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RESEARCH ARTICLE

Biological performance and profitability study of different medicinal plants grown as intercrops in arecanut plantations

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Abstract

Monocropping of arecanut (*Areca catechu* L.) results in underutilised resources. However, including medicinal and aromatic plants (MAPs) provides a sustainable way to enhance soil health, resource efficiency and financial rewards. In Odisha, favourable climate and arecanut canopy structure support MAP cultivation, yet adoption remains limited. To explore the productivity and economics of arecanut based cropping systems, a field experiment was conducted in a 5-year-old arecanut plantation during 2021–23. Three cropping systems combined with varied nutrient management strategies including organic recycling and biofertilizers were evaluated. The results indicated that application of biofertilizers consortia along with organic recycling of biomass + 75 % of nitrogen (N), phosphorus (P) and potassium (K) through soil test based dose (STD) in arecanut + *Withania somnifera* (ashwagandha) + *Rauvolfia serpentina* (sarpagandha) system recorded higher *chali* yield (2.33 kg palm^{-1}). Whereas highest arecanut equivalent yield (84.46 q ha^{-1}) was obtained with arecanut + turmeric + black turmeric under 100 % NPK and organic recycling. Maximum system productivity (91.35 q ha^{-1}) was noted in arecanut + *Andrographis paniculata* (kalmegh) + *Ocimum sanctum* (tulsi) with organic recycling of biomass and application of 75 % NPK and biofertilizer consortia. Arecanut + *Curcuma longa* (turmeric) + *C. caesia* (black turmeric) system with organic recycling of biomass and 100 % NPK (STD) exhibited the maximum net return (₹1069363), while arecanut + *W. somnifera* (ashwagandha) + *R. serpentina* (sarpagandha) reported the maximum benefit-cost (B:C) ratio (2.66). These findings highlight arecanut based cropping system as an economically viable, resource-efficient cropping strategy for Odisha.

Keywords: arecanut based cropping system; arecanut equivalent yield; benefit-cost ratio; *chali* yield; system productivity index

Introduction

Arecanut (*Areca catechu* L.), a member of the Arecaceae family, is a key plantation crop in India, providing livelihoods to nearly ten million people, predominantly small and marginal farmers. India is the largest producer and consumer of arecanut globally (1). However, arecanut monocropping often leads to inefficient use of land and resources. Even with optimal planting density, considerable space beneath the canopy remains underutilized, resulting in lower economic returns. These vacant areas are prone to weed growth, which competes with the crop for water and nutrients, ultimately reducing productivity. The tall and upright growth habit of arecanut, however, creates a favourable microclimate for intercropping by allowing sufficient light penetration and conserving soil moisture. Studies have shown that arecanut palms utilize only 43 % of incident light, which can be increased to 95 % through strategic intercropping (2). Moreover, the root spread, which occupies about 2.27 m^2 or 68.9 % of the basin area, still allows space for intercrop establishment. With assured irrigation, the integration of multiple crops becomes both feasible and profitable (3).

Intercropping within arecanut plantations has been widely studied and proven effective in improving land productivity and profitability. During the initial non-bearing years, short-duration annuals and biennials can be successfully cultivated, while in later stages, shade-tolerant and high-value crops such as spices, vegetables, tubers, flowers and particularly medicinal and aromatic plants (MAPs), can be integrated (4, 5). Intercrops like banana, pepper, cocoa, elephant foot yam and MAPs have shown significant improvements in productivity and economic returns (3, 6-8). Arecanut based cropping systems are especially beneficial in enhancing income stability, optimizing resource use, conserving soil and increasing resilience to climatic variations. Furthermore, diversified cropping in arecanut based cropping system substantially increases labour demand up to 900 man-days annually compared to only 405 in monoculture systems thereby contributing to rural employment (9).

The incorporation of MAPs into arecanut based cropping system has demonstrated notable increase in income and agronomic advantages. MAPs such as *R. serpentina*, *O. basilicum* and *Piper longum* have recorded high net returns per rupee invested (1.95-4.25), along with yield enhancements in arecanut ranging from 11 % to 53 % (3). Integrated nutrient management, including the use of chemical fertilizers, biofertilizers and organic amendments, further supports sustained productivity (10-12). Trials conducted at Central Plantation Crops Research Institute (CPCRI), Vittal revealed that crops like *Asparagus racemosus*, lemongrass and basil significantly enhanced system productivity and profitability (13, 14). Land equivalent ratios (LER) above 1.7 and increased kernel and *chali* equivalent yields highlight the efficiency of such diversified systems. Though intercropping may reduce yield in some component crops, overall net returns consistently outperform monoculture, validating the ecological and economic sustainability of arecanut based cropping system (15, 16).

Odisha, with its tropical climate and diverse agro-ecological zones, presents significant potential for implementing arecanut based cropping system, particularly involving MAPs. The canopy structure in arecanut gardens supports shade-loving medicinal crops such as turmeric, black turmeric, kalmegh and sarpagandha (2). Despite this, awareness and adoption of MAP cultivation remain limited among farmers in Odisha, largely due to unfamiliarity with cultivation practices and concerns about the long gestation period in monoculture. Intercropping MAPs with arecanut provides a practical alternative, generating intermediate income and reducing risk. Economic analyses have shown that such combinations can improve land-use efficiency and ensure better income stability. With targeted promotion, training and market linkages, Odisha could emerge as a major hub for arecanut based cropping system with MAP integration, contributing to rural livelihoods and enhancing the agricultural economy of the state.

To tackle these issues, it is essential to develop sustainable nutrient management strategies tailored for arecanut cropping systems. At present, combining organic amendments, biofertilizers and chemical fertilizers in appropriate proportions is encouraged to achieve sustainable enhancement of crop productivity.

Materials and Methods

The present study was carried out from 2021 to 2023 at the experimental field of All India Coordinated Research Project on Medicinal & Aromatic Plants and Betelvine, Horticulture Research Station, Odisha University of Agriculture and Technology, Baramunda, Bhubaneswar. The experiment involved two factors: the main factor included three cropping system types (C), combining arecanut with intercrops such as *C. longa* (turmeric), *C. caesia* (black turmeric), *W. somnifera* (ashwagandha), *R. serpentina* (sarpagandha), *A. paniculata* (kalmegh) and *O. sanctum* (tulsi); the subplot factor comprised three levels of nutrient management practices (N). The treatment combinations are enlisted in Table 1.

Table 1. Detail of treatment combinations for arecanut based cropping system

Treatments		Symbolized as
Main plot (cropping systems)	:	C
Arecanut + turmeric + black turmeric	:	C_1
Arecanut + kalmegh + tulsi	:	C_2
Arecanut + ashwagandha + sarpagandha	:	C_3
Sub plot (nutrient management)	:	N
Organic recycling + 100 % NPK through a recommended dose of fertilizer (RDF)	:	N_1
Organic recycling + 100 % NPK through soil test -based fertilizer dose (STD)	:	N_2
Organic recycling + 75 % NPK through soil test-based fertilizer dose (STD) + biofertilizer consortia	:	N_3

Design and layout

The experimental site was segmented into 27 plots, each measuring 8.1 m × 8.1 m (covering 65.61 m^2). Each plot contained 6 arecanut plants, totalling 162 plants across the entire 1200 m^2 experimental area. The study was arranged using a split plot design (SPD), featuring three main plot treatments and three subplot treatments, each replicated three times.

Inputs used

Nutrient management for each treatment included both organic and inorganic components. Inorganic nutrients were supplied using urea (46 % N), single super phosphate (16 % P_2O_5) and muriate of potash (60 % K_2O). Organic treatments involve *in-situ* recycling of organic matter generated from the various cropping systems within each treatment. Additionally, some treatments incorporated biofertilizers- a consortia mixture of *Azotobacter, Azospirillum* and phosphate solubilizing bacteria (PSB) in equal proportions (1:1:1) sourced from the Department of Soil Science and Agricultural Chemistry, OUAT, Bhubaneswar. These biofertilizers were applied to both arecanut and intercrops according to the specific treatment protocols.

The experiment was conducted in a five-year-old arecanut plantation (cv. Mohitnagar) sourced from ICAR-Central Plantation Crops Research Institute Regional Research Centre, Mohitnagar, West Bengal, planted at a spacing of 2.7 m × 2.7 m. The site was prepared in early May of both 2021 and 2022 before the commencement of the study. Intercrops, turmeric (cv. Roma), black turmeric (cv. Pottangi local), sarpagandha (cv. RS-1), tulsi (cv. CIM Soumya), kalmegh (cv. Anand Kalmegh -1) and ashwagandha (cv. Jawahar Ashwagandha 20) were either sown or transplanted within the arecanut plantation, maintaining a 0.75 m radius clear space around each arecanut plant.

Observations recorded

The biological efficiency of arecanut based intercropping systems was calculated through some indices to know the yield advantages of associated crops over main crop.

Chali yield of arecanut

The fully matured nuts (9 months old) freshly harvested from each palm were selected and sun-dried for 40-50 days. The fully dried fruits were then dehusked to estimate the *chali* yield using a digital weighing balance.

Biological indices of arecanut based cropping system

Arecanut equivalent yield

The yield of different intercrops recorded per hectare of arecanut garden was converted into equivalent yield of main crop (arecanut) based on price of produce (17). Arecanut equivalent yield (AEY) of the intercropping system was calculated as demonstrated in equation 1.

$$AEY = \text{Yield of arecanut} + \frac{\text{Yield price intercrop 1}}{\text{Price of arecanut}} + \frac{\text{Yield price intercrop 2}}{\text{Price of arecanut}} \quad \text{(Eqn. 1)}$$

Land equivalent ratio

The land equivalent ratio of arecanut based intercropping system was calculated by summing up the partial LER of component crops such as arecanut and intercrops. It is an index of intercropping advantage that indicated the amount of interspecific competition or facilitation in an intercropping system (18). It is calculated as demonstrated in equation 2 and 3.

$$\text{Partial LER} = \frac{\text{Economic yield obtained in intercroping}}{\text{Economic yield obtained in sole crop}} \quad \text{(Eqn. 2)}$$

System LER =

partial LER of main crop + partial LER of intercrop I + partial LER of intercrop II (Eqn. 3)

Relative yield total (RYT)

It is a measure of the yield advantage of crop mixture. The RYT is designed as a measure of the extent to which various crop components shared common resources rather than as a direct measure of yield advantage (19). It can be calculated as demonstrated in equation 4 and 5.

$$RYT = \frac{Yab}{Yaa} + \frac{Yba}{Ybb} \quad \text{(Eqn. 4)}$$

Where, Yaa= Biomass yield of crop 'a' in pure stand

Yab= Biomass yield of crop 'a' grown with crop 'b'

Ybb= Biomass yield of crop 'b' in pure stand

Yba= Biomass yield of crop 'b' grown with crop 'a'

System RYT=

RYT of main crop + RYT of intercrop I + RYT of intercrop II

(Eqn. 5)

System productivity index (SPI)

It converts the yield of a component crop in terms of another crop in the mixture utilizing the monocrops yield ratio. Intercropping is advantageous if the SPI of intercrops > SPI of monocrops (20). The SPI of the cropping system is demonstrated in equation 6.

$$SPI = \frac{Y1m}{Y2m} xY2_c + \frac{Y1_m}{Y3^m} xY3_c + Y1c \quad \text{(Eqn. 6)}$$

Where,

$Y1_c$, $Y2_c$ or $Y3_c$ = expected yield of crop 1,2 or 3 as a companion crop

$Y1_m$, $Y2_m$ or $Y3_m$ = expected yield of crop 1,2 or 3 as monocrop

Economics of intercropping systems

Economics of different arecanut based intercropping system was worked out considering the prevailing cost of inputs like labourer, seeds, manures and fertilizers, pesticides and sale price of produce during 2021-22 and 2022-23. The cost of various inputs and sale price of produce remained same during both the years of study. The gross return was calculated by multiplying the average yield (q/ha) of different crops during the experimental study with prevailing market price per quintal and net return was worked out by deducting the cost of cultivation from gross return. The benefit-cost ratio (B:C) of intercropping systems were worked out as mentioned in equation 7.

B:C of intercropping system =

$$\frac{\text{Gross return of intercropping system}}{\text{Cost of cultivation of intercropping system}} \quad \text{(Eqn. 7)}$$

Statistical analysis

The data were analyzed using analysis of variance (ANOVA) to assess the impact of cropping systems and nutrient management on the arecanut based cropping systems, along with the statistical significance of treatment effects. Treatment means were separated using Duncan's multiple tange test (DMRT) at a significance level of $p \leq 0.05$, executed through R-Studio software (version 4.1.2).

Result and Discussion

Productivity of arecanut

Chali yield (kg palm^{-1})

The cropping system and nutrient management has a significant impact on *chali* yield of arecanut. The maximum *chali* yield of arecanut (2.24 kg palm^{-1}) was observed in C_3: arecanut + ashwagandha + sarpagandha which was significantly superior to all other treatments while the minimum (2.14 kg palm^{-1}) was noted in C_1: arecanut + turmeric + black turmeric (Table 2). Among the nutrient management practices, the maximum *chali* yield of arecanut (2.27 kg palm^{-1}) was observed in N_3: organic recycling + 75 % NPK (STD) + biofertilizer consortia, while the minimum (2.09 kg palm^{-1}) was recorded with N_1: organic recycling + 100 % NPK (RDF). The interaction effect of the cropping system and nutrient management practices revealed that there was a significant variation among the treatment. The maximum *chali* yield of arecanut (2.33 kg palm^{-1}) was recorded in C_3N_3: arecanut + ashwagandha + sarpagandha with organic recycling + 75 % NPK (STD) + biofertilizer consortia whereas the minimum (2.06 kg palm^{-1}) was noted in C_1N_1: arecanut + turmeric + black turmeric with organic recycling + 100% NPK (RDF). Integrating medicinal intercrops within arecanut based cropping systems, along with the application of 75 % soil test-based NPK combined with organic biomass and biofertilizer consortia,

Table 2. Yield of different component crops under different arecanut based cropping systems

Treatment	Economic yield (q ha^{-1})		Biomass yield (t ha^{-1})	
	Intercrop I	Intercrop II	Intercrop I	Intercrop II
C_1N_1	97.48	37.99	34.81	33.56
C_1N_2	101.53	39.53	36.77	35.83
C_1N_3	97.95	35.82	35.79	34.66
C_2N_1	31.12	87.10	24.31	26.29
C_2N_2	33.75	88.48	27.42	27.54
C_2N_3	32.83	88.13	25.02	26.73
C_3N_1	3.79	10.43	20.80	25.34
C_3N_2	3.88	10.56	21.79	27.84
C_3N_3	3.82	10.46	21.45	25.82

significantly boosts *chali* yield. This yield improvement is mainly due to better soil health, improved nutrient uptake and a more favourable microclimate created by the intercrops. Medicinal intercropping enhances overall crop performance by efficiently utilizing soil and environmental resources (21). Integrated approaches enrich soil fertility and support higher nut productivity in arecanut (22). Studies on coconut based systems also affirm that diversified cropping practices promote sustained yields through improved nutrient cycling and plant vigour (23). Therefore, the increased *chali* yield can be attributed to better resource management and plant growth conditions provided by these integrated systems. These were aligned with the findings of several studies (24-28).

Biological indices of arecanut

Arecanut equivalent yield (q ha^{-1})

The yield realised from different intercrops is presented in the Table 2. The cropping system and nutrient management practices significantly influenced the arecanut equivalent yield (Table 3). The pooled analysis revealed that the maximum arecanut equivalent yield (82.03 q ha^{-1}) was observed in C_1, which was significantly superior to all other treatments while the minimum (52.60 q ha^{-1}) was noted in C_2. Among the nutrient management practices, the maximum arecanut equivalent yield (66.34 q ha^{-1}) was observed in N_2, while the minimum (63.59 q ha^{-1}) was recorded with N_1. The interaction effect of the cropping system and nutrient management practices revealed that there was a significant variation among the treatment. The maximum arecanut equivalent yield (84.46 q ha^{-1}) was recorded in C_1N_2, whereas the minimum (50.62 q ha^{-1}) was noted in C_2N_1. Turmeric and black turmeric's substantial biomass and economic value contribute significantly to the AEY, reflecting the system's high productivity. Due to intercropping of medicinal plants, the productivity per unit area in terms of arecanut equivalent increased considerably (13). The better performance of medicinal and aromatic plants as intercrops in arecanut plantation might be attributed to congenial microclimate in the plantation and better soil fertility status (29). Earlier reports also suggested that mixed cropping of coconut with cocoa had a buffering effect against drastic fluctuations in microclimate (30). Improved microbial activity and soil fertility was reported earlier in arecanut based cropping system (31).

Land equivalent ratio

The pooled data of the year 2021-22 and 2022-23 exhibited that the cropping system and nutrient management has a significant impact on land equivalent ratio (Table 4). The maximum land equivalent ratio (3.28) was observed in C_3, which was significantly superior to all other treatments, while the minimum (2.86) was noted in C_1. Among the nutrient management practices, the maximum land equivalent ratio (3.07) was observed in N_3, while the minimum (2.99) was recorded with N_1. The interaction effect of the cropping system and nutrient management practices revealed that there was a

Table 3. Effect of arecanut based cropping system on *chali* yield and arecanut equivalent yield

Treatment	*Chali* yield (kg palm^{-1})	Arecanut equivalent yield (q ha^{-1})
Cropping system		
C_1	2.14 c	82.03 a
C_2	2.20 b	52.60 c
C_3	2.24 a	60.82 b
S.E. (m)±	0.0041	1.00
C.D. (0.05)	**0.0134**	**3.27**
Nutrient management		
N_1	2.09 c	63.59 c
N_2	2.22 b	66.34 a
N_3	2.27 a	65.51 b
S.E. (m)±	0.0042	0.06
C.D. (0.05)	**0.0124**	**0.18**
Interaction: C × N		
C_1N_1	2.06 h	80.94 b
C_1N_2	2.17 f	84.46 a
C_1N_3	2.20 e	80.70 b
C_2N_1	2.08 h	50.62 h
C_2N_2	2.23 d	53.35 g
C_2N_3	2.28 b	53.82 f
C_3N_1	2.14 g	59.23 e
C_3N_2	2.26 c	61.21 d
C_3N_3	2.33 a	62.01 c
S.E (m)±	0.0073	0.11
C.D. (0.05)	**0.0214**	**0.31**
S.E (m)± for C x N x Year	0.0104	0.15
C.D. (0.05) for C x N x Year	**0.0303**	**0.44**
Sale price	Arecanut: ₹ 200/kg	
	Turmeric: ₹ 30/kg	Black turmeric: ₹ 200/kg
	Kalmegh: ₹ 30/kg	Tulsi: ₹ 40/kg
	Ashwagandha: ₹ 200/kg	Sarpagandha: ₹ 500/kg

Table 4. Effect of arecanut based cropping system on different biological indices

Treatment	Land equivalent ratio	Relative yield total	System productivity index (q ha^{-1})
		Cropping system	
C_1	2.86 c	3.02 a	78.24 c
C_2	3.28 a	2.72 b	89.70 a
C_3	2.97 b	2.73 b	81.28 b
S.E. (m)±	0.012	0.014	0.327
C.D. (0.05)	**0.039**	**0.045**	**1.067**
		Nutrient management	
N_1	2.99 c	2.83 ab	81.84 c
N_2	3.05 b	2.84 a	83.48 b
N_3	3.07 a	2.82 b	83.89 a
S.E. (m)±	0.002	0.001	0.042
C.D. (0.05)	**0.006**	**0.004**	**0.123**
		Interaction: C × N	
C_1N_1	2.84 i	3.02 a	77.75 i
C_1N_2	2.89 g	3.03 a	78.99 g
C_1N_3	2.85 h	3.00 b	77.99 h
C_2N_1	3.21 c	2.71 g	87.77 c
C_2N_2	3.29 b	2.73 de	89.97 b
C_2N_3	3.34 a	2.73 d	91.35 a
C_3N_1	2.93 f	2.75 c	80.01 f
C_3N_2	2.98 e	2.72 f	81.49 e
C_3N_3	3.01 d	2.73 ef	82.35 d
S.E. (m)±	0.004	0.002	0.073
C.D. (0.05)	0.011	0.007	0.212
S.E. (m)± for C x N x Year	0.005	0.003	0.103
C.D. (0.05) for C x N x Year	0.016	0.010	0.300

significant variation among the treatment. The maximum land equivalent ratio (3.34) was recorded in C_2N_3, whereas the minimum (2.84) was reported in C_1N_1. This increase in LER in arecanut based cropping system suggests an economic yield advantage and increased production efficiency of arecanut + kalmegh + tulsi over other cropping systems. By combining shallow-rooted kalmegh and tulsi with deep-rooted arecanut in the arecanut + kalmegh + tulsi cropping system, a reduction in interspecific competition and better distribution of light, nutrients and water were observed. Additionally, recycling of organic biomass along with application of 75 % of the soil-test NPK dosage and inoculating with a biofertilizer consortia improved soil microbial activity and nutrient availability, leading to greater land-use efficiency and synergistic yield benefits across all components (4).

Relative yield total

The pooled data of both the years exhibited that the cropping system and nutrient management has a significant impact on relative yield total (Table 4). The maximum relative yield total (3.28) was observed in C_1, which was significantly superior to all other treatments while the minimum (2.73) was recorded in C_3. Among the nutrient management practices, the maximum relative yield total (3.07) was observed in N_2, while the minimum (2.82) was recorded with N_3. The interaction effect of the cropping system and nutrient management practices revealed that there was a significant variation among the treatment. The maximum relative yield total (3.03) was recorded in C_1N_2, whereas the minimum (2.71) was recorded in C_2N_1. Intercropping in arecanut plantations has been shown to enhance resource utilization and improve input use efficiency. Monoculture arecanut systems intercepted only 43 % of available light, however, mixed cropping arrangements could intercept up to 95 %, thereby optimizing light use for better crop development (4). This might have attributed to increased biomass yield production, which in turn increased the RYT of the arecanut based cropping systems.

System productivity index (q ha^{-1})

The pooled data of both the years exhibited that the cropping system and nutrient management has a significant impact on system productivity index (Table 4). The maximum system productivity index (89.70 q ha^{-1}) was observed in C_2, which was significantly superior to all other treatments while the minimum (78.24 q ha^{-1}) was recorded in C_1. Among the nutrient management practices, the maximum system productivity index (83.89 q ha^{-1}) was observed in N_3, while the minimum (81.84 q ha^{-1}) was recorded with N_1. The interaction effect of the cropping system and nutrient management practices revealed that there was a significant variation among the treatment. The maximum system productivity index (91.35 q ha^{-1}) was recorded in C_2N_3, whereas the minimum (77.75 q ha^{-1}) system productivity index was noted in C_1N_1. The results clearly indicate that integrating medicinal plants with arecanut along with reduced chemical inputs and biofertilizers can achieve high overall system productivity. The SPI accounts for the combined yield of all components in the system, emphasizing the benefits of crop diversification and integrated nutrient management in enhancing total farm output. According to the ICAR-Central Plantation Crops Research Institute, maintaining a canopy spread of 3.8 to 4.0 meters and a height of 2.7 meters is ideal for optimal yield in cocoa when intercropped with arecanut and coconut. This structured canopy architecture facilitates efficient light interception and resource utilization, thereby promoting better growth and productivity (32).

Economics of arecanut based cropping systems as influenced by different nutrient management practices

The average cost of cultivation, gross return, net return and B:C of both the years of study were worked out and presented in Table 5. The result revealed that C_1N_3 recorded the maximum cost of cultivation (₹ 824881), while C_2N_1 recorded the lowest (₹ 415531). The maximum gross return of ₹ 1892330 was recorded with C_1N_2, whereas the minimum was noted with C_2N_1 (₹ 1027455). The treatment C_1N_2 exhibited highest net return (₹ 1069363), whereas the lowest value was noted with C_2N_1 (₹ 611924). The average B:C of both the year of study indicated that the highest B:C was estimated in C_3N_3 (2.66) and lowest in C_1N_3 (2.19).

In tropical small-scale farming, arecanut cultivation is evolving towards maximizing profits and efficient resource use, notably through intercropping and improved nutrient management. The arecanut + turmeric + black turmeric cropping system with organic biomass recycling and 75 % of the recommended NPK through soil test along with biofertilizer consortia exhibited highest cost of cultivation. This is due to the higher input cost of black turmeric. The highest gross return and net return were noted in arecanut + turmeric + black turmeric with organic recycling + 100 % NPK (STD). The higher gross return also is due to the high market price of the fresh black turmeric rhizome. The arecanut + ashwagandha + sarpagandha system, using a lower nutrient level (75 % NPK) with biofertilizers and organic recycling, offers a higher benefit-cost ratio of 2.66. This system shows greater profit per unit of investment, highlighting a complex relationship between input intensity, system design and economic return. These findings align with extensive research on the economic advantages of intercropping in arecanut plantations. Regional studies, such as in Dakshina Kannada, show significant net return increases from intercropping with banana and pepper. Similarly, research in Northeast India emphasizes the enhanced productivity and profitability of high-density, multispecies arecanut cropping systems with black pepper, banana and citrus. These studies collectively illustrate intercropping's transformative potential for arecanut farming, shifting it from monoculture to a diversified, economically resilient model. A key factor in this shift is the strategic use of biofertilizers.

Table 5. Cost-benefit analysis of arecanut based cropping systems

Treatment	Total cost of cultivation (₹)	Total gross return (₹)	Total net return (₹)	Benefit-Cost ratio (B:C)
C_1N_1	820696	1813766	993070	2.21
C_1N_2	822967	1892330	1069363	2.30
C_1N_3	824881	1809922	985041	2.19
C_2N_1	415531	1027455	611924	2.47
C_2N_2	420883	1090561	669678	2.59
C_2N_3	421572	1096753	675181	2.60
C_3N_1	492163	1202383	710220	2.44
C_3N_2	483350	1241974	758624	2.57
C_3N_3	476445	1266267	789822	2.66

Research consistently shows that biofertilizers improve soil health and crop yields, leading to better economic outcomes. Studies on turmeric intercropped with arecanut and on arecanut plantations in general, indicate that integrated nutrient management with biofertilizers increases both yield and net income by improving soil conditions and nutrient availability. In conclusion, the evidence presented here, combined with previous research, strongly supports the idea that arecanut based cropping systems that strategically include intercrops and optimize nutrient management, including biofertilizer use, offer economically viable and sustainable options for farmers. While systems like arecanut + turmeric + black turmeric show high net returns. Whereas arecanut + ashwagandha + sarpagandha system provides a better return on investment, demonstrating the potential for both maximizing income and optimizing resource use. MAPs like ashwagandha and sarpagandha are a profitable alternative to traditional crops for smallholders in the tropics, with the potential to access niche markets and higher premiums (33). The superior economic performance of these systems is attributable to their enhanced biological productivity and favourable market prices. Furthermore, these findings are consistent with broader literature (2, 34-36) indicating the economic superiority of medicinal and aromatic plants, with net profits per rupee investment ranging from 1.95 to 4.25 and the significant enhancement of system productivity through intercropping. Multispecies intercropping consistently outperforms monoculture in plantation systems.

In West Bengal, six coconut based models (2003–2008) and found that the coconut + black pepper + pineapple system (model V) was most profitable, yielding ₹45600 ha^{-1} with a B:C of 1.16, followed by coconut + black pepper + banana (model IV) at ₹ 36050 ha^{-1} and a B:C of 1.20, without reducing coconut yield (37). In Karnataka, intercropping arecanut with cardamom and pepper raised net returns to ₹ 352858 ha^{-1} (141.3 % increase over sole arecanut) while the arecanut + pepper combination still achieved a 119.7 % profit gain of ₹ 169539 ha^{-1} (38). Additionally, in the West Bengal, arecanut + banana + turmeric model (model III) earned the highest income of Rs 36919.95 ha^{-1} with a B:C of 3.68:1 (39). Thus, medicinal plants like turmeric, tulsi, kalmegh and ashwagandha, when incorporated into cropping system models with perennial crops such as coconut and arecanut, enhance profitability and ecological benefits in tropical Indian conditions (40).

Conclusion

The study demonstrated that integrating medicinal and aromatic plants into arecanut based systems, along with appropriate nutrient management significantly improved arecanut growth and productivity. Application of 75 % NPK (STD) with organic recycling of biomass and biofertilizer consortia in arecanut + ashwagandha + sarpagandha cropping system exhibited higher *chali* yield and benefit cost ratio. Whereas the highest arecanut equivalent yield, relative yield total and net return was obtained with arecanut + turmeric + black turmeric system integrated with 100 % NPK (STD) and organic recycling. The maximum system productivity, land equivalent ratio was recorded in arecanut + kalmegh + tulsi with organic recycling of biomass and application of 75 % NPK and biofertilizer consortia. The present findings emphasize the economic feasibility of arecanut based cropping system involving medicinal plants under Odisha condition. Future study needs to be undertaken to assess the long-term sustainability and economic viability of arecanut based intercropping systems under different agro-ecological situations.

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Authors' contributions

SM carried out the research work with formal analysis and drafted the manuscript. SCS participated in curating the research work methodology and data and revised the manuscript. SS participated in manuscript writing and data curation. RKN participated in the nutrient-related methodology curation. RB participated in the design of study. SKP participated in manuscript revision and curation of data. ZAM performed the statistical analysis. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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