	99.3	100.3
	SEd			1.38		6.22	6.25
	CD (0.05)			2.81		12.68	12.74

IC: intercropping; PC: pure cropping; DAS: days after sowing.

Table 2. Effect of intercropping with *Casuarina junghuhniana* on collar diameter of intercrops in the first crop cycle (mm)

Sl.No.	Intercrops	30 DAS IC	30 DAS PC	60 DAS IC	60 DAS PC	Harvest IC	Harvest PC
1.	Kodo millet	4.2	4.4	6.5	6.8	7.1	7.4
2.	Foxtail millet	5.5	5.8	7.1	7.5	8.2	8.6
3.	Finger millet	4.9	5.1	8.1	8.5	9.2	9.6
4.	Barnyard millet	6.8	7.2	7.7	8.1	8.5	9.2
5.	Little millet	7.3	7.7	9.5	10.2	10.7	11.9
6.	Proso millet	5.6	5.8	8.1	8.4	8.8	9.0
	SEd			0.20	0.25		0.15
	CD (0.05)			0.40	0.55		0.31

IC: intercropping; PC: pure cropping.

Table 3. Dry matter production and grain yield of millet intercrops in the first crop cycle under *Casuarina junghuhniana* agroforestry

Sl.No.	Intercrops	DMP-IC (kg ha ⁻¹)	DMP-PC (kg ha ⁻¹)	Yield IC (kg ha ⁻¹)	Yield PC (kg ha ⁻¹)	CEY (kg ha ⁻¹)
1.	Kodo millet	1975	2175	720	1600	-
2.	Foxtail millet	2200	2320	1330	1760	-
3.	Finger millet	2178	2378	1220	1960	-
4.	Barnyard millet	2420	2520	860	1245	-
5.	Little millet	2560	2660	1890	2250	Highest
6.	Proso millet	2450	2540	750	840	-
	SEd	31.38		11.69		
	CD (0.05)	72.36		25.47		

DMP: dry matter production; IC: intercropping; PC: pure cropping; CEY: crop equivalent yield.

Second-cycle intercrop performance (6–12 months after tree planting)

In the second crop cycle, finger millet (T₃) recorded the greatest plant height at 60 DAS (49.5 cm) under intercropping, followed by proso millet (T₆) (42.7 cm). At final harvest, little millet attained the highest plant height (105.2 cm) under intercropping. The DMP and grain yield trends were consistent with the first cycle: Little millet registered the highest DMP (2650 kg ha⁻¹) and grain yield (1870 kg ha⁻¹) under intercropping, while kodo millet continued to perform least favourably (DMP: 2075 kg ha⁻¹; yield: 820 kg ha⁻¹). The highest CEY was again recorded for little millet (Table 4).

Third-cycle intercrop performance (12–18 months after tree planting)

By the third cycle (12–18 months after tree planting), increasing canopy closure progressively reduced light penetration to the understory, resulting in an overall decline in intercrop productivity compared to the first two cycles. Proso millet (T₆) exhibited the greatest plant height (39.4 cm at 60 DAS) in the third cycle, whereas little millet recorded the highest collar diameter (7.2 mm). Despite the reduced yields across all treatments in the third cycle, little millet maintained its superiority with the highest DMP (2560 kg ha⁻¹) and grain yield (770 kg ha⁻¹) under intercropping and Kodo millet recorded the lowest grain yield (510 kg ha⁻¹). The highest CEY in the third cycle was again associated with little millet (Table 5).

Effect of intercropping on *Casuarina junghuhniana* growth and wood production

All intercropped treatments produced significantly greater tree height, basal diameter and mean tree volume than the tree-alone control at 6, 12 and 18 months after planting (Table 6). The current

annual increment (CAI) in tree height over the 6–18-month period was highest in *C. junghuhniana* + little millet (4.37 m) and lowest in the tree-alone control (3.68 m). At 18 months, the *C. junghuhniana* + little millet treatment recorded the highest mean tree height (5.63 m) and mean tree volume (0.0142 m³ tree⁻¹), resulting in the greatest wood production of 29.84 t ha⁻¹. The tree-alone control produced only 19.93 t ha⁻¹ of wood, a value significantly lower than all intercropped treatments. Kodo millet produced the least benefit to tree growth among the intercrop treatments, although it still outperformed the tree-alone control.

Post-harvest soil properties

Post-harvest soil analysis indicated no significant treatment differences in soil pH, which remained near-neutral (7.60–7.65) across all treatments (Table 7). However, significant differences were observed in EC, OC, available N, available P and available K. The *C. junghuhniana* + foxtail millet treatment recorded the highest soil OC (0.843 %) and EC (0.473 dS m⁻¹), while the tree-alone control registered the lowest values for EC (0.455 dS m⁻¹) and OC (0.585 %). The highest available N (280 kg ha⁻¹), available P (18.0 kg ha⁻¹) and available K (199.1 kg ha⁻¹) were recorded in the little millet treatment, whereas the tree-alone control had the lowest available N (210 kg ha⁻¹) and barnyard millet showed the lowest available P (9.7 kg ha⁻¹) and K (133.5 kg ha⁻¹) among the intercropped treatments. Notably, barnyard millet also recorded the lowest post-harvest soil OC (0.493 %) of all intercropped treatments, an anomaly discussed further below.

Economic analysis and land equivalent ratio

The *C. junghuhniana* + little millet system yielded the highest gross income (₹38000), net income (₹26000) and B : C ratio (3.16) among all treatments, followed by Barnyard millet (B : C = 3.10) and Proso

Table 4. Dry matter production and grain yield of millet intercrops in the second crop cycle under *Casuarina junghuhniana* agroforestry

Sl.No.	Intercrops	DMP-IC (kg ha ⁻¹)	DMP-PC (kg ha ⁻¹)	Yield IC (kg ha ⁻¹)	Yield PC (kg ha ⁻¹)	CEY
1.	Kodo millet	2075	2125	820	1560	-
2.	Foxtail millet	2275	2310	1400	1640	-
3.	Finger millet	2220	2900	1210	1880	-
4.	Barnyard millet	2330	2500	870	1245	-
5.	Little millet	2650	2670	1870	2160	Highest
6.	Proso millet	2555	2510	800	890	-
	SEd	30.22		11.61		
	CD (0.05)	71.26		21.41		

DMP: dry matter production; IC: intercropping; PC: pure cropping; CEY: crop equivalent yield.

Table 5. Dry matter production and grain yield of millet intercrops in the third crop cycle under *Casuarina junghuhniana* agroforestry

Sl.No.	Intercrops	DMP-IC (kg ha ⁻¹)	DMP-PC (kg ha ⁻¹)	Yield IC (kg ha ⁻¹)	Yield PC (kg ha ⁻¹)	CEY
1.	Kodo millet	1975	2175	510	620	Lowest
2.	Foxtail millet	2200	2320	700	860	-
3.	Finger millet	2178	2378	780	860	-
4.	Barnyard millet	2420	2520	680	945	-
5.	Little millet	2560	2660	770	950	Highest
6.	Proso millet	2450	2540	720	740	-
	SEd	31.38		10.10		
	CD (0.05)	72.36		20.11		

DMP: dry matter production; IC: intercropping; PC: pure cropping; CEY: crop equivalent yield.

Table 6. Effect of intercropping on tree height, volume and wood production of *Casuarina junghuhniana* at 6, 12 and 18 months after planting

Treatment	Height 6 mo (m)	Height 12 mo (m)	Height 18 mo (m)	CAI Height	Vol 18 mo (m ³ tree ⁻¹)	Wood 18 mo (t ha ⁻¹)
<i>C. junghuhniana</i> + Kodo millet	1.24	3.42	5.08	3.84	0.0137	28.69
<i>C. junghuhniana</i> + Foxtail millet	1.15	3.08	5.16	4.01	0.0117	25.96
<i>C. junghuhniana</i> + Finger millet	1.26	3.37	5.47	4.21	0.0139	29.10
<i>C. junghuhniana</i> + Barnyard millet	1.25	3.33	5.45	4.20	0.0120	25.15
<i>C. junghuhniana</i> + Little millet	1.26	3.48	5.63	4.37	0.0142	29.84
<i>C. junghuhniana</i> + Proso millet	1.17	3.24	5.36	4.19	0.0124	24.53
Tree alone (Control)	0.94	2.86	4.72	3.68	0.0120	19.93
SEd	0.047	0.096	0.131	0.111	0.000085	2.359
CD (0.05)	0.12	0.261	0.354	0.273	0.0017	4.67

CAI: current annual increment for the 6–18-month period.

Table 7. Influence of millet intercropping on post-harvest soil physicochemical properties under *Casuarina junghuhniana* agroforestry

Treatment	pH	EC (dSm ⁻¹)	OC (%)	N (kg ha ⁻¹)	P (kg ha ⁻¹)	K (kg ha ⁻¹)
<i>C. junghuhniana</i> + kodo millet	7.60	0.457	0.768	266	14.2	171.4
<i>C. junghuhniana</i> + foxtail millet	7.65	0.473	0.843	277	14.4	164.1
<i>C. junghuhniana</i> + finger millet	7.61	0.470	0.818	254	14.3	171.8
<i>C. junghuhniana</i> + barnyard millet	7.64	0.460	0.493	211	9.7	133.5
<i>C. junghuhniana</i> + Little millet	7.61	0.470	0.614	280	18.0	199.1
<i>C. junghuhniana</i> + proso millet	7.62	0.463	0.675	256	13.9	142.3
Tree alone (Control)	7.64	0.455	0.585	210	10.7	156.8
SEd	0.014	0.0015	0.015	1.193	0.119	1.366
CD (0.05)	NS	0.0032	0.033	2.698	0.2698	3.091

OC: organic carbon; N: available nitrogen; P: available phosphorus; K: available potassium; NS: non-significant.

millet (B : C = 2.62). Kodo millet produced the lowest gross income (₹31500), net income (₹16500) and B : C ratio (2.10). All intercropped systems recorded total LER values exceeding 2.0, confirming a substantial productivity advantage over sole cropping of either component. The highest total LER was recorded for the little millet treatment (2.92), followed by barnyard millet (2.51) and finger millet (2.49). The lowest total LER was associated with the foxtail millet treatment (2.34), though this value still indicates a 134 % advantage over monoculture land use (Tables 8 and 9). An integrated synthesis of LER, B : C ratio, yield, wood production and soil-improvement metrics across all six intercrops is presented in Table 9 for direct comparative reference by farmers and extension practitioners.

Principal component analysis

The consolidated treatment-variable matrix was subjected to PCA to gain comprehensive insight into the multivariate relationships between understorey millet performance, overstorey tree growth parameters, post-harvest soil fertility indicators and overall system

economics. The treatments showed clear spatial separation along the first two principal components (PC1 and PC2), which together captured most of the experimental variance, indicating strong overall differentiation in agroforestry compatibility among the 6 millet intercrops (Fig. 1).

Inter-variable correlation analyses

To elucidate the directional interdependencies governing the *C. junghuhniana*-millet agroforestry components, a Pearson correlation matrix was constructed across all monitored crop, tree, soil and financial variables (Fig. 2). The correlogram revealed robust positive correlations ($r = 0.70$) between post-harvest rhizosphere soil macronutrient pools (Soil N, Soil P, Soil K) and overstorey growth parameters (Tree height and tree wood density). Notably, available soil N exhibited a strong positive linear correlation with 18-month tree wood production ($r = 0.81$), validating that below-ground nutrient enhancements translate directly into accelerated above-ground timber volume. Total land use efficiency (Total LER) and

Table 8. Economics and land equivalent ratio (LER) of *Casuarina junghuhniana*-based millet agroforestry systems

Intercrop	Gross income (₹)	Net income (₹)	B : C ratio	LER (Intercrop)	LER (Tree)	LER (Total)
Kodo millet	31,500	16,500	2.10	0.97	1.63	2.60
Foxtail millet	38,064	23,064	2.53	0.93	1.41	2.34
Finger millet	24,900	14,800	2.46	0.97	1.52	2.49
Barnyard millet	31,200	21,200	3.10	0.99	1.52	2.51
Little millet	38,000	26,000	3.16	0.94	1.99	2.92
Proso millet	31,450	19,450	2.62	0.97	1.42	2.39

B : C: benefit-to-cost ratio.

Table 9. Integrated synthesis of key agronomic, economic and soil-improvement metrics across all six millet intercrops under *Casuarina junghuhniana* agroforestry

Intercrop	Mean DMP (kg ha ⁻¹)	Mean Yield (kg ha ⁻¹)	Total LER	B : C Ratio	Soil OC (%)	Soil N (kg ha ⁻¹)	Wood Prod. (t ha ⁻¹)	Overall Rank
Kodo millet	1,975	583	2.60	2.10	0.768	266	28.69	6
Foxtail millet	2,225	1,143	2.34	2.53	0.843	277	25.96	4
Finger millet	2,192	1,070	2.49	2.46	0.818	254	29.10	3
Barnyard millet	2,390	803	2.51	3.10	0.493	211	25.15	2
Little millet	2,590	1,510	2.92	3.16	0.614	280	29.84	1
Proso millet	2,468	757	2.39	2.62	0.675	256	24.53	5

DMP: dry matter production (average across three cycles); Yield: mean grain yield (kg ha⁻¹, average across three cycles); LER: total land equivalent ratio; B : C: benefit-to-cost ratio; Soil OC: post-harvest organic carbon (%); Soil N: post-harvest available nitrogen (kg ha⁻¹). Ranking: 1 = best, 6 = worst.

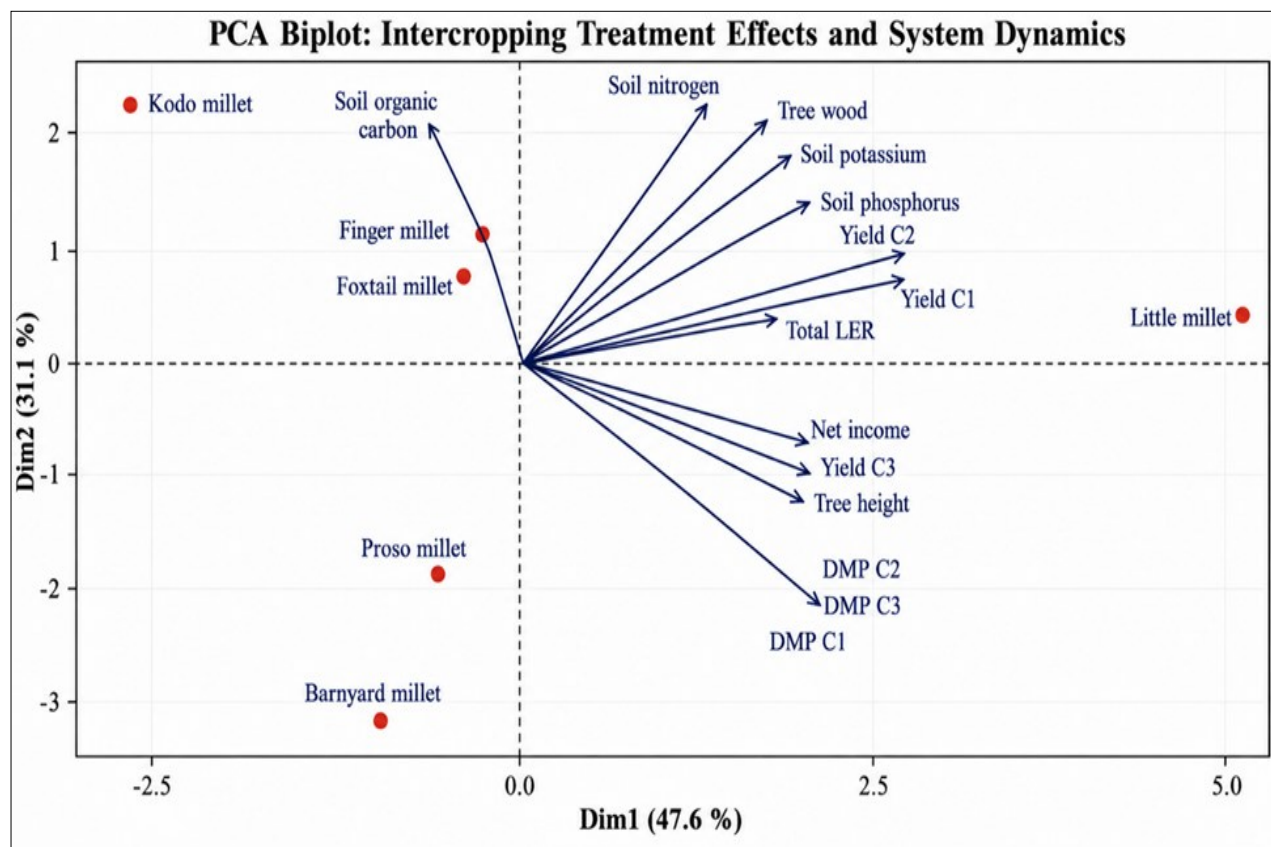


Fig. 1. Principal component analysis (PCA) biplot illustrating the relationships between different millet intercropping treatments and evaluated system parameters.

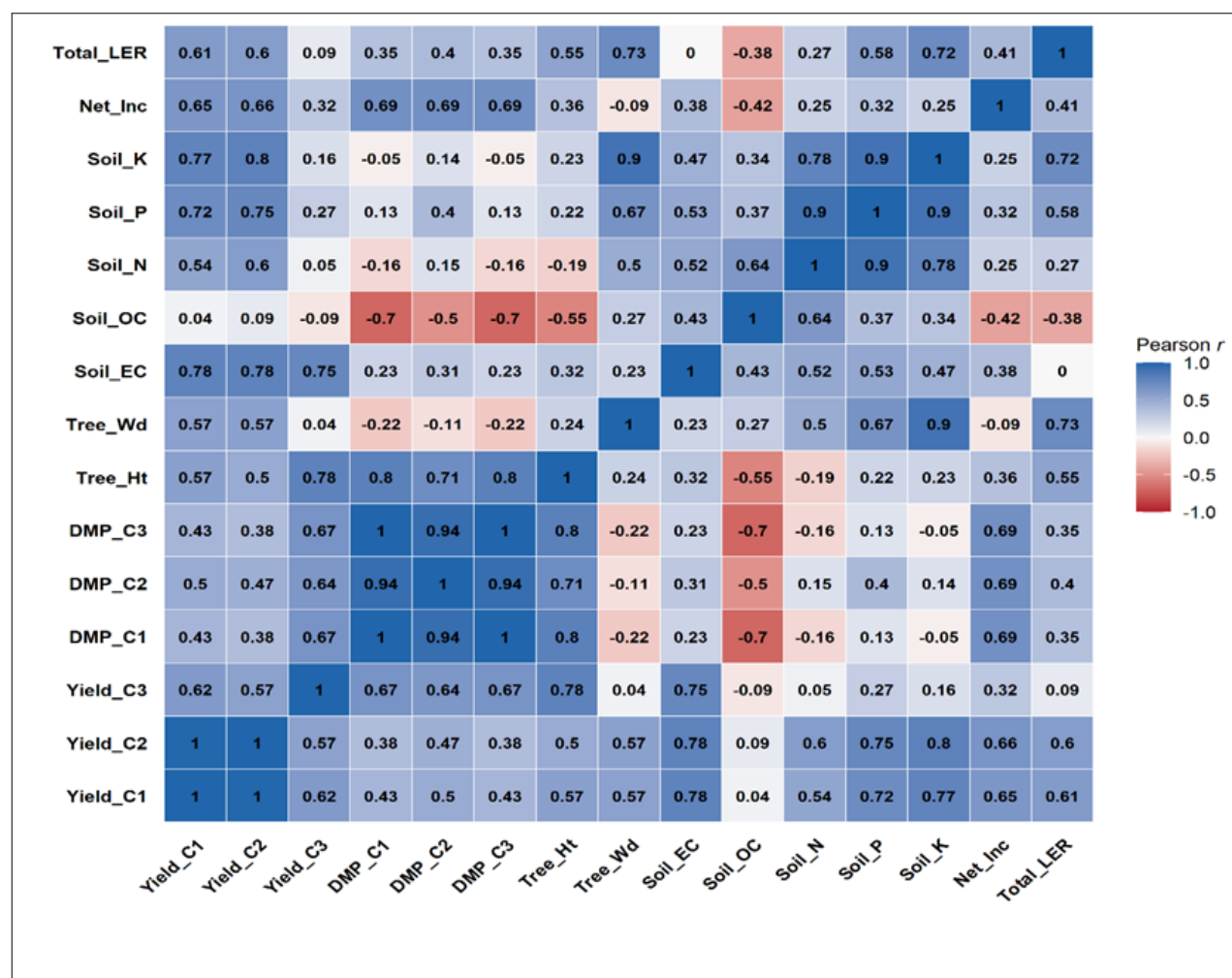


Fig. 2. Pearson correlation matrix heatmap (correlogram) illustrating the inter-variable linkages in the *Casuarina junghuhniana*-millet agroforestry system.

financial returns were also strongly coupled with cycle-1 and cycle-2 understorey grain productivity. In contrast, the grain yield of the final cycle (Yield C3) exhibited an inverse, negative correlation with advanced tree dimensions ($r = -0.64$), reflecting the transition from early-rotation complementarity to intensive competition for solar radiation as canopy closure progressed.

Discussion

The consistent superiority of little millet (*P. sumatrense*) throughout the three intercrop cycles in terms of DMP, grain yield and CEY could be explained by the fact that it is a shade tolerant species, has a short crop duration (about 90–100 days) and is able to utilise diffuse and low intensity radiation efficiently under tree canopy conditions. Little millet can also thrive in marginal lands with moisture stress which is suitable for agroforestry with early rotation (12). This increase in the soil carbon and nutrient pools is in line with the priming effect of the combined tree and crop litter inputs observed in agroforestry systems with *Casuarina* (7, 17). Competitive advantage in understorey environments of trees is well documented as the ability to maintain radiation use efficiently in low-light conditions (11, 22). The present results agree with those of previous researchers for intercropping with *Casuarina equisetifolia* L., where larger tree spacing (2 m × 2 m) always gave better intercrop growth than the smaller spacings (9). It was also found that understorey light availability was the most important factor affecting intercrop productivity in intercropping with *C. equisetifolia* (19). Intercropping effects on enhanced tree growth have been attributed to the increased availability of soil nutrients and mechanical disturbance effects reported in several agroforestry systems (1, 8).

The decrease in performance of intercrops in the 1st, 2nd and 3rd crop cycle, especially the plant height and grain production of 3rd crop cycle, agrees with the reduction in photosynthetically active radiation (PAR) received by the crop canopy with an increase in tree size. The fact that this phenomenon has been reported in various tree-crop combinations and that the small stature, shade tolerant millets are well suited for later stages of tree rotation (10), highlights the need for choosing small stature, shade tolerant millets. Temporal patterns of light competition in agroforestry systems can be further influenced by tree management, such as pruning and spacing, through the expansion of the productive phase of understorey crops (2). Proso millet had the tallest plant height in the third cycle (39.4 cm at 60 DAS); this tallest plant height might be a morphological adaptation to low-light conditions, stimulated by stem elongation (etiolation). In contrast, kodo millet had the lowest adaptation in all 3 cycles focusing on its moderate light requirement and low understorey plasticity (23).

The negative trends of productivity as canopy closure increases are like other fast-growing plantation agroforestry systems (11, 18). This positive result of intercropping on the growth of *C. junghuhniana* in the form of a significant increase in tree height, basal diameter and wood production for all the intercropping treatments over the tree-alone treatment is remarkable. The stimulatory effect of intercrops on tree growth has earlier been explained by soil aeration and increased root penetration due to intermittent mechanical disturbance of soil under the crop (1) and by increasing mineralisation of the organic residues from the tree roots and stubble, which increases the nutrient supply in the tree

rhizosphere (1). Previous researchers also reported facilitative interactions between trees and crops in mixed-species plantations with nitrogen-fixing trees and showed how complementary resource utilisation between the tree and crop components is important (8). From a practical point of view, the increase in wood production in the *C. junghuhniana* + little millet treatment compared with the tree-alone treatment (29.84 vs. 19.93 t ha⁻¹ at 18 months) is significant and will be valuable to the success of short-rotation woodland production of *Casuarina*.

Improvements in post-harvest soil EC, OC, available N, P and K from the intercropped treatments over the tree-alone treatment are like the well documented priming effects of combined litter inputs from trees and annual crops (7, 24). *Casuarina junghuhniana* is a *Frankia* symbiont, which can fix atmospheric nitrogen; in the soil system it contributes an estimated 50–100 kg N ha⁻¹ year⁻¹ (5, 25). Clearly, the other organic inputs from the decomposition of millet root biomass and stubble further stimulate microbial activity and nutrient cycling. Previous studies have reported increased long-term soil fertility of actinorhizal agroforestry systems, which supports the hypothesis that *Casuarina*-based systems can contribute to sustainable productivity gains beyond the rotation period (6, 7, 26). There was no pH change among treatments, which agreed with the relatively short duration of the study and the buffering capacity of the experimental soil.

In all intercropping systems, the total LER is significantly higher than the global meta-analysis average LER of 1.38 for legume intercropping systems (14), which shows the effects of intercropping in the two-component systems. As stated in earlier reports, the LER concept highlights the fact that values above 1.0 mean intercropping is more efficient in land use than sole cropping (13). The partial LER of the tree component in little millet (1.99) suggests that a monoculture of the tree would need almost twice as much land to produce the same wood yield, which has great implications for land limited farming systems. The economic information also supports the productivity benefit, as the B : C ratios range from 2.10–3.16 for all systems, all suggesting commercially viable returns (18). The present results (17, 18, 27) were also consistent with those observed in other tree-millet systems in sub-Saharan Africa and South Asia, which had B : C ratios greater than 2.0 (38). One of the significant anomalies in the soil data is the very low level of post-harvest organic carbon (0.493 %) under barnyard millet, which is close to the pre-experiment baseline (0.43 %) and is significantly lower than under all other intercropped treatments despite barnyard millet's relatively high dry matter production (2390 kg ha⁻¹) and second highest B : C ratio (3.10). This was an indication that proportionate return of stable organic residues to the soil did not happen with Barnyard millet contribution for standing dry matter. This may be because barnyard millet has a higher proportion of above-ground biomass removed as fodder or straw, resulting in a reduced proportion of root tissue and stubbles as potential carbon sources for incorporation with the soil, while the root system is coarser and more rapidly mineralisable, which could have increased the rate of microbial decomposition of existing soil carbon (a priming effect) relative to the input of new carbon from the root system and stubbles. Partly, it may be that the spatial distribution of the carbon inputs had changed because of differences in root architecture and rooting depth when compared to the 0–30 cm sampling depth. This result is not what has been generally seen for the improvement of soil quality under intercropping, so it should be considered as treatment-specific and

not as a general constraint of millet intercropping and needs a follow-up measurement of the quantity of residue returned to the soil and root biomass under different treatments.

There was an inverse relationship between grain yield and advanced tree dimensions ($r = -0.64$) in the late cycle (third cycle) which has management implications. As the crop canopy grows denser, the resource-capture priority should be expected to change; for crops planted after about 12 months, millet varieties that are shorter but more tolerant to shade conditions might be better than varieties designed to thrive with the more open crop canopy present during the initial 6 months after emergence. It also means that the economic benefit of intercropping in a rotation of *C. junghuhniana* is limited and that economic benefit may be lost or even negative if intercropping is continued beyond a certain level of substantial canopy closure, unless shade adapted management practices are used.

The present results must be used together with knowledge about possible negative aspects of tree-crop intercropping which are not only expressed in yield and income figures. Although all treatments that were intercropped outperform the tree-alone treatment with respect to tree growth, below-ground competition between the tree and the millet root system for soil moisture and nutrients, especially in the top layer of the soil that share, may be mitigating this facilitative effect, especially in drier years or when relying entirely on rainfall. This is partly because of the absence of a significant pH change and only small differences in the uptake of phosphorus and potassium among some treatments, which could be due to competition between these nutrients and the nutrient additions due to litter and residues. To understand this facilitation-competition trade-off and how it influences the overall productivity of the rotation, it is necessary to monitor the dynamics of soil moisture and root distribution over longer time periods but should be made clear to the farmer as a consequence and not just as a net productivity result reported here.

Practically, the results of this study can be summarised as the following recommendations for the farmers and extension practitioners. For the first, priority should be given to using little millet as intercrop in all 3 cycles with finger millet and foxtail millet as alternate options, based on availability of seed and market demand. Kodo millet is not recommended under this tree spacing. Secondly, because yield is progressive after 12 months, farmers should plan their cropping so that the millet that is the lightest demanding and/or the tallest is planted into the first two rotations and the most shade tolerant into the third rotation, or for those who do not produce millet, into a non-cereal rotation. Third, it may be recommended that intercropping be limited to the first 18 months of operation after planting, or possibly even the first 10 months, while tree spacing is 2 m × 2 m, due to the expected loss of productivity advantage and wider spacing or selective pruning may be considered to open the intercropping window. Lastly, moderate, split fertiliser applications timed to the tree and crop nutrient requirement and additional irrigation during dry periods, may be recommended to compensate for any below-ground competition for water and nutrients, especially under treatments like barnyard millet where soil carbon build-up does not seem to be unlimited.

A PCA biplot (Fig. 1) will further highlight this multi-dimensional synergy. The low directional deviation and modest range of vector angles for tree wood production, total LER and post-harvest available soil N in this study is mathematically confirmed to

be agronomic facilitation due to the integrated below-ground resource sharing and complementary nutrient cycling. The increase in overstorey wood volume and the increase of understorey soil enrichment is coupled with processes when optimal management is applied. The unique effect of the little millet (T_5) treatment at the end of these system-benefit vectors provides clear statistical evidence that this treatment has greater physiological plasticity regarding resource utilisation and higher efficiency under developing tree canopy. In contrast, the biplot shows a distinct spatial trend for kodo millet (T_1), reinforcing its requirement for open sunlight, along with its poor morphological adaptation ability, which could exclude kodo millet from early-rotation *C. junghuhniana* field configurations.

This biological coordination is further verified by the linear associations mapped in the system correlogram (Fig. 2). The strong, positive Pearson correlation coefficients linking rhizosphere nitrogen and phosphorus availability with overstorey wood production support the presence of a strong "facilitative loop" within the agroforestry system. Intermittent cultivation, residue turnover from millet root biomass and leaf litter deposition do not merely enrich the soil matrix in isolation; they systematically accelerate the growth rate and structural volume of the overstorey canopy. However, the concurrent negative correlation between advanced tree height and late-cycle understorey grain yield ($r = -0.64$) confirms that this facilitative phase is bounded by clear microclimatic thresholds. As tree volume expands, light limitation becomes the primary overriding constraint governing understorey carbon assimilation. Managing this trade-off requires selecting specialised, shade-tolerant understorey crops that maximise light use efficiency before canopy closure becomes restrictive.

Conclusion

The present study demonstrates that little millet (*Panicum sumatrense*) is the most compatible and productive intercrop for *Casuarina junghuhniana*-based agroforestry systems during the early rotation period (3 to 18 months after planting). Its consistent superiority in dry matter production (DMP), grain yield, crop equivalent yield (CEY) and economic returns across three successive crop cycles, combined with the greatest positive effect on tree growth and wood production and the highest total land equivalent ratio (LER) of 2.92, establishes it as the recommended intercrop for this system. Finger millet and foxtail millet are viable secondary choices, whereas kodo millet is the least suitable species under this tree spacing. The concomitant improvement in soil organic carbon and nutrient pools under most intercropped treatments highlights the soil health benefits of millet-based agroforestry as an additional rationale for its adoption, although the anomalously low soil organic carbon recorded under barnyard millet indicates that this benefit is treatment-specific rather than universal and requires further investigation.

Based on these findings, an optimal crop calendar for *C. junghuhniana*-millet agroforestry at 2 m × 2 m spacing would prioritise little millet across all 3 cycles (0–6, 6–12 and 12–18 months), with the more light-demanding types such as proso millet best confined to the first two cycles and intercropping discontinued or shifted to shade-tolerant alternatives once substantial canopy closure occurs beyond 18 months. From an economic standpoint, treatments returning a benefit-to-cost ratio (B : C) ratio below approximately 2.5 (e.g., Kodo millet) should be

considered marginal under current price conditions and are not recommended where profitability is the primary objective; growers operating under tighter cost margins should therefore favour little millet, barnyard millet, or proso millet, which returned the highest B : C ratios in this study.

Future research should prioritise: (i) longer-term studies extending beyond the first 18-month rotation window to evaluate whether the observed soil fertility gains and yield trade-offs persist or intensify across a full *Casuarina* rotation of three to four years; (ii) direct measurement of soil moisture dynamics and root distribution to quantify the balance between facilitation and below-ground competition for water and nutrients between trees and intercrops, particularly under rainfed conditions; (iii) investigation of the mechanisms underlying the anomalously low soil organic carbon under Barnyard millet, including residue return and root turnover measurements; and (iv) assessment of pest, disease and weed interactions under the intercropped canopy microclimate, which were not evaluated in the present study. The findings are consistent with the broader evidence base supporting the use of shade-tolerant, short-duration cereals in early-rotation plantation agroforestry systems (2, 8, 10, 18). Short-rotation *C. junghuhniana* plantations in South India can thus be substantially enhanced in economic value and ecological performance through systematic integration of little millet as an intercrop during the first 18 months after establishment, guided by the crop-calendar and economic-threshold recommendations outlined above.

Acknowledgements

The authors sincerely acknowledge the support and facilities provided by Tamil Nadu Agricultural University, Coimbatore and the Forest College and Research Institute, Mettupalayam, for carrying out this study. The authors also thank the field and technical staff for their assistance during the field investigations and data collection.

Authors' contributions

BS conceptualised the study, developed the methodology, conducted field investigations, performed formal analysis and wrote the original draft. KA conceptualised and supervised the study, provided resources, administered the project and reviewed and edited the manuscript. AB supervised the study, provided resources and reviewed and edited the manuscript. SR and BM performed formal analysis and data curation, with BM also reviewing and editing the manuscript. PR conducted the investigation, developed the methodology and curated the data. SNK, RA and PRRS carried out field investigations and data collection. SAK conducted field investigations, collected data, performed formal analysis and wrote the original draft. All authors have read and approved the manuscript.

Compliance with ethical standards

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

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During preparation of this manuscript, the authors used Claude (Anthropic, PBC) solely to assist with language editing, grammar correction and improving the clarity and academic tone of the text. The tool was not used to generate, analyse, or interpret any research data and it was not used to draft original scientific content or conclusions. After using this tool, the authors reviewed and edited the content as necessary and take full responsibility for the content of the publication.

References

1. Nair PKR. State-of-the-art of agroforestry research and education. *Agrofor Syst.* 1991;17(3):223–42.
2. Kumar BM, Nair PKR. Carbon sequestration potential of agroforestry systems: Opportunities and challenges. Springer; 2006.
3. Garrity DP. Agroforestry and the achievement of the Millennium Development Goals. *Agrofor Syst.* 2004;61–62(1–3):5–17. <https://doi.org/10.1023/B:AGFO.0000028986.37502.7c>
4. Mbow C, Smith P, Skole D, Duguma L, Bustamante M. Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Curr Opin Environ Sustain.* 2014;6:8–14. <https://doi.org/10.1016/j.cosust.2013.09.002>
5. Sayed WF. Improving *Casuarina* growth and symbiosis with *Frankia* under different soil and environmental conditions: Review. *Folia Microbiol.* 2011;56(1):1–9. <https://doi.org/10.1007/s12223-011-0002-8>
6. Parrotta JA. Productivity, nutrient cycling and succession in single- and mixed-species plantations of *Casuarina equisetifolia*, *Eucalyptus robusta* and *Leucaena leucocephala* in Puerto Rico. *For Ecol Manage.* 1999;124(1–2):45–77. [https://doi.org/10.1016/S0378-1127\(99\)00049-3](https://doi.org/10.1016/S0378-1127(99)00049-3)
7. Dommergues Y. Contribution of actinorhizal plants to tropical soil productivity and rehabilitation. *Soil Biol Biochem.* 1997;29(5–6):931–47. [https://doi.org/10.1016/S0038-0717\(96\)00227-1](https://doi.org/10.1016/S0038-0717(96)00227-1)
8. Forrester DI, Bauhus J, Cowie AL, Vanclay JK. Mixed-species plantations of *Eucalyptus* with nitrogen-fixing trees: A review. *For Ecol Manage.* 2007;233(2–3):211–30. <https://doi.org/10.1016/j.foreco.2006.05.012>
9. Kannan P, Muthukrishnan P, Ravichandran M. Influence of tree spacing on understorey crop performance in *Casuarina*-based agroforestry systems in Tamil Nadu. *Indian J Agrofor.* 2022;24(1):45–52.
10. Jose S, Gillespie AR, Pallardy SG. Interspecific interactions in temperate agroforestry. *Agrofor Syst.* 2004;61–62(1–3):237–55. <https://doi.org/10.1023/B:AGFO.0000029002.85273.9b>
11. Tomlinson I, Potter C, Cook P. Shading effects on understorey crop productivity in agroforestry systems: Mechanisms and implications for management. *Agrofor Syst.* 2012;85(1):1–15. <https://doi.org/10.1007/s10457-011-9472-z>
12. Vetriventhan M, Upadhyaya HD. Variability and trait-specific accessions for grain yield and nutritional traits in germplasm of little millet (*Panicum sumatrense* Roth. ex Roem. & Schult.). *Crop Sci.* 2021;61(4):2658–73. <https://doi.org/10.1002/csc2.20527>
13. Willey RW. The concept of a 'Land Equivalent Ratio' and advantages in yields from intercropping. *Exp Agric.* 1980;16(3):217–28. <https://doi.org/10.1017/S0014479700010978>
14. Bedoussac L, Journet E-P, Hauggaard-Nielsen H, et al. Boosting resource use efficiency, soil fertility, food security, ecosystem services and climate resilience with legume intercropping: A review. *Front Sustain Food Syst.* 2025;9:1527256. <https://doi.org/10.3389/fsufs.2025.1527256>

15. Ong CK, Black CR, Wilson J. Tree-Crop Interactions: Agroforestry in a Changing Climate. 2nd ed. CABI; 2015. <https://doi.org/10.1079/9781780645117.0000>
16. Quinkenstein A, Wöllecke J, Böhm C, Grünewald H, Freese D, Schneider BU, et al. Ecological benefits of the alley cropping agroforestry system in sensitive regions of Europe. Environ Sci Policy. 2009;12(8):1112–21. <https://doi.org/10.1016/j.envsci.2009.08.007>
17. Rao MR, Nair PKR, Ong CK. Biophysical interactions in tropical agroforestry systems. Agrofor Syst. 1998;38(1–3):3–50. <https://doi.org/10.1023/A:1005971525590>
18. Sida TS, Baudron F, Kim H, Giller KE. Climate-smart agroforestry: *Faidherbia albida* trees buffer against seasonal temperature extremes in the Ethiopian and Kenyan highlands. Agric For Meteorol. 2018;248:339–47. <https://doi.org/10.1016/j.agrformet.2017.10.011>
19. Krishnan SN, Balasubramanian A, Radhakrishnan S, Sekar I, Chitdeshwari T, Varadharaj S, et al. A review on biomass productivity of *Casuarina* (*Casuarina equisetifolia* L.) through fertilization and irrigation approaches. Appl Ecol Environ Res. 2025;23(3):4149–66. https://doi.org/10.15666/aeer/2303_41494166
20. El Mouridi Z, Ziri R, Douaik A, Bennani S, Lembaid I, Bouharou L, et al. Comparison between Walkley-Black and Loss on Ignition methods for organic matter estimation in different Moroccan soils. Ecol Eng Environ Technol. 2023;24(4):253–9. <https://doi.org/10.12912/27197050/163121>
21. Jung DR, Vendrametto O. Agroforestry for food security and public health: A comprehensive review. Int J Environ Res Public Health. 2025;22(4):645. <https://doi.org/10.3390/ijerph22040645>
22. Seetha A, Durga Rani CV, Anuradha N, Bhadru D, Mallaiah B. Shade tolerance and yield stability of small millets as intercrops in tree-based systems: A review. Crop Sci. 2023;63(2):521–36. <https://doi.org/10.1002/csc2.20906>
23. Barad SD, Karanjikar PN, Sabale AP, Sneha SB, Gawande MN. Growth and yield of little millet (*Panicum sumatrense* L.) as influenced by varieties and row spacings under rainfed condition. Int J Res Agron. 2024;7(11S):29–32. <https://doi.org/10.33545/2618060X.2024.v7.i11Sa.1926>
24. Balakrishnan M, Nair S, Mohan Kumar B. Long-term soil macronutrient dynamics under *Casuarina*-crop associations in peninsular India. Land Degrad Dev. 2024;35(7):2341–56. <https://doi.org/10.1002/ldr.4990>
25. Prabakaran N, Senthil Kumar P, Sivakumar C. Soil fertility dynamics under *Casuarina junghuhniana*-based agroforestry systems in Tamil Nadu: nitrogen fixation and organic carbon accumulation. Agrofor Syst. 2023;97(4):689–701. <https://doi.org/10.1007/s10457-022-00798-3>
26. Kaushal R, Tomar JMS, Thakur TN, Chaturvedi OP, Alam NM, Mandal D, et al. Actinorhizal agroforestry species and soil fertility improvement: a global synthesis. Ann For Sci. 2021;78:52. <https://doi.org/10.1007/s13595-021-01063-2>
27. Kumar A, Paliwal A, Singh SB, S TS, Kishore A. Productivity and economics of intercropping of finger millet (*Eleusine coracana*) and amaranth (*Amaranthus* spp.) in rainfed hills of Uttarakhand. Int J Bio-resource Stress Manag. 2022;13(12):1482–87. <https://doi.org/10.23910/1.2022.3053>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc. See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.