npj | sustainable agriculture

Article

https://doi.org/10.1038/s44264-025-00080-2

Sustainable intensification in coconut for building system resilience and nutritional security of smallholders in Eastern India

Check for updates

Rohan Khopade, Gajanan Sawargaonkar ✉, Santosh Kale, Moses Davala, S. Rakesh, Susree Snigdha Das, RamVikas Verma, Kapil Raje, Ramesh Singh & M. L. Jat

Coconut-based cropping systems are vital to the coastal rural economy, which faces challenges like declining soil fertility, low productivity, pest invasions, and climate change. The study conducted in the eastern Indian state of Odisha investigated strategies for sustainable intensification in coconut through multi-storied and intercropping, reinforced with soil test-based fertilizer management (STBFM). Multi-storied cropping with STBFM (T6) recorded significantly higher coconut equivalent yield (33,407 nuts ha^{-1}) and net income (USD 4344.67 ha^{-1}) annually. Correlation study revealed the importance of magnesium, calcium, and copper in enhancing system productivity and profitability. Multi-storied cropping with and without STBFM recorded the highest sustainability yield index (0.91 and 0.86). Nutritional composition was higher in T6 (energy—110,632 Kcal, fat—902 g, carbohydrates —22,344 g, and iron—5190 mg). The Present study highlights the need for the adoption of multi-storied/intercropping with judicious nutrient management for reinvigorating sustainable coconut farming at landscapes, besides ensuring smallholders' nutritional security in eastern Indian states.

Coconut-based cropping systems are integral to the coastal agrarian economy and rural subsistence in Odisha, India. These systems, however, face numerous challenges such as declining soil fertility, pest and disease invasions, and climate change impacts. Climate change has disrupted traditional farming practices due to irregular rainfall patterns and unseasonal storms[1,2] specifically in coastal areas. The coconut tree (*Cocos nucifera L.*) cultivated globally which offers multiple advantages such as food, nutrition, livelihood security etc. Yet, when it is grown as a monocrop, the efficiency of land use is markedly lower as canopy and solar radiation utilization is not being potentially exploited[3,4].

Odisha contributes significantly to India's coconut production, but despite the extensive cultivation, the potential for productivity is yet to be fully realized[5]. This is often attributed to suboptimal nutrient management and monocultural practices[6]. Soil Test-Based Fertilizer Management (STBFM) has emerged as a promising strategy, advocated for a balanced application of chemical fertilizers, organic amendments, and biofertilizers to improve soil health and crop yields[7]. Multi-storied cropping and intercropping are innovative approaches that are garnering interest for their ability to maximize land use and diversify cropping systems[3,8]. These approaches have been demonstrated to enhance resource use efficiency, decrease pest and disease incidence, and improve overall farm productivity and resilience[9,10].

The monocropping of coconut results in poor land area utilization, estimated at 22%, canopy space at 30%, and solar radiation at 45%[3,6,11]. In a monocropping system, production is poor, and resource loss is considerable[12]. In most coconut-growing locations, intercropping is a common method to increase land use efficiency. In order to maximize land usage and crop diversification, coconut can be grown alongside more than 100 different crops and systems[3,10]. Smallholder farmers may face economic challenges due to the significant investment required to establish a crop until it reaches bearing age. On the other hand, intercropping offers advantages over monocropping in terms of crop output through the complementary interaction between intercrop components and the competition levels for environmental resources[13]. Intercropping is more efficient than monocropping because the plants use environmental resources differently and complement each other's use of those resources, resulting in increased yield[9,12]. Farmers can benefit from intercropping because it is more agronomically sound than monocropping[14]. The root system of the mature coconut palm is primarily found within a 1.8-m radius of the base, with 95% of the roots located between 0 and 120 centimeters beneath the soil surface. An earlier study by Perfecto[15] revealed that intercropping can enhance soil fertility, water retention, and soil temperature. This study delves into the exploration of various coconut-based cropping systems, examining their potential to deliver a harmonious combination of productivity, sustainability, and economic viability. It also focuses on the adoption of Soil Test-Based Fertilizer Management (STBFM), multi-storied cropping, and intercropping as innovative agronomic practices aimed at reinvigorating the coconut farming landscape and nutritional security in Khorda district of Odisha (Fig. 1).

International Crops Research Institute for the Semi-Arid Tropics, Patancheru, Hyderabad, India. ✉e-mail: gajanan.sawargaonkar@icrisat.org

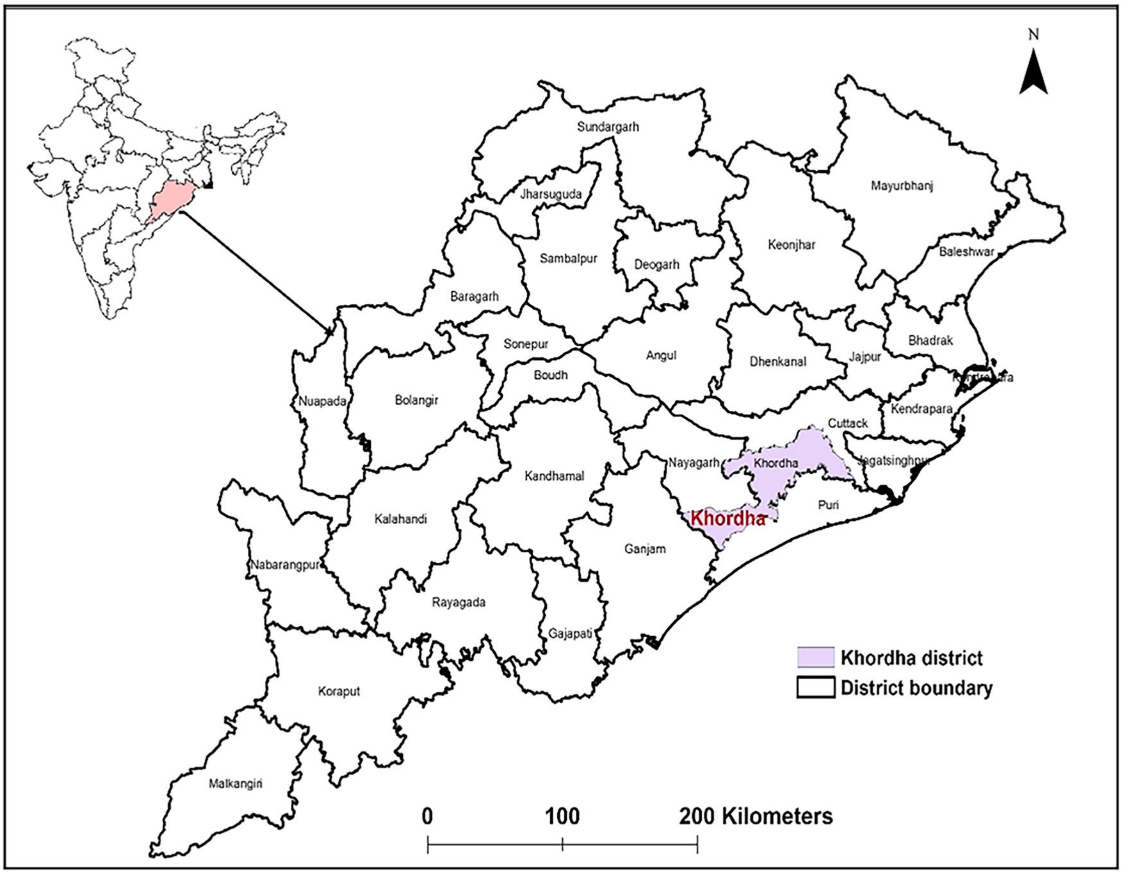

Fig. 1 | Location of the experimental area. The figure shows the geographical location of Khorda district, Odisha, India, where the on-farm coconut-based cropping system trials were conducted between 2021 and 2023 (Fig. 1).

Therefore, the present investigation was focused on the key objectives viz., Identifying sustainable practices for coconut farming, assessing the economic viability of coconut-based farming systems, and analyzing the correlation between soil chemical properties and coconut equivalent yield.

Results

Comparative analysis of coconut equivalent yield under various cropping systems

The Soil Test-Based Fertilizer Management (STBFM) in coconut cultivation (T2) recorded the maximum yield of 3802.67 nuts ha^{-1} followed by the conventional method of coconut cultivation without STBFM (T1) (2130 nuts ha^{-1}). Intercropping in coconut with STBFM (T5) recorded highest yield of 11,971.52 nuts ha^{-1}; while without STBFM (T3) resulted in a yield of 7782.36 nuts ha^{-1}, while with STBFM (T5) recorded 11,971.52 nuts ha^{-1} (Fig. 2). Similarly, multi-storied systems with and without STBFM (T6 and T4) yielded 13,362.99 and 8058.10 nuts ha^{-1}, respectively. Traditional cultivation of sole coconut without STBFM (T1) resulted in lowest coconut equivalent net income (CENI) of USD 296.21 ha^{-1} with a BCR of 1.58, whereas implementing STBFM in coconut cultivation (T2) significantly improved the CENI to USD 660.49 ha^{-1} with a BCR of 1.85 (Fig. 3). Intercropping and multi-storied systems without STBFM (T3 and T4) led to higher CENI of USD 1810.10 and USD 1961.56 ha^{-1} with BCRs of 1.97 and 2.06, respectively. Notably, these systems combined with STBFM (T5 and T6) showed the higher economic returns, with T5 yielding a CENI of USD 3402.69 ha^{-1} and a BCR of 2.50, and T6 achieving the highest CENI of USD 4344.67 ha^{-1} and a BCR of 3.21.

Interpretation of the correlation matrix

The heatmap analysis revealed significant associations between various soil parameters and coconut equivalent yield. Among them, magnesium (Mg), calcium (Ca), and copper (Cu) exhibited the strongest positive correlations with yield, suggesting a potential link between higher concentrations of these nutrients and increased crop productivity. Organic carbon (OC) and boron (B) also demonstrated notable positive correlations with coconut equivalent yield (Fig. 4). In contrast, manganese (Mn) showed a slight negative correlation with yield. Other parameters such as soil pH, electrical conductivity (EC), phosphorus (P), potassium (K), and zinc (Zn) were found to have moderately positive correlations with yield.

Multivariate analysis of soil properties affecting coconut yield

In the principal component analysis (PCA) of soil parameters and their relationship to coconut equivalent yield, the first two principal components (Dim1 and Dim2) accounted for 31.5% and 22.4% of the variance, respectively. This indicated that over 50% of the total variation in the data is explained by these two components. The biplot (Fig. 5) showed the projection of soil variables onto these principal components. Exchangeable Ca, Mg, and K were closely aligned with Dim1, suggesting that these nutrients played a significant role in coconut yield.

One-way analysis of variance comparison of various coconut-based cropping systems on coconut equivalent yield

A one-way analysis of variance (ANOVA) was conducted to compare the effect of different coconut-based cropping systems on the equivalent yield of coconuts (Table 1). The treatments included variations in inter- and multi-storied cropping approaches, both with and without STBFM. The ANOVA revealed a statistically significant difference in coconut equivalent yields (COEY) between the treatments, with an F-statistic value of 38.47 and a p-value less than 0.000001 (F 5, 12) = 38.47, $p < 0.000001$). Post hoc comparisons using Tukey's HSD test indicated that the mean yield for the multi-storied treatment with STBFM (T6 = 33,407.47 nuts ha^{-1}) was significantly

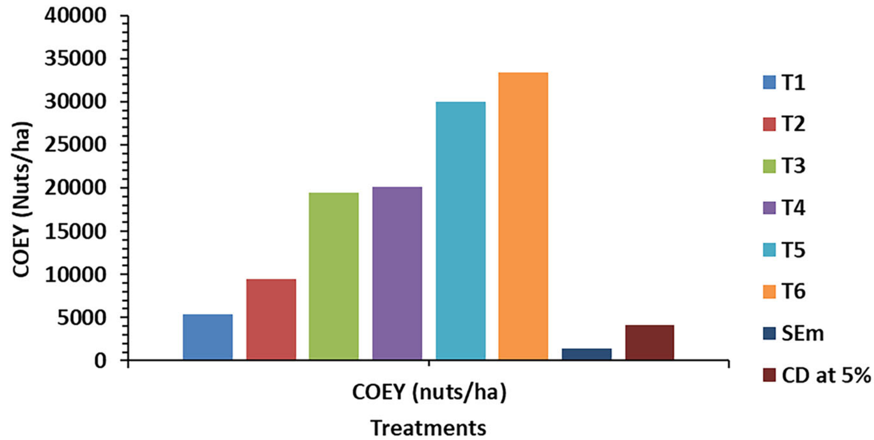

Fig. 2 | Comparative analysis of coconut equivalent yield under various cropping systems, economic evaluation of coconut cultivation under various cropping systems. This figure shows the coconut equivalent yield (nuts ha^{-1}) across six treatments during 2021–2023 in Khorda, Odisha.

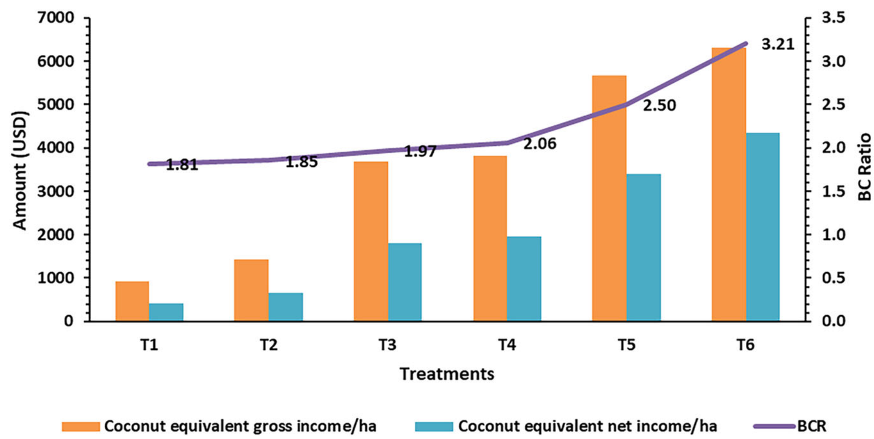

Fig. 3 | Economic evaluation of coconut cultivation under various cropping systems. This figure presents the coconut equivalent net income (USD ha^{-1}) and benefit-cost ratio (BCR) for each treatment.

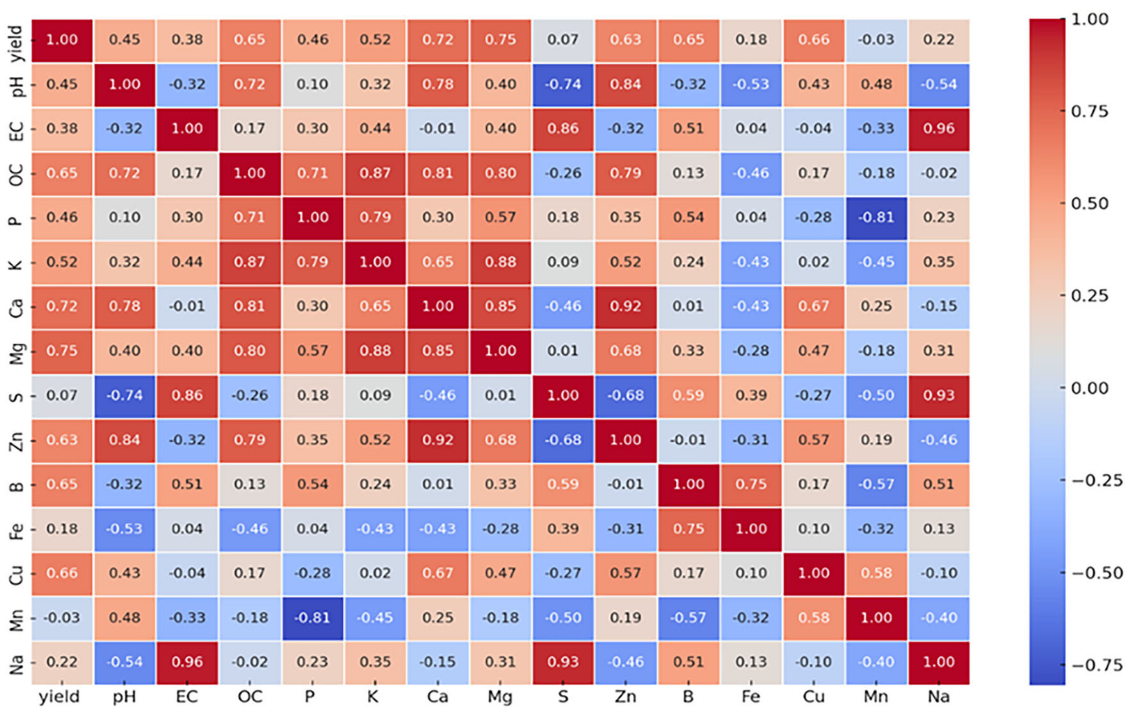

Fig. 4 | Correlation heatmap between coconut equivalent yield and soil parameters. The heatmap shows Pearson correlation coefficients among soil nutrients and coconut equivalent yield.

Fig. 5 | Biplot principal component analysis of soil parameters and their relationship with coconut equivalent yield. The PCA biplot shows the clustering of soil nutrients and their contribution to the first two principal components. Contribution of each variable to the principal component. The color gradient indicates the level of contribution, with warmer colors (such as red, orange, yellow) suggesting a higher contribution, and cooler colors (such as blue, green) indicating a lower contribution.

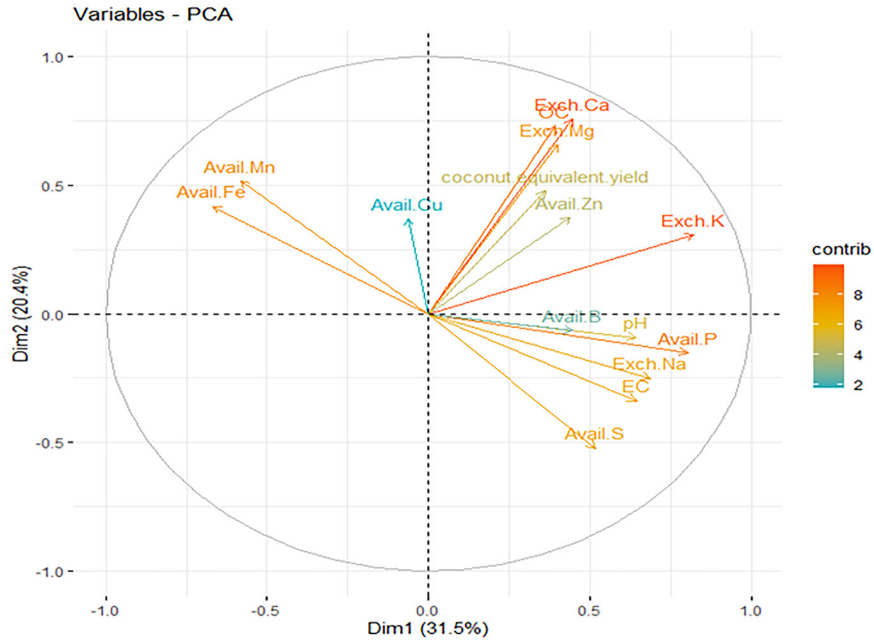

Table 1 | One-way analysis of variance comparison of various coconut-based cropping systems on coconut equivalent yield

Source	Sum of squares	Degrees of freedom	*F*-value	Pr(>*F*)
C (Treatment)	1.809885e + 09	5.0	38.471957	5.562985e-07
Residual	1.129062e + 08	12.0	-	-

F-statistic is approximately 38.47, and the corresponding *p*-value is very small (approx. 5.56e-07), which indicates that there are significant differences between the treatments.

higher than all other treatments (Fig. 6). The subsequent highest yields were recorded in intercropping with STBFM (T5 = 29,928.80 nuts ha^{-1}), followed by the multi-storied without STBFM (T4 = 20,145.25 nuts ha^{-1}), and intercropping without STBFM (T3 = 19,455.89 nuts ha^{-1}). The treatments involving only coconut cultivation, with (T2 = 9506.66 nuts ha^{--1}) and without STBFM (T1 = 5325 nuts ha^{-1}), had the lowest yields.

Sustainability yield index

The Sustainability yield index (SYI) revealed that coconut-based multi-storied cropping systems with or without STBFM recorded the highest sustainable yield index (0.91 and 0.86, respectively) and promise to be a scalable and sustainable approach to significantly enhance productivity, profitability, and climate resilience of coconut-based cropping systems in similar agro-ecologies in India (Fig. 7). Conversely, the lowest SYI was observed in the sole coconut without STBFM (T1).

Analysis of nutritional availability from various coconut-based cropping systems

The nutritional benefit analysis (Fig. 8) revealed that multi-storied cropping in coconut with STBFM (T6) provided highest energy (110,632 Kcal), fat (902 gm), carbohydrates (22,344 gm), and iron (5190 mg); whereas, the Intercropping + coconut with STBFM (T5) provided maximum protein (3156 gm), fiber (4916 gm), and calcium content (44,137 mg) to households ha^{-1}, annually. However, the sole coconut system, with or without STBFM, i.e., T1 and T2, provided the least support to households in terms of nutrition, which was limited to only energy, i.e., 10520 and 21,508 Kcal, respectively, and carbohydrates, i.e., 609 and 1246 gm ha^{-1}, respectively.

Discussion

The study on coconut equivalent yield and economic returns highlighted the significant positive impact of STBFM and diversified cropping systems. The increased yields under intercropping and multi-storied systems, especially when integrated with STBFM, demonstrated improved efficiency in land use and nutrient management. The findings are consistent with Bari & Rahim[16], who investigated three medicinal plants in a coconut-based agroforestry system and found significant effects on yield. Intercropping and multi-storied systems, particularly in combination with STBFM, have shown remarkable efficiency in optimizing land use and potentially improving microclimatic conditions in coconut cropping systems[17,18]. Integrated farming enhances income and nutritional security for small farmers through resource integration and increased productivity[8,19]. Shinde et al.[20], revealed the success of 'Lakhi Baug,' a multi-storied coconut-based cropping system, which has doubled farmer incomes in the Konkan region by integrating nutmeg, cinnamon, black pepper, and fruit crops. These results highlighted the substantial economic benefits of integrating advanced cultivation techniques with STBFM in coconut farming[17]. The results are also consistent with Bari and Rahim[16], who investigated coconut-based agroforestry systems which generated higher returns due to additional contributions from fruit crop (coconut + guava) having the highest benefit-cost ratio (BCR).

The correlation interpretation showed that nutrients such as Mg, Ca, and Cu are vital for enhancing coconut productivity, consistent with previous findings regarding their key roles in photosynthesis, enzyme activation, and nutrient transport[21,22]. The positive relationship between organic carbon and yield indicated that OC significantly contributes to soil fertility, enhancing nutrient retention and biological activity[23]. Boron is an essential element for cell wall integrity and reproductive development, justifying its role in yield enhancement[24]. The negative correlation with Mn suggested that while this micronutrient is essential, its deficiency and toxicity can limit plant growth, particularly in specific soil pH conditions[25]. Moderate correlations with pH, EC, P, K, and Zn highlighted

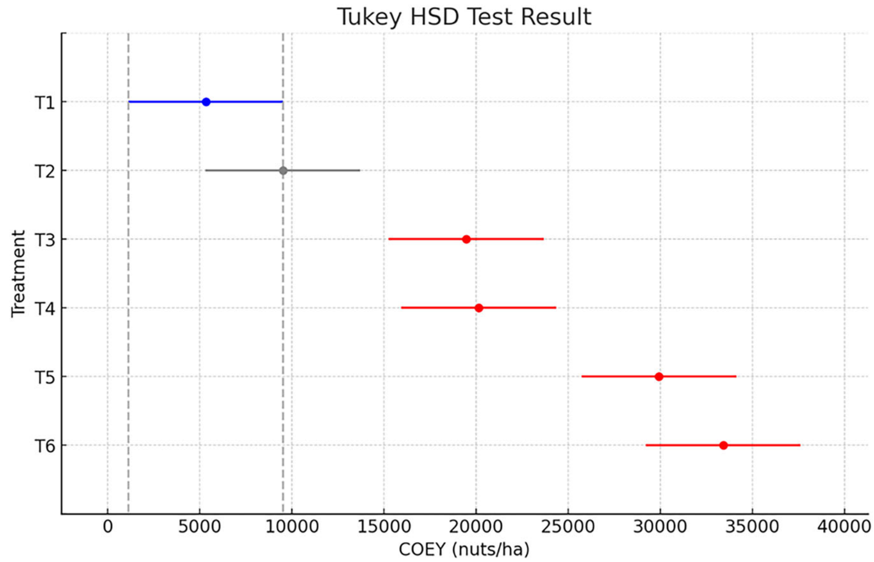

Fig. 6 | Tukey's honestly significant difference (HSD) test for coconut equivalent yield (COEY) across treatments. This figure presents the mean values of coconut equivalent yield (COEY) across different treatments, illustrating statistically significant treatment differences.

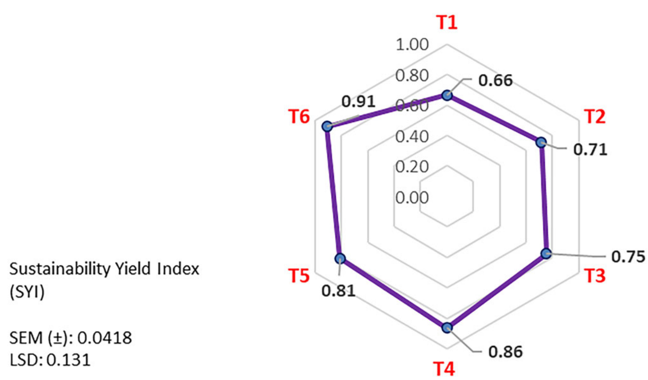

Fig. 7 | Sustainability yield index (SYI) under various coconut-based cropping systems. This figure presents the SYI values for each treatment.

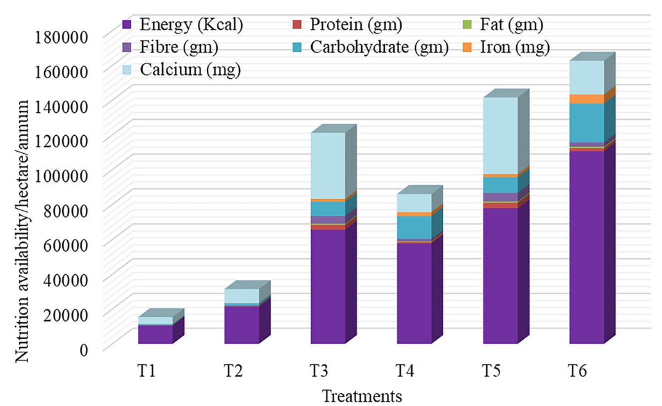

Fig. 8 | Nutritional availability per hectare of land area under different treatments. The bar graph compares the content of energy, protein, fat, carbohydrates, calcium, iron, and fiber in terms of nutritional availability per hectare per annum across different treatments.

the complex interactions between soil chemistry and nutrient availability. Notably, pH affects the solubility and uptake of most nutrients, and its connection to yield reflects the soil's role in fostering optimal nutrient availability and microbial activity[26]. The PCA results highlighted that exchangeable Ca, Mg, and K are the most influential soil parameters affecting coconut yield variability[27]. These findings are in line with the study of Kueklang et al.,[28] who reported that these nutrients are essential for coconut palm growth and fruit development. The alignment of the coconut equivalent yield with Exch. K and Avail. Zn on the biplot suggested that these nutrients may be particularly critical for yield optimization[29]. This indicated the multifaceted nature of soil fertility and its complex relationship with crop yield[30,31].

The ANOVA results showed that the coconut-based cropping system and the use of STBFM significantly affect coconut yield. The superior performance of T6 and T5 demonstrated the synergistic effect of combining STBFM with multi-storied and intercropping systems, likely due to enhanced nutrient use, space efficiency, and improved soil health. These findings align with Bhol et al.[32], an investigation conducted in Puri district of Odisha during 2012–2013 to study the composition, structure, and role of coconut (*Cocos nucifera L.*) based farming systems. The study found that among the farming systems studied, the 0.8-hectare coconut-based agroforestry system was identified as the most viable land use. This may be due to the enhanced nutrient utilization efficiency, better space utilization that these methods provide, and potential improvements in soil health[33–35]. The higher SYI values in multi-storied systems reflected their potential as scalable and climate-resilient models for enhancing productivity and sustainability in coconut-based farming. The combination of STBFM with system diversification further amplified these benefits by improving nutrient recycling, resource use efficiency, and soil health. The study conducted by Farsanashamin and Anilkumar[22] to investigate the influence of the STBFM approach (basin management of coconut with in situ green manuring, recycling of palm waste, FYM application @ 50 kg + 5 kg ash + 25 g Azospirillum per palm per year combined with the application of 75% of RDF of NPK each for the component crops viz. noni, banana, and long pepper) found beneficial for spreading awareness of the multi-storied cropping system in coconuts in coastal sandy soil about its productivity, profitability, and sustainability. The study indicated that adopting multi-storied cropping or intercropping in addition to the STBFM approach in a coconut-based system improves the overall nutritional security of the households as compared to a sole coconut cropping system and could be a viable and effective means of supplying food, nutrition, and financial stability to the expanding Indian population[8,36]. Considering the many advantages and agricultural sustainability, intercropping systems can be deemed appropriate for ensuring small-scale farmers' food and livelihood

Fig. 9 | Diverse agricultural practices in coconut cultivation. This figure illustrates the different coconut-based cropping systems evaluated in the study: **a** Multi-storied cropping system with various plant species. **b** Soil Test-Based Fertilizer Management (STBFM) applied to coconut. **c** Intercropping methods utilized between rows of coconut. **d** Harvested yield.

security[37]. Similarly, several studies highlighted the importance of multiple cropping in supplementing the farm income by growing additional crops valued financially, such as minor export crops, vegetables, fruit crops, grains, and tuber crops, as it ensures the nation's food security[8,38,39].

The present study demonstrated the importance of introducing multi-storied cropping in coconut-based production systems like intercropping comprising pulses and vegetables, and/or multi-storied cropping comprising pineapple, banana, turmeric, tomato, brinjal, etc. Similarly, the study highlighted the significance of soil test-based fertilizer management (STBFM) in coconut-based production systems, which can sustainably boost yield and economic returns from coconut homesteads. Among all the treatments, the multi-storied cropping system with STBFM (T6) showed the highest COEY (33,407 nuts ha^{-1}), energy (110,632 Kcal), fat (902 gm ha^{-1} $annum^{-1}$), carbohydrates (22344 gm ha^{-1} $annum^{-1}$), iron (5190 mg ha^{-1} $annum^{-1}$) and also recorded the highest net income (USD 4344.67 ha^{-1}) and benefit-cost ratio (3.21). Correlation analyses further revealed that specific soil nutrients, particularly magnesium, calcium, and potassium, were positively associated with the coconut-based system productivity. The outcomes of this research underscore the potential of sustainable management practices in transforming the livelihoods of coconut farmers. The study findings indicate that scaling out multi-storied cropping or intercropping at the landscape level, with STBFM, improves the nutritional availability and security of households. This approach ensures environmental health promotion, food security, and sustainable agricultural development. The study also feeds into developing suitable policy guidelines for sustainable and lasting impacts on the livelihoods of smallholder farmers across similar agroecologies in India.

Future research should concentrate on the long-term sustainability of the proposed cultivation methods in the coconut-based cropping system, their impact on soil health over time, and the exploration of different intercropping combinations suited for various climatic conditions. It is essential to examine how different coconut-based cropping systems adapt to climate variability and contribute to carbon sequestration. Evaluating the carbon storage potential of various intercropping and multi-storied systems can provide insights into their role in mitigating climate change. Additionally, studies should investigate how these practices influence greenhouse gas emissions and their overall carbon footprint. Considering our findings, we propose several strategic actions to foster sustainable practices for developing coconut-based livelihoods in Odisha. These actions are intended to enable a transition to more sustainable, productive, profitable, and environment-friendly management practices in coconut-based cropping systems across similar agroecologies. This requires extensive advocacy and scaling through capacity building and policy development for Farmers.

Methods

The investigation was carried out during 2021–23 in the Khorda district of Odisha, India, which is located at 20.1301° N latitude and 85.4788° E longitude along the Bay of Bengal. The study area was spread across 600 households in the Khorda district. However, the paper presents the findings from the strategic on-farm research conducted across 18 farmers' fields.

The experiment followed a randomized block design (RBD) with three replications, where each replication represented a different farmer's field. Six treatment combinations were evaluated to assess the performance of coconut-based cropping systems.

The treatments included sole coconut cultivation with and without STBFM, coconut intercropped with brinjal, tomato, chilli, cauliflower, radish, and amaranth, with and without STBFM (Fig. 9). Multi-storied coconut-based systems involved cultivating banana, pineapple, turmeric, and ginger, with and without STBFM. Strata-wise species arrangements were followed in multi-storied cropping systems, where coconut formed the upper canopy, banana occupied the middle stratum, while pineapple, turmeric, and ginger formed the lower canopy. Treatments ranged from no

Table 2 | Experimental treatment combination

Treat. No	Treatment details	Crop details	Soil test-based fertilizer recommendations				
			N	P	K	Zn	B
T1	Coconut without STBFM	Coconut	-	-	-	-	-
T2	Coconut with STBFM	Coconut**	600	800	800	14	1.4
T3	Intercropping: Coconut Without STBFM + Brinjal, Tomato, Chilli, Cauliflower, Radish, Amaranthus	Coconut	-	-	-	-	-
		Brinjal, Tomato, Chilli, Cauliflower, Radish, Amaranthus	-	-	-	-	-
T4	Multi-storied Cropping System: Coconut Without STBFM + Banana, Pineapple, Turmeric, Ginger	Coconut, Banana, Pineapple, Turmeric Ginger	-	-	-	-	-
T5	Intercropping: Coconut With STBFM + Brinjal, Tomato, Chilli, Cauliflower, Radish, Amaranthus	Coconut**	600	800	800	14	1.4
		Brinjal*	80	40	60	2	0.10
		Tomato*	100	60	60	2	100
		Chilli*	24	16	20	2	0.10
		Cauliflower*	60	24	32	2	0.10
		Radish*	20	20	30	2	0.10
		Amaranthus*	24	16	16	2	0.10
T6	Multi-storied Cropping System: Coconut with STBFM + Banana, Pineapple, Turmeric, Ginger	Coconut**	600	800	800	14	1.4
		Banana**	1000	200	1000	1	0.1
		Pineapple*	202	75.9	60.6	0	2
		Turmeric*	76	30	48	2	0.10
		Ginger*	20	10	10	2	0.20

STBFM - Soil Test-Based Fertilizer Management, * Kg/acre, **gm/plant, Coconut variety—Sakhigopal Local.

fertilizer application to precise nutrient management based on soil tests, with fertilizers applied at specific rates depending on the crop and cropping system. Treatment details, including fertilizer doses and crop species, are presented in Table 2.

Coconut Equivalent Yield (COEY): Measured in nuts per hectare

$$\mathbf{COEY}\left(\mathbf{nuts\ ha^{-1}}\right) = \frac{(\mathbf{Y_i} \times \mathbf{P_i}) + (\mathbf{Y_c} \times \mathbf{P_c})}{\mathbf{P_c}} \quad (1)$$

Where:

$\mathbf{Y_i}$ = Yield of intercrop (kg ha^{-1}), $\mathbf{P_i}$ = Price of intercrop (US kg^{-1}), $\mathbf{Y_c}$ = Yield of coconut (nuts ha^{-1}), $\mathbf{P_c}$ = Price of coconut (USD nut^{-1})

Coconut Equivalent Net Income (CENI): Measured in currency (USD).

$$\text{CENI (USD)} = \text{Coconut Equivalent Yield (COEY)} \times \text{Price of coconut} \quad (2)$$

Sustainability Yield Index (SYI): The SYI was computed as per the formula followed by Gokhale et al.[40]

$$\mathbf{SYI} = \frac{(\bar{\Upsilon} - \sigma)}{Y_{max}} \quad (3)$$

σ is standard deviation (nuts ha^{-1}), $\bar{\Upsilon}$ is average coconut equivalent yield (nuts ha^{-1}) and Y_{max} is the maximum coconut equivalent yield in all experimental years (nuts ha^{-1}).

The methodology followed for estimating various parameters as furnished below.

Parameter measured	Method	Reference
pH	The soil pH was measured by a glass electrode using a soil-water suspension ratio of 1:2	41
EC	The soil electrical conductivity (EC) was measured by a calomel electrode using a soil-water suspension ratio of 1:2 after settling the sample overnight using an EC meter	41
Organic carbon	Soil samples were ground to pass through a 0.25-mm sieve for organic carbon analysis by Walkley-Black method	42
Exchangeable bases	Exchangeable bases viz., K, Ca, and Mg were determined using the neutral normal ammonium acetate method	43
Available P	Available P in acidic soils was estimated by using Brays extractant no 1- 0.03 *M* NH_4F in 0.025 *M* HCl. Available P in alkaline soils was estimated by using sodium bicarbonate ($NaHCO_3$) of pH 8.5 as an extractant for soils respectively.	44 45
Available micronutrients	Available micronutrients viz., Fe, Cu, Mn, and Zn were extracted by DTPA reagent of pH 7.3	46
Available Boron	Available Boron was extracted by hot water	47
Available S	Measured using 0.15% calcium chloride ($CaCl_2$) as an extractant	48

Macro and micronutrients were measured on microwave plasma atomic emission spectroscopy whereas boron and sulphur were measured on inductively coupled plasma-optical emission spectroscopy (ICP-OES).

Soil samples were collected from each coconut-based cropping system using a systematic sampling approach. Sampling was performed at a depth of 0-30 cm. Care was taken to avoid contamination from surface debris,

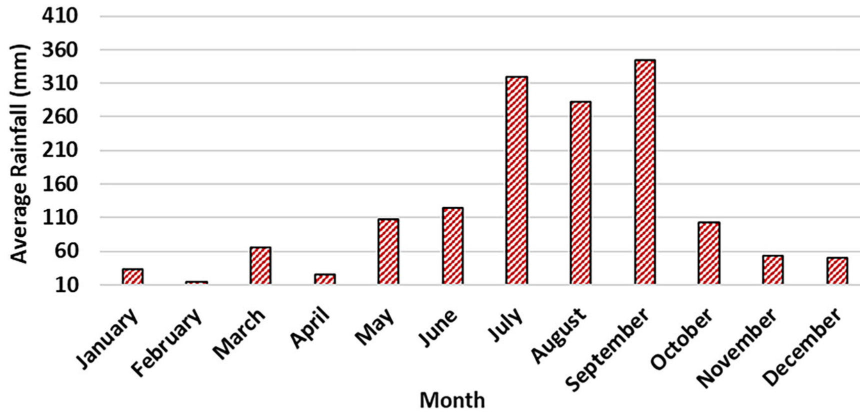

Fig. 10 | Average monthly rainfall of Khorda district. This figure presents the monthly rainfall pattern for Khorda district over the 2021–2023 period.

vegetation, or other external sources. The collected samples were then air-dried and powdered with a wooden hammer to pass through a 2-mm sieve and stored in a plastic container for chemical analysis. Average monthly rainfall data for the years 2021–2023 were collected and analyzed to understand the climatic conditions during the study period (Fig. 10). Statistical analysis was performed to compare the treatment effects on coconut yield, income, and soil parameters. Analysis of variance (ANOVA) and post-hoc tests (Tukey's Honestly Significant Difference (HSD) test to identify significant differences among the treatments) were conducted to determine significant differences among treatments. Statistical software [R software 4.3.2 version] was used for data analysis.

Principal component analysis (PCA) was carried out as described by Dunteman[49], Jolliffe[50] and Krzanowski[51]. The PCAs were determined as a linear combination of 14 soil parameters, comprising, soil pH, electrical conductivity, micro and macro nutrients.

Following the scaling of the data, principal components were derived to transform the original variables into a new coordinate system. The principal components (P) are linear combinations of the n original variables (X), where the coefficients a_{ij} represent the loadings of the original variables on the principal components. The principal components can be expressed as follows:

$$P_1 = a_{11}X_1 + a_{12}X_2 + --------- + a_{1k}X_k \quad (4)$$

$$P_2 = a_{21}X_1 + a_{22}X_2 + --------- + a_{2k}X_k \quad (5)$$

Here, $P1$ represents the first principal component, which captures the maximum variance in the data, and $a_{11}X_1 + a_{12}X_2 + -------- + a_{1k}X_k$ are the loadings of the first principal component on each of the original variables $X1$, $X2$,…,Xk. Similarly, $P2$ is the second principal component, $a21$, $a22$,…,$a2k$ are the corresponding loadings, and so on.

This study was conducted in accordance with the institutional ethical guidelines of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the Department of Mission Shakti, Government of Odisha. Field activities were carried out with prior informed consent from participating farmers. As no human or animal subjects were involved, formal ethics committee approval was not required.

Data availability

All data generated or analyzed during this study are included in this published article.

Code availability

Data analysis for this study was performed using R software (version 4.4.2).

Received: 4 May 2024; Accepted: 26 May 2025;
Published online: 23 July 2025

References

1. Kumar, N. V. et al. Harnessing the potential of pigeonpea and maize feedstock biochar for carbon sequestration, energy generation, and environmental sustainability. *Bioresour. Bioprocess.* **11**, 5 (2024).
2. Pasumarthi, R. et al. Innovative bio-pyrolytic method for efficient biochar production from maize and pigeonpea stalks and their characterization. *J. Clean. Prod.* **448**, 141573 (2024).
3. Nuwarapaksha, T. D., Udumann, S. S., Dissanayaka, D. M., Dissanayake, D. K. & Atapattu, A. J. Coconut based multiple cropping systems: an analytical review in Sri Lankan coconut cultivations. *Circ. Agric. Syst.* **2**, 1–7 (2022).
4. Bhalerao, P. P., Patel, B. N., Maheswarappa, H. P. & Jilu, V. S. Status, problems and prospects of coconut cultivation in Gujarat. *Indian Coconut J.* **60**, 4–7 (2018).
5. Panda, N. K., Sarangi, S. K., Das, H. K. & Kar, M. R. Role of coconut (Cocos nucifera) based agroforestry system in coastal Odisha. *J. Pharmacogn. Phytochem.* **9**, 1742–1745 (2020).
6. Sawargaonkar, G. et al. Bundled management practices for enhanced finger millet productivity in acid soils: empirical evidence from Odisha, India. *J. Agri. Food Res.* **21**,101946 (2025).
7. Patra, S. K. & Dash, M. Advances in integrated nutrient management for coconut cultivation. *J. Plant Nutr.* **44**, 622–637 (2021).
8. Sawargaonkar, GL. et al. Envirotyping helps in better understanding the root cause of success and limitations of rainfed production systems. *Front. Environ. Sci.* **12**, 1417199 (2024a).
9. Manasa, R. et al. Biochar as a strategy to manage stem rot disease of groundnut incited by Sclerotium rolfsii. *Front. Agron.* **6**, 1470194 (2024).
10. Iyer, P. & Joshi, D. Evaluating the benefits of intercropping in coconut-based farming systems in coastal Odisha. *J. Sustain. Agri.* **55**, 210–225 (2023).
11. Atapattu, A. J., & Udumann, S. S. in *Handbook of Nature-Based Solutions to Mitigation and Adaptation to Climate Change.* 1–28 (Springer International Publishing, Cham, 2024).
12. Khopade, R. Y. et al. Vegetable grafting: a scientific innovation to enhance productivity and profitability of tomato growers under climate change. *Front. Agron.* **7**, 1514673 (2025).
13. Jensen, E. S. Grain yield, symbiotic N2 fixation and interspecific competition for inorganic N in pea-barley intercrops. *Plant Soil.* **182**, 25–38 (1996).
14. Sawargaonkar, G. et al. Valorization of peanut shells through biochar production using slow and fast pyrolysis and its detailed physicochemical characterization. *Front. Sustain.* **5**, 1417207 (2024b).
15. Perfecto, I. & Vandermeer, J. Microclimatic changes and the indirect loss of ant diversity in a tropical agroecosystem. *Oecologia* **108**, 577–582 (1996).

16. Bari, M. S. & Rahim, M. A. Economic evaluation and yield performance of some medicinal plants in coconut based multi-storied agroforestry systems. *Agriculturists* **10**, 71–80 (2012).
17. Nair, K. P. Technological advancements in coconut, arecanut and cocoa research: A century of service to the global farming community by the Central Plantation Crops Research Institute, Kasaragod, Kerala State, India. In *Tree Crops: Harvesting Cash from the World's Important Cash Crops,* pp. 377–536 (Springer International Publishing, Cham, 2021). https://doi.org/10.1007/978-3-030-62140-7.
18. Raj, A. J. & Lal, S. B. in *Agroforestry Theory and Practices*. ch. 38. 671–681 (Scientific Publishers, 2014).
19. Walia, S. S., Dhawan, V., Dhawan, A. K. & Ravisankar, N. Integrated farming system: enhancing income source for marginal and small farmers. In: *Human Centered Computing*, pp. 63–94 (Springer, Cham, 2019). https://doi.org/10.1007/978-3-319-99768-1_5.
20. Shinde, V. V. et al. Coconut-real kalpavriksha to raise farmers' income. *Adv. Agri. Res. Technol. J.* **2**, 148–159 (2018).
21. Yan, S., Hu, Q. & Shen, J. Calcium nutrition nanoagent rescues tomatoes from mosaic virus disease by accelerating calcium transport and activating antiviral immunity. *Front. Plant Sci.* **6**, 1092774 (2022).
22. Farsanashamin, P. & Anilkumar, A. S. Sustainable soil fertility management in coconut-based multi-storied cropping system. *J. Plant. Crops* **44**, 1–7 (2016).
23. Gerke, J. The central role of soil organic matter in soil fertility and carbon storage. *Soil Syst.* **6**, 33 (2022).
24. Dameto, L. S., Moraes, L. A. & Moreira, A. Effects of boron sources and rates on grain yield, yield components, nutritional status, and changes in the soil chemical attributes of soybean. *J. Plant Nutr.* **46**, 2077–2088 (2023).
25. Skorka, M., Sieprawska, A. & Telk, A. The implication of manganese surplus on plant cell homeostasis: a review. *J. Plant Growth Regul.* **42**, 1327–1341 (2023).
26. Mishra, A., Singh, L. & Singh, D. Unboxing the black box—one step forward to understand the soil microbiome: a systematic review. *Microb. Ecol.* **85**, 669–683 (2023).
27. Bandyopadhyay, A., Ghosh, D. K., Biswas, B., Parameswarappa, M. H. & Timsina, J. Fertigation effects on productivity, and soil and plant nutrition of coconut (Cocos nucifera L.) in the Eastern Indo-Gangetic Plains of South Asia. *Int. J. Fruit. Sci.* **19**, 57–74 (2019).
28. Kueklang, M., Krisanapook, K., Havananda, T., Phavaphutanon, L. & Luengwilai, K. Seasonal variation of fruit yield and leaf macronutrient concentrations of Thai aromatic coconut. *Agri. Nat. Resour.* **55**, 854–862 (2021).
29. Rehman, H. U., Aziz, T., Farooq, M., Wakeel, A. & Rengel, Z. Zinc nutrition in rice production systems: a review. *Plant soil.* **361**, 203–226 (2012).
30. Khan, H. & Krishna kumar, V. Soil productivity and nutrition. In Krishna kumar, V., Thampan, P. K. & Nair, M. A. (eds), *The Coconut Palm (Cocos nucifera L.)—Research and Development Perspectives,* pp. 323–442. (Springer, Singapore, 2018). https://doi.org/10.1007/978-981-13-2754-4.
31. Singh, V. K., Malhi, G. S., Kaur, M., Singh, G., & Jatav, H. S. in *Ecosystem Services: Types, Management and Benefits*. (ed. Jatav, H. S.) ch. no.15, 259–278 (Nova Science Publishers, Inc., Hauppauge, NY, USA, 2022).
32. Bhol, N., Sarangi, S. K. & Behera, U. K. Coconut (*Cocos nucifera*)-based farming system: a viable land use option for small and marginal farmers in coastal Odisha. *Indian J. Agric. Sci.* **85**, 1488–1497 (2015).
33. Maheswarappa, H. P., Palaniswami, C., Dhanapal, R. & Subramanian, P. Cropping system for coastal sandy soil management. In Thomas, G. V., Krishnakumar, V., Maheswarappa, H. P. & Palaniswami, C. (eds), *Coconut Based Cropping/Farming Systems*, pp. 9–31 (Central Plantation Crops Research Institute, Kasaragod, India, 2010).
34. Zainol, F. A. et al. Coconut value chain analysis: a systematic review. *Agriculture* **13**, 1379 (2023).
35. Tiemann, T., & Douxchamps, S. Opportunities and challenges for integrated smallholder farming systems to improve soil nutrient management in Southeast Asia. *World Dev. Sustain.* **3**, 100080 (2023).
36. Awasthi, O. P. & Pareek, O. P. Horticulture based cropping system for arid region—a review. *Range Manag. Agrofor.* **29**, 67–75 (2008).
37. Maitra, S. et al. Intercropping—a low input agricultural strategy for food and environmental security. *Agronomy* **11**, 343 (2021).
38. Subramanian, P. et al. Coconut (Cocos nucifera L.). In Thomas, G. V. & Krishnakumar, V. (eds), *Soil Health Management for Plantation Crops: Recent Advances and New Paradigms,* pp. 37–109 (Springer Nature, Singapore, 2024). https://doi.org/10.1007/978-981-97-0092-9_2.
39. Maitra, S. et al. Agroforestry: A resource conserving technology for efficient utilization of agricultural inputs, leads to food and environmental security. In Jatav, H. S., Rajput, V. D., Minkina, T., Van Hullebusch, E. D. & Dutta, A. (eds), *Agroforestry to Combat Global Challenges: Current Prospects and Future Challenges,* pp. 15–52 (Springer Nature, Singapore, Pte Ltd., 2024).
40. Gokhale, D. N., Dhaipahale, V. V., Bhale, V. M. & Sawargaonkar, G. L. Sustainability of different cropping systems under varying sowing dates in Marathwada region. *J. Oilseeds Res.* **30**, 23–26 (2013).
41. Rhoades, J. D. Salinity: Electrical conductivity and total dissolved solids. In Sparks D. L. (ed), *Methods of Soil Analysis. Part 3: Chemical Methods, SSSA Book Series No. 5,* pp. 417–435, (Soil Science Society of America and American Society of Agronomy, Madison, WI, 1996). https://doi.org/10.2136/sssabookser5.3.c14.
42. Nelson, D. W. & Sommers, L. E. Total carbon, organic carbon, and organic matter. In Sparks D. L. (ed), *Methods of Soil Analysis. Part 3: Chemical Methods, SSSA Book Series No. 5,* pp. 961–1010 (Soil Science Society of America and American Society of Agronomy, Madison, WI, 1996). https://doi.org/10.2136/sssabookser5.3.c34.
43. Okalebo, J. R., Gathua, K. W. & Woomer, P. L. in *Laboratory Methods Of Soil And Plant Analysis: A Working Manual Second Edition*. Vol. 21, 25–26 (SACRED Africa, Nairobi Office, 2002).
44. Bray, R. H. & Kurtz, L. T. Determination of total, organic, and available forms of phosphorus in soils. *Soil Sci.* **59**, 39–4 (1945).
45. Olsen, S. R. & Sommers, L. E. in *Methods of Soil Analysis*. (eds Page A. L., Miller, R. H., and Keeney, D. R.). 2nd edn. Agronomy Series No. 9, Part 2. 403–430 (Soil Science Society of America, Inc., Madison, WI., 1982).
46. Lindsay, W. L. & Norvell, W. Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Sci. Soc. Am. J.* **42**, 421–428 (1978).
47. Keren, R. in *Methods of Soil Analysis, Part 3: Chemical Methods*. Vol. 5, 603–626 (Wiley, 1996).
48. Tabatabai, M. A. in *Methods of Soil Analysis, Part 3: Chemical Methods.* Vol. 5, 921–960 (Wiley, 1996).
49. Dunteman, G. H. *Principal Components Analysis*. (Sage Publications, Newbury Park, California, 1989).
50. Jolliffe, I. T. *Principal Component Analysis*. (Springer-Velag, New York, 1986).
51. Krzanowski, W. J. Some exact percentage points of a statistic useful in analysis of variance and principal component analysis. *Technometrics* **21**, 261–263 (1979).

Acknowledgements

We gratefully acknowledge the support of the officials from headquarters and the Khorda district of Odisha Livelihoods Mission (OLM) for their support and facilitation during project implementation. This study was funded by the Odisha Livelihoods Mission, Department of Mission Shakti, Government of Odisha, India.

Author contributions
All authors contributed to the study's conception and design. Conceptualization, methodology, and supervision performed by R.K., G.S., S.K., and M.D. Project administration and supervision by R.K. and G.S. Material preparation, data collection, and analysis were performed by R.V., S.S.D., R.K., S.K., S.R. Validation and formal analysis done by S.K., R.K., M.D., K.R., S.R. Resources were managed by M.L., R.S., G.S., R.K. The first draft of the manuscript was written by R.K., G.S. and S.K. All authors read and approved the final manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to Gajanan Sawargaonkar.

Reprints and permissions information is available at http://www.nature.com/reprints

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

© The Author(s) 2025