Enhancing Agro-Economic Viability and Climate Resilience through Multi-Tier Cropping Models of Medicinal Plants under Coconut Plantations in Telangana

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Abstract

Agricultural sustainability under changing climatic conditions requires production systems that enhance resource-use efficiency, farm profitability, and ecological resilience. The present study evaluated the performance of medicinal plant-based multi-tier cropping systems under mature coconut (*Cocos nucifera* L.) plantations in Telangana, India. Thirteen treatments comprising sole coconut, coconut with individual medicinal crops, and three multi-tier medicinal Cropping Systems were assessed in a Randomized Block Design. Growth, yield, biochemical quality attributes, economics, and Coconut Yield Equivalent Yield were evaluated. Among the medicinal intercrops, Tulasi (*Ocimum tenuiflorum*) recorded superior vegetative growth, while Kalmegh (*Andrographis paniculata*) produced the highest herbage yield and Coleus (*Coleus forskohlii*) generated maximum root yield. Coconut productivity remained statistically unaffected by intercropping, indicating complementary resource utilization among component crops. Significant improvements in system productivity and profitability were observed under diversified cropping systems. The multi-tier model comprising Coconut + Cassia (*Cassia angustifolia*) + *Solanum nigrum* + Peppermint (*Mentha piperita*) recorded the highest benefit-cost ratio (2.46) and achieved a Coconut Yield Equivalent Yield of 42,122.5 nuts ha^{-1}, substantially surpassing the other Cropping Systems. Biochemical analyses revealed considerable variation in medicinal quality traits, with Bhumi Amla (*Phyllanthus niruri*), Tulasi, Peppermint, and Kalmegh exhibiting higher phenolic content, flavonoid concentration, and antioxidant activity, while *Tribulus terrestris* and Ashwagandha (*Withania somnifera*) accumulated greater saponin levels. The findings demonstrate that medicinal plant integration effectively exploits underutilized ecological niches within coconut plantations, enhances economic returns, improves land-use efficiency, improves farmers livelihoods and generates phytochemical-rich raw materials without compromising coconut yield. The Coconut + Cassia + *Solanum nigrum* + Peppermint model emerged as the most productive, profitable, and climate-resilient system, offering a viable strategy for sustainable intensification of coconut-based agro ecosystems in tropical regions.

Key Words:

Coconut-based agroforestry, Multi-tier cropping, Medicinal plants, Climate resilience, Sustainable intensification, Phytochemical quality

Agriculture is presently confronted with multiple challenges including climate change, degradation of natural resources, shrinking landholdings, and the need to ensure food, nutritional, and livelihood security for a growing population, with limited scope for horizontal expansion of cultivated land, increasing productivity through efficient utilization of available resources has become imperative. Sustainable intensification through diversified cropping systems has consequently gained considerable attention as a viable strategy for enhancing productivity, profitability, and resilience of agricultural systems. Multi-tier cropping systems utilize the vertical space available in crop canopies and maximize the capture and conversion of solar radiation, thereby improving resource-use efficiency and overall productivity (Martin et al. 2018; Bari and Rahim, 2012; Brooker et al. 2015; Kumari et al.

2024; Tong et.al. 2024; Willmott, et.al. 2024; and Khopade et al. 2025). Such systems promote efficient utilization of sunlight, water, nutrients, and biological resources while reducing production risks associated with climate variability. Agroforestry-based production systems are increasingly recognized as climate smart agricultural interventions that simultaneously enhance productivity, biodiversity conservation, carbon sequestration, and ecosystem services. Recent studies have highlighted that diversified agroecosystems improve resilience against climatic extremes and contribute significantly to sustainable agricultural development (Nuwarapaksha et al. 2022; Dissanayaka et al. 2023; Samarakoon et al. 2023). Multi-tier cropping systems also provide opportunities for income diversification and efficient land utilization, particularly in perennial plantations where a substantial portion of light and space remains underutilized. Coconut (*Cocos nucifera* L.) is one of the most suitable plantation crops for developing multi-tier cropping systems owing to its canopy architecture, wider spacing, and fibrous-rooted nature. The coconut palm allows considerable penetration of sunlight to lower strata, facilitating the cultivation of compatible intercrops. Coconut based multi-storeyed cropping systems have been reported to improve overall system productivity, profitability, nutrient-use efficiency, and soil health compared to monocropping systems (Nuwarapaksha et al. 2022 and Namitha et al. 2025). Studies conducted by the All India Coordinated Research Project (AICRP) on Palms and the Central Plantation Crops Research Institute (CPCRI) have demonstrated that high-density multispecies cropping systems under coconut significantly increase coconut equivalent yield and overall farm returns while enhancing soil biological activity and carbon sequestration (Maheswarappa et al. 2004; Naveen Kumar and Maheswarappa, 2019; Shinde et al. 2020, Nuwarapaksha et al. 2022; Namitha et al. 2025).

Mature coconut palms possess a localized root system, with 80–86% of active roots confined to 30–120 cm soil depth and within 2 m of the palm base, leaving much of the soil profile underutilized. Similarly, coconut canopies intercept only 45–50% of incoming solar radiation, allowing substantial light penetration to the understory. This incomplete utilization of below- and above-ground resources provides opportunities for integrating compatible intercrops to improve resource-use efficiency and system productivity. Light availability in coconut plantations varies with plantation age. Young plantations (<8 years) receive >70–80% light transmission and support sun-loving crops, whereas middle-aged plantations (8–20 years) receive only 20–30% light due to dense canopy cover. In mature plantations (>20 years), increased canopy openness enhances light transmission to about 50–56%, creating favorable conditions for shade-tolerant and multi-tier cropping systems. (Nelliat et al. 1974; Nair, 1983; Rajagopal et al. 1997; Nuwarapaksha et al. 2022; Dissanayaka et al. 2023)

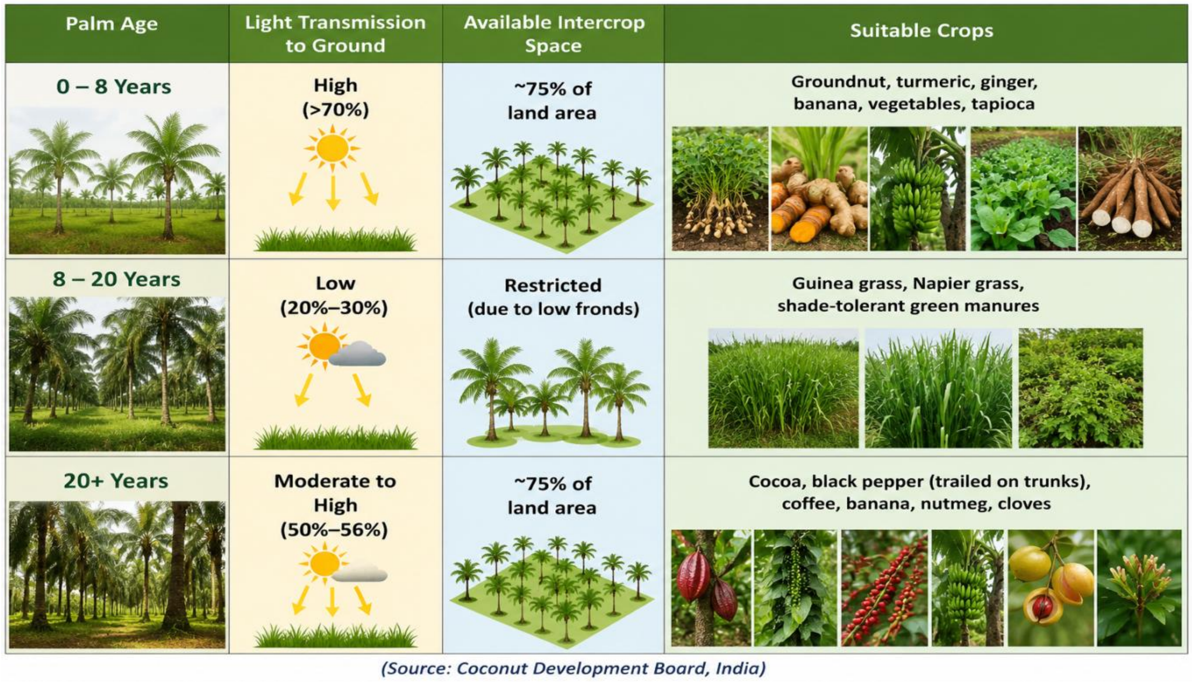

Fig1: Intercropping Potential in Coconut Ecosystems as Influenced by Palm Age and Canopy Structure

Coconut occupies about 5.0–5.1 thousand ha in Telangana, producing 41–42 million nuts annually with productivity exceeding 8,000 nuts ha^{-1} (Indiastat, 2025). Despite its relatively small cultivation area, coconut productivity remains high due to irrigated cultivation and improved management practices. During the past decade, coconut area and production in Telangana increased by 42.86% and 79.17%, respectively, with a CAGR of 6% (Telangana Horticulture Perspective Plan, 2035). Although cocoa and banana are commonly grown as intercrops, further diversification is needed. Integration of medicinal plants offers considerable potential to enhance land-use efficiency and farm income without affecting coconut productivity. Medicinal and aromatic plants constitute one of the fastest-growing sectors of agriculture due to increasing global demand from pharmaceutical, nutraceutical, cosmetic, and wellness industries. According to the World Health Organization, nearly 80 percent of the world's population relies partly on plant-based traditional medicines for primary healthcare (Bodeker 1996; Bodeker 2013; WHO 2019). The increasing preference for natural and herbal products has further accelerated the demand for medicinal plant raw materials. Several medicinal plant species such as *Withania somnifera* (Ashwagandha), *Asparagus racemosus* (Shatavari), *Coleus forskohlii*, *Andrographis paniculata* (Kalmegh), *Aloe vera*, *Kaempferia galanga*, turmeric (*Curcuma longa*), and ginger (*Zingiber officinale*) possess good shade tolerance and adaptability, making them suitable adoptions for cultivation under coconut plantations (Rao et al. 2004; Alam et al. 2014; Kumar et al. 2021; Nuwarapaksha et al. 2022; Dissanayaka et al. 2023; Shanmugam et al. 2024; Namitha et al. 2025).

Recent investigations have shown that intercropping medicinal and spice crops under coconut plantation improve nutrient cycling, soil organic carbon, microbial activity, and overall ecosystem functioning (Namitha et al. 2025). Diversification of coconut plantations through multi-species agroforestry systems enhances carbon storage both above- and below-ground, improves nutrient cycling, buffers climatic variability, and reduces production risks compared with sole coconut cultivation, thereby increasing the ecological and economic resilience of farming systems (Jose 2009; Naveen Kumar and Maheswarappa 2019; Shinde et al. 2020; Nuwarapaksha et al. 2022; Dissanayaka et al. 2023; Ramanan et al. 2024). Furthermore, intercropping with turmeric and ginger has been found to substantially increase coconut equivalent yield, system productivity, net returns, and soil biological activity while reducing fertilizer requirements through improved nutrient-use efficiency (Namitha et al. 2025). Despite the considerable potential of medicinal plant integration in coconut ecosystems, systematic research on medicinal plant-based multi-tier Cropping Systems under the agro-climatic conditions of Telangana is limited. Identification of suitable medicinal plant combinations that can maximize productivity, profitability, and climate resilience while maintaining soil health is essential for promoting sustainable coconut-based farming systems in the state. Therefore, the present study entitled "Enhancing Agro-Economic Viability and Climate Resilience through Multi-Tier Cropping Systems of Medicinal Plants under Coconut Plantations in Telangana" was proposed to develop scientifically validated, economically viable, and environmentally sustainable multi-tier Cropping Systems for coconut-growing regions of Telangana.

Medicinal crops *viz*., Tulasi, Cassia, *Solanum nigrum*, Colues, Aswagandha, Bhumi Amla, Peppermint, *Tribulus terrestris* and *Tinospora* are suitable to grow in different storeys under coconut plantation. These medicinal crops are seasonal in nature, further, they have high medicinal value and these plants provide major raw material for many pharmaceutical, ayurvedic and cosmetic industries. Multi-tier cropping of coconut and medicinal plants will provide the staggered income to the farmers there by the socio economic status will be increased. Further, there was no sign of research in this area to explore the benefits of multi-tier Cropping System of coconut with medicinal plants.

Material and Methods

Location

The experimental site is located at Agricultural College, Aswaraopet, Bhadradri Kothagudem Dist., Telangana, India. The Bhadradri Kothagudem Dist. is one of the important districts of Telangana in terms of Agriculture and Horticulture. Aswaraopet mandal is one among the district with a geographical area of 103.79 sq. km. The average annual rainfall of Bhadradri Kothagudem is 1200 mm while the annual average temperature is 28.4^{o}C, relative humidity of approximately 64%. The soils of the districts are predominated by black and red soils.

Major crops and Cropping patterns

The major crops of the district are paddy, chilly, maize, vegetables, cotton, red gram, green gram and black gram. Further, it is the hub of horticulture, this area is having highest area under cultivation of coconut and oil palm, which are highly suitable for intercropping, mixed cropping and multi-tier Cropping Systems. The treatment details of the experiment are as follows

Treatments

T_1 Coconut as Sole Crop

T_2 Coconut + Tulasi

T_3 Coconut + Cassia

T_4 Coconut + Kalmeg

T_5 Coconut + Coleus

T_6 Coconut + *Solanum nigram*

T_7 Coconut + Aswagandha

T_8 Coconut + *Tribulus terrestris*

T_9 Coconut + Peppermint

T_{10} Coconut + Bhumi Amla

T_{11} Coconut + Tulasi+ Coleus + *Tribulus terrestris* **(Cropping System -1)**

T_{12} Coconut + Cassia + *Solanum nigram*+ Peppermint **(Cropping System -2)**

T_{13} Coconut + Kalmeg + Aswagandha+ Bhumi Amla **(Cropping System -3)**

In the Agricultural College, Aswaraopet, a coconut plantation of **20** years old is existing with a spacing of 9.0 m × 9.0 m. All the above said treatments or the Cropping Systems were planned in inter rows of coconut (4.0 m × 4.0 m). All the medicinal plants as sole and multi-tier crops were transplanted at recommended spacing. All the treatments replicated thrice. All the inter-cultural operations and plant protection measures were taken as and when required.

Observations Recorded

Growth Parameters

Plant Height (cm)

Plant height was measured from the base of the plant to the tip of the apical leaf using a measuring scale. Observations were recorded from tagged plants in each treatment and expressed as mean plant height (cm).

Plant Spread (cm)

Plant spread was determined by measuring the canopy width in the East–West direction between the two extreme ends of the plant. Measurements were recorded from tagged plants and expressed in centimeters.

Leaf Area Index (LAI)

Leaf area was measured using a digital leaf area meter. Representative leaves were sampled from the upper, middle, and lower canopy positions of each tagged plant. The Leaf Area Index (LAI) was calculated as:

LAI = Leaf area per plant (cm^2) / Land area occupied per plant (cm^2)

Herbage Yield (kg plant^{-1})

Fresh herbage yield was recorded at harvest by weighing the economically important aerial plant parts from each treatment and expressed as kilograms per plant.

Root/Tuber Yield (kg plant^{-1})

The fresh weight of harvested roots or tubers was recorded immediately after harvest and expressed as kilograms per plant.

Herbage Dry Weight (g plant^{-1})

Representative fresh herbage samples were oven-dried at 60 ± 2°C until constant weight and expressed as dry matter accumulation (g plant^{-1}).

Coconut Yield

Coconut yield was assessed by recording the number of marketable nuts produced per palm annually and expressed as nuts $palm^{-1}$ $year^{-1}$.

Coconut Yield Equivalent Yield (CYEY)

The productivity of different coconut-based multi-tier cropping systems was evaluated using Coconut Yield Equivalent Yield (CYEY). The yields of medicinal intercrops were converted into coconut yield equivalents based on their prevailing market prices and subsequently added to the actual coconut yield. This approach enabled comparison of different cropping systems on a common economic basis.

The Coconut Yield Equivalent Yield was calculated using the following formula:

$$CYEY = \text{Coconut yield} + (\text{Medicinal crop yield} \times \text{Price of medicinal crop} / \text{Price of coconut})$$

For multi-tier cropping systems comprising more than one medicinal crop, the total gross returns from all component crops were summed and converted into coconut equivalent yield using the market price of coconut:

For multi-tier cropping systems comprising more than one medicinal crop, the formula was:

$$CYEY = \text{Coconut yield} + (\text{Gross returns from all medicinal crops}/\text{Price of coconut})$$

$$CYEY = \text{Coconut yield} + (Y_1P_1+Y_2P_2+Y_3P_3+\cdots+Y_nP_n/P_c)$$

Where:

- CYEY = Coconut Yield Equivalent Yield (nuts ha^{-1})
- Y_1, Y_2, Y_3 ... Y_n = Yield of individual medicinal crops (kg ha^{-1})
- P_1, P_2, P_3 ... P_n = Market price of individual medicinal crops (₹ kg^{-1})
- P_nc = Market price of coconut (₹ nut^{-1})
- Coconut yield = Actual coconut yield (nuts ha^{-1})

The prevailing farm-gate market prices during the experimental period were used for computation. Coconut price was considered at ₹20 per nut. The CYEY was expressed as nuts ha^{-1} and used as an indicator of overall system productivity by integrating the contribution of both coconut and medicinal intercrops into a single economic yield parameter (Willey, R.W., 1979).

Quality Analysis of Medicinal Plants

Fresh samples of medicinal crops from each treatment were collected at harvest and thoroughly washed with distilled water to remove adhering soil particles and impurities. The samples were shade-dried followed by oven drying at 60 ± 2°C until constant weight was achieved. The dried material was finely ground and stored in airtight containers for subsequent biochemical analyses.

Moisture Content and Dry Matter

Moisture content was determined by drying fresh samples at 105°C to constant weight following AOAC (2019) procedures. Dry matter percentage was calculated from the ratio of oven-dried weight to fresh weight.

Total Ash Content

Total ash content was estimated by incinerating dried samples in a muffle furnace at 550°C for 5–6 h until a constant white ash was obtained and expressed as percentage dry weight.

Crude Fiber Content

Crude fiber was determined using sequential acid and alkali digestion according to standard AOAC (2019) methods and expressed as percentage dry weight.

Total Phenolic Content (TPC)

Total phenolic content was quantified using the Folin–Ciocalteu colorimetric method (Singleton and Rossi, 1965). Methanolic extracts were reacted with Folin–Ciocalteu reagent and sodium carbonate solution, and absorbance was measured at 765 nm using a UV–Visible spectrophotometer. Results were expressed as milligrams of gallic acid equivalents (mg GAE g^{-1} DW). TPC = mg Gallic Acid Equivalent (GAE) per gram dry weigh

Total Flavonoid Content (TFC)

Total flavonoid content was estimated by the aluminium chloride colorimetric assay (Chang et al. 2002). Absorbance was recorded at 415 nm and results were expressed as milligrams of quercetin equivalents (mg QE g^{-1} DW). TFC = mg Quercetin Equivalent (QE) per gram dry weight

Antioxidant Activity

Antioxidant potential was evaluated through the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay following Brand-Williams et al. (1995). Absorbance was measured at 517 nm and antioxidant activity was expressed as percentage inhibition of DPPH radicals.

Total Alkaloid Content

Total alkaloids were determined using the gravimetric procedure of Harborne (1973). Powdered samples were extracted with 10% acetic acid in ethanol, concentrated, precipitated with ammonium hydroxide, filtered, dried, and weighed. Results were expressed as percentage dry weight.

Total Saponin Content

Total saponin content was estimated according to Obadoni and Ochuko (2001). Samples were extracted with aqueous ethanol, purified using n-butanol, and quantified gravimetrically. Results were expressed as percentage dry weight.

The biochemical quality assessment included total phenolic content, total flavonoid content, antioxidant activity, total alkaloids, and total saponins, which collectively served as indicators of medicinal quality and phytochemical richness of the selected species.

Harvesting and Yield Assessment

Medicinal crops were harvested at physiological maturity according to species-specific recommendations. Fresh and dry biomass yields were recorded separately. Herbage yield, root/tuber yield, and dry matter production were estimated based on the economically important plant part and extrapolated to unit area wherever required.

Economic Analysis

The economics of different coconut-based multi-tier cropping systems were evaluated by calculating the total cost of cultivation, gross returns, net returns, and benefit–cost (B) ratio.

The cost of cultivation included expenditures incurred on planting materials, fertilizers, plant protection chemicals, organic inputs, irrigation, intercultural operations, harvesting, and labour charges. Gross returns were computed based on prevailing market prices of coconut and medicinal crop produce. Net returns were obtained by deducting the total cost of cultivation from gross returns.

The Benefit–Cost Ratio (B ratio) was calculated as:

B Ratio = Gross Returns (₹ ha^{-1}) / Total Cost of Cultivation (₹ ha^{-1})

Statistical Analysis

The experimental data generated for growth, yield, quality, and economic parameters were subjected to Analysis of Variance (ANOVA) appropriate for a Randomized Block Design (RBD) following the procedures described by Panse and Sukhatme (1967). The significance of treatment effects was tested using the F-test at the 5% probability level. Standard Error of Mean [SE(m) ±] was calculated for all parameters. Whenever treatment effects were found significant, Critical Difference (CD) values at P = 0.05 were computed to compare treatment means. The coefficient of variation (CV%) was also estimated to assess experimental precision and variability among treatments.

To visualize treatment responses and multivariate relationships among growth, yield, quality, and economic parameters, graphical analyses were performed using R software (version 4.6.0). Heat maps were generated to illustrate the relative performance of medicinal crop treatments across measured traits. Principal Component Analysis (PCA) was employed to identify the major variables contributing to treatment variability and to assess associations among growth, yield, and quality parameters. Radial (radar) plots were constructed to compare the overall performance of different medicinal crop-based intercropping systems across multiple attributes. Prior to PCA, data were standardized to zero mean and unit variance to eliminate scale effects.

Results

In the present context, medicinal plants are in great demand since many pharmaceuticals industries needs medicinal plant products as raw materials. They can be grown successfully in varied agro-climatic conditions and are suitable for wide range of soils. Some crops are best suited to the mixed and relay cropping. Medicinal crops don't require high management of pest and diseases. The data regarding vegetative growth, *viz*., plant height, plant spread, leaf area index, yield parameters *viz*., herbage and root fresh and dry yield of medicinal plants and yield of coconut as sole and intercropped with medicinal plants were subjected to mean data and their analysis of variance have been furnished with the levels of significance.

Growth and Yield Performance of Medicinal Intercrops under Coconut-Based Cropping System

The growth and yield attributes of medicinal intercrops grown under coconut plantation exhibited significant variation among the treatments (Table 1). Among the medicinal crops evaluated, Tulasi (T2) recorded the highest plant height (195.00 cm), plant spread (155.00 cm), and leaf area index (4.31), indicating its superior vegetative growth under coconut-based conditions. However, the differences in plant height and plant spread among Tulasi, Cassia, and Kalmeg were statistically comparable. Cassia (T3) produced the second-highest plant height (151.00 cm) and plant spread (129.00 cm), along with a leaf area index of 3.92.

The highest herbage yield was recorded in Kalmeg (T4) (31.58 t ha^{-1}), followed by Cassia (T3) (28.56 t ha^{-1}) and *Solanum nigrum* (T6) (21.54 t ha^{-1}). Tulasi (T2) also produced a substantial herbage yield of 18.85 t ha^{-1}.

In contrast, Peppermint (T9) and *Tribulus terrestris* (T8) recorded the lowest herbage yields of 1.01 and 2.45 t ha^{-1}, respectively.

Among the root-yielding medicinal crops, Coleus (T5) produced a tuber yield of 26.54 kg $plant^{-1}$, indicating its suitability as a root crop under coconut plantations. Root yield was not recorded for the remaining medicinal species owing to their harvested economic produce being herbage.

The highest dry matter accumulation was observed in Cassia (T3), which recorded a dry weight of 7.33 q ha^{-1}, followed by Tulasi (T2) (6.54 q ha^{-1}) and Kalmeg (T4) (6.27 q ha^{-1}). The lowest dry matter production was registered in Bhumi Amla (T10) (3.33 q ha^{-1}), followed by Peppermint (T9) (3.57 q ha^{-1}) and Aswagandha (T7) (3.87 q ha^{-1}).

Overall, Tulasi and Cassia exhibited superior vegetative growth characteristics, whereas Kalmeg produced the maximum herbage yield. Coleus emerged as the most productive root crop under the coconut-based intercropping system, demonstrating its potential for enhancing productivity and land-use efficiency in coconut plantations.

Treatments	**Plant height (cm)**	**Plant spread (E-W) (cm)**	**Leaf area index**	**Herbage yield (t/ha)**	**Root / tuber yield (kg)**	**Herbage or root dry weight (q/ha)**
T_1	Standing coconut plantation	Standing coconut plantation of	Standing coconut plantation	Standing coconut plantation	Standing coconut plantation	Standing coconut plantation
T_2	195.00	155.00	4.31	18.85	-	6.54
T_3	151.00	129.00	3.92	28.56	-	7.33
T_4	101.67	118.33	2.58	31.58	-	6.27
T_5	113.33	86.67	3.67	-	26.54	5.98
T_6	97.67	65.67	3.40	21.54	-	4.38
T_7	85.67	74.67	4.21	4.98	-	3.87
T_8	69.67	54.67	2.98	2.45	-	4.23
T_9	45.67	39.67	2.64	1.01	-	3.57
T_{10}	42.67	36.67	2.81	12.54	-	3.33
CD	13.65	12.67	13.89	14.85	-	12.89
SE.m	4.55	3.97	4.61	4.57	-	4.33

Table1: Different vegetative and yield parameter of medicinal plants as intercrops under coconut plantation

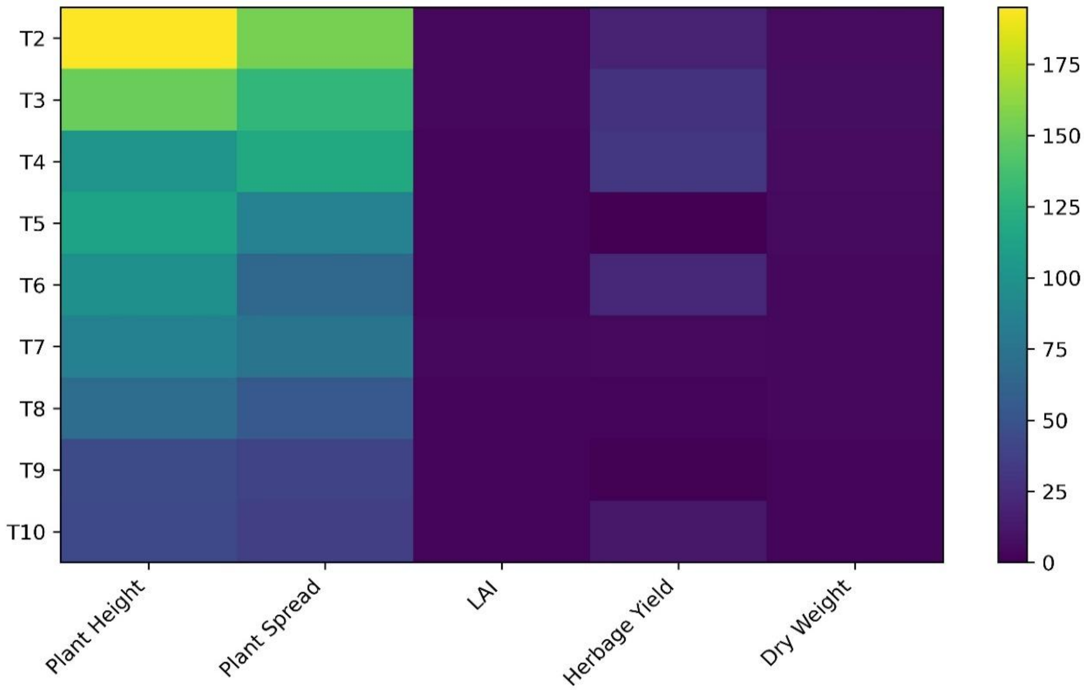

Figure 2: Heatmap Visualization of Growth and Yield Traits of Medicinal Intercrops under Coconut Plantation

Dry Matter Content of Medicinal Plants

Dry matter content varied significantly among medicinal plants under the coconut-based multi-tier system, ranging from 18% in *Solanum nigrum* to 32% in Cassia and Ashwagandha (Table 2). Kalmegh (28%), *Tribulus terrestris* (26%), and Coleus (25%) also exhibited relatively high dry matter accumulation, while Bhumi Amla (24%) and Tulasi (23%) showed intermediate values. The higher dry matter content in Cassia and Ashwagandha indicates superior biomass accumulation and suitability for dried medicinal produce, whereas lower values in *Solanum nigrum* and Peppermint (19%) may be attributed to greater moisture retention. These results demonstrate considerable interspecific variation in biomass accumulation and adaptation under coconut-based multi-tier cropping systems.

Plant	Dry Matter (%)
Tulasi	23
Cassia	32
Kalmegh	28
Coleus	25
Solanum nigrum	18
Ashwagandha	32
Tribulus terrestris	26
Peppermint	19
Bhumi Amla	24

Table: 2. Dry matter (%) of various medicinal plant species under coconut plantation

Proximate Composition and Biochemical Characteristics of Medicinal Plants

Substantial interspecific variation was observed in the proximate composition and biochemical constituents of the medicinal plants cultivated under the coconut-based multi-tier cropping system (Fig. 3), reflecting differences in physiological characteristics, biomass composition, and secondary metabolite accumulation.

Moisture Content

Moisture content ranged from 69.5% in Cassia (*Senna alexandrina*) to 85.3% in *Solanum nigrum*, indicating marked variation in tissue water retention among the species. Relatively high moisture contents were also recorded in Bhumi Amla (81.3%)**,** Kalmegh (81.2%)**,** *Tribulus terrestris* (79.6%)**,** Coleus (79.3%), and Peppermint (79.3%), whereas Ashwagandha (72.3%) and Tulasi (78.9%) exhibited comparatively lower values. The lower moisture content of Cassia suggests a greater proportion of structural dry matter and enhanced storage stability of the harvested material.

Ash Content

Ash content, an indicator of total mineral accumulation, varied from 6.3% in Coleus and Ashwagandha to 12.3% in *Solanum nigrum*. Bhumi Amla recorded the second-highest ash content (10.1%), followed by Kalmegh and *Tribulus terrestris* (9.3% each) and Cassia (9.1%). The elevated ash content observed in *Solanum nigrum* indicates a greater capacity for mineral uptake and accumulation under the coconut-based production environment.

Crude Fiber Content

Considerable differences were observed in crude fiber concentration among the medicinal species. The highest crude fiber content was recorded in *Tribulus terrestris* (19.9%), followed by Ashwagandha (17.6%) and *Solanum nigrum* (16.6%). In contrast, Coleus exhibited the lowest crude fiber content (9.3%), while Tulasi, Kalmegh, Cassia, Peppermint, and Bhumi Amla recorded intermediate values ranging from 11.3 to 13.6%. The higher fiber content in *Tribulus terrestris* and Ashwagandha indicates greater deposition of structural carbohydrates within plant tissues.

Total Phenolic Content

Marked variation was observed in total phenolic concentration among the medicinal plants. Bhumi Amla (*Phyllanthus niruri*) recorded the highest total phenolic content (95.3 mg GAE g^{-1} DW), followed by Kalmegh (79.6 mg GAE g^{-1} DW), Peppermint (63.5 mg GAE g^{-1} DW), and Tulasi (61.6 mg GAE g^{-1} DW). The lowest phenolic content was recorded in Cassia (31.8 mg GAE g^{-1} DW), closely followed by Coleus (34.6 mg GAE g^{-1} DW). The substantially higher phenolic accumulation in Bhumi Amla and Kalmegh suggests enhanced biosynthesis of antioxidant secondary metabolites.

Total Flavonoid Content

Flavonoid concentration varied widely across species, with Bhumi Amla recording the highest value (71.6 mg QE g^{-1} DW), followed by Peppermint (58.3 mg QE g^{-1} DW) and Tulasi (45.5 mg QE g^{-1} DW). Moderate flavonoid levels were observed in Kalmegh (39.3 mg QE g^{-1} DW) and *Tribulus terrestris* (33.6 mg QE g^{-1} DW), whereas *Solanum nigrum* exhibited the lowest flavonoid concentration (20.5 mg QE g^{-1} DW). The elevated flavonoid content in Bhumi Amla and Peppermint highlights their potential as rich sources of bioactive phytochemicals with antioxidant properties.

Antioxidant Activity (DPPH Radical Scavenging Activity)

DPPH radical scavenging activity differed substantially among the medicinal plants. The highest antioxidant activity was observed in Tulasi and Bhumi Amla (80.3%), followed by *Solanum nigrum* (75.3%), Coleus (71.3%), and Peppermint (71.2%). The lowest antioxidant activity was recorded in Ashwagandha (49.3%), whereas Cassia, Kalmegh, and *Tribulus terrestris* exhibited intermediate values ranging from 68.3 to 69.3%. The strong antioxidant activity exhibited by Tulasi and Bhumi Amla corresponds with their elevated concentrations of phenolic and flavonoid compounds.

Total Alkaloid Content

Among the medicinal species, the highest alkaloid content was recorded in Kalmegh and *Solanum nigrum* (2.4%), followed by Bhumi Amla (1.3%) and Ashwagandha (1.2%). Lower alkaloid concentrations were observed in Coleus and *Tribulus terrestris* (0.9% each), Cassia (0.8%), Tulasi (0.7%), and Peppermint (0.6%). The relatively higher alkaloid concentration in Kalmegh and *Solanum nigrum* reflects their medicinal significance and pharmacological potential.

Total Saponin Content

Saponin concentration exhibited substantial variation among the medicinal plants. *Tribulus terrestris* recorded the highest saponin content (7.59%), followed by Ashwagandha (4.67%)**,** *Solanum nigrum* (3.67%), and Cassia (3.54%). In contrast, Peppermint exhibited the lowest saponin concentration (1.89%). The exceptionally high saponin content observed in *Tribulus terrestris* confirms its importance as a valuable medicinal species rich in steroidal saponins.

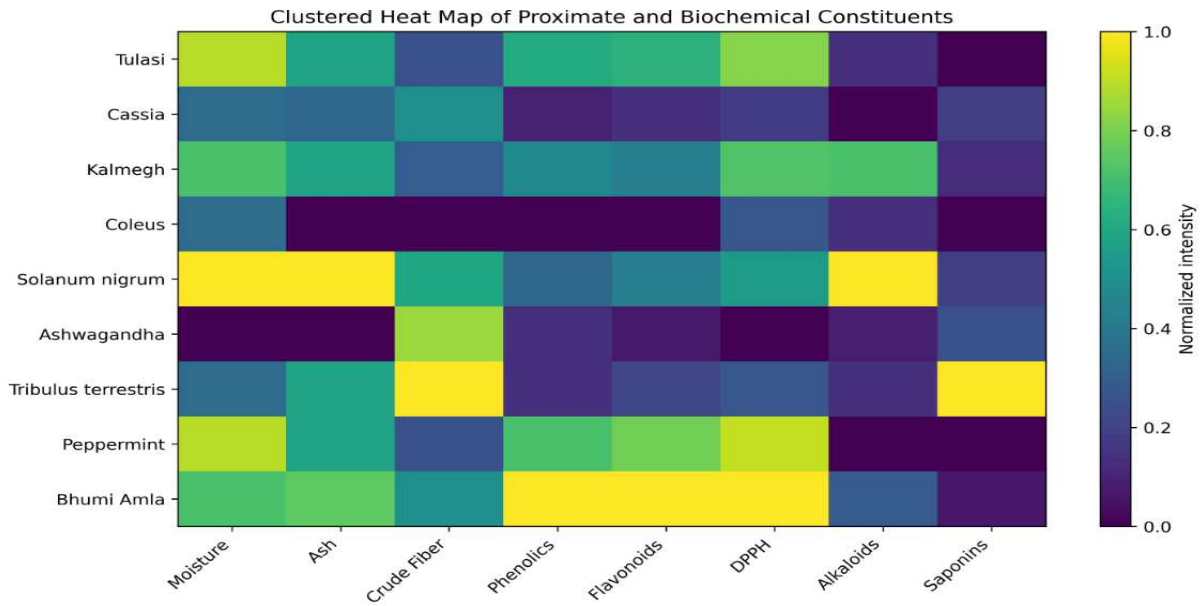

Figure.3 Clustered Heat Map of Proximate and Biochemical Constituents in Selected Medicinal Plants

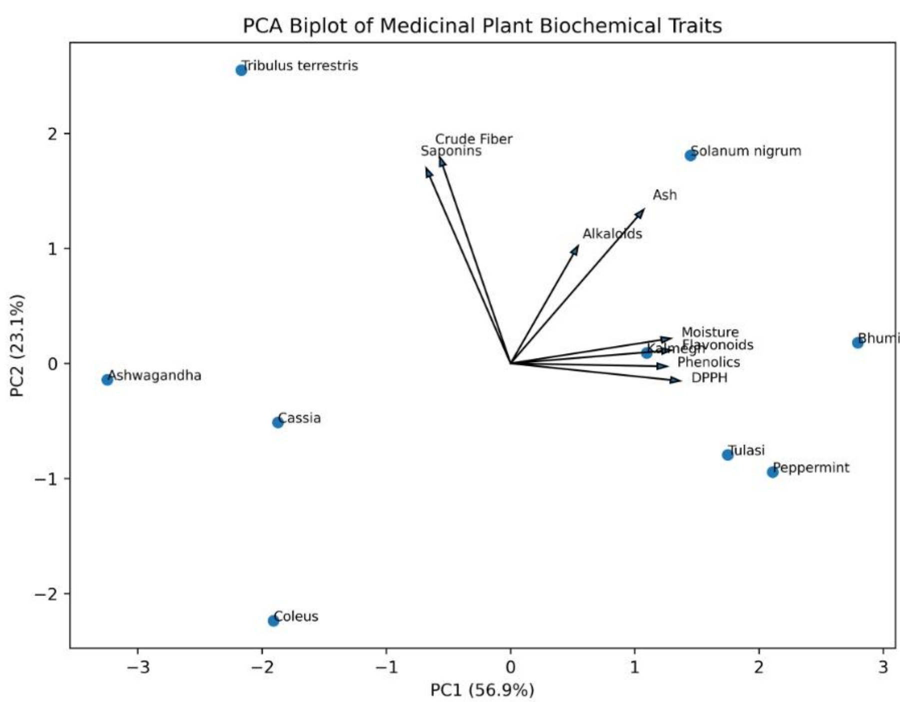

Figure.4: Principal Component Analysis (PCA) Biplot of Proximate and Biochemical Constituents in Selected Medicinal Plants

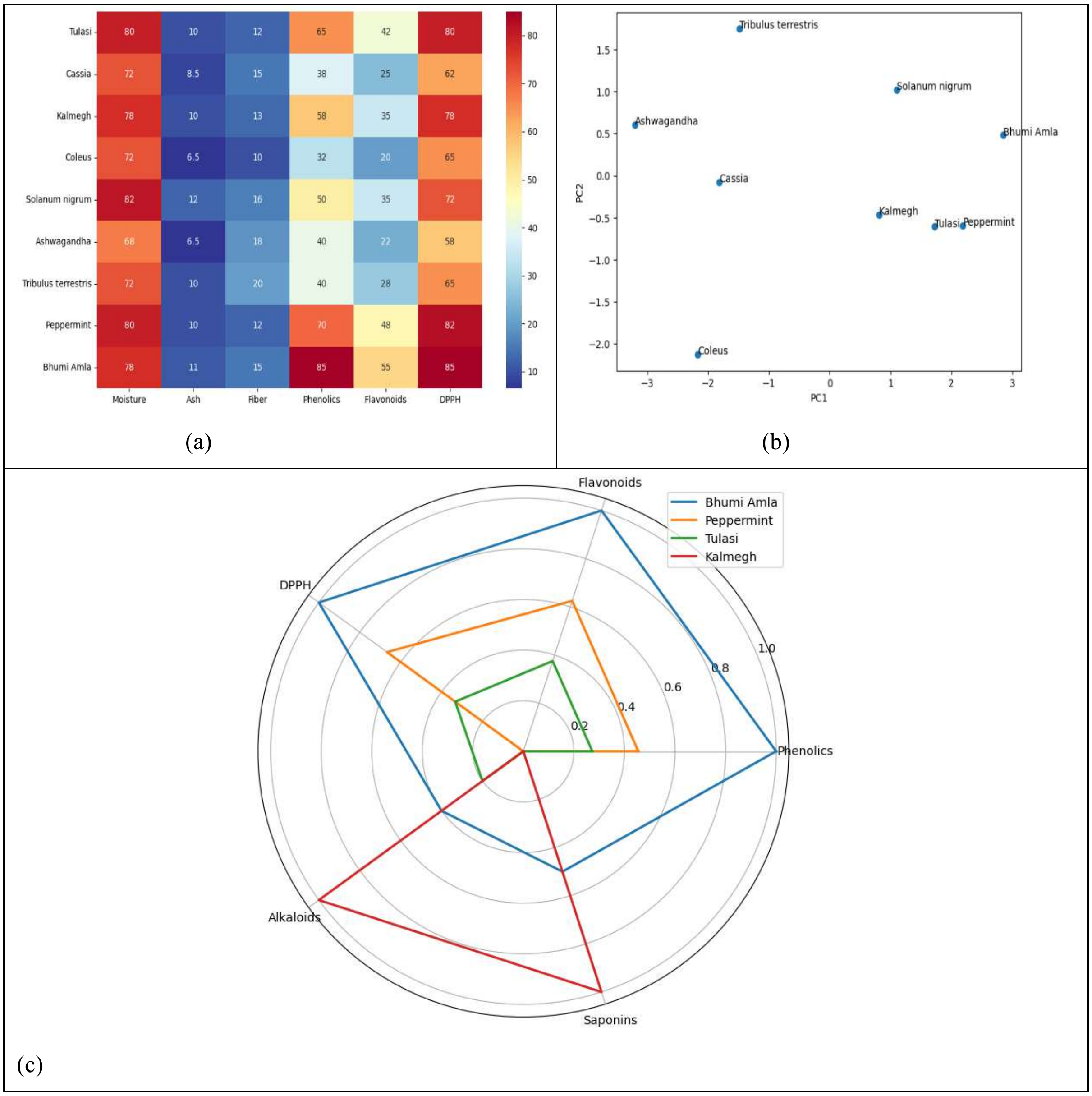

Figure.5: Multivariate Visualization of Bioactive Compounds and Antioxidant Properties in Medicinal Plants

Fig 5.a revealed a strong positive association among total phenolics, flavonoids, and DPPH radical scavenging activity (r = 0.93–0.99), indicating that phenolic and flavonoid compounds are major contributors to antioxidant potential. In contrast, crude fiber exhibited weak to moderate negative correlations with most biochemical traits (r = −0.19 to −0.44), suggesting distinct accumulation patterns between structural and bioactive constituents.

Fig 5.b demonstrated substantial biochemical diversity among the medicinal plants, with PC1 effectively discriminating species based on antioxidant-related compounds. The close proximity of Bhumi Amla, Peppermint, and Tulasi suggests similar phytochemical profiles, whereas the separation of Coleus and *Tribulus terrestris* indicates distinct compositional characteristics contributing to overall variability.

Fig 5.c established that Bhumi Amla possessed the most balanced and superior biochemical profile, exhibiting the highest levels of phenolics, flavonoids, and antioxidant activity (DPPH), indicating strong bioactive potential. In contrast, Kalmegh was characterized by elevated alkaloid and saponin contents, while Peppermint and Tulasi showed intermediate biochemical performance with notable antioxidant properties.

Coconut Yield Equivalent Yield (CYEY)

The productivity advantage of multi-tier medicinal cropping systems was further reflected in coconut equivalent yield (CYEY) values (Fig. 6). Among the three medicinal cropping models evaluated, Cropping Model-2 (T12: Coconut + Cassia + *Solanum nigrum* + Peppermint) proved superior by recording the highest coconut yield of 145 nuts palm^{-1} year^{-1} and 17,835 nuts ha^{-1} year^{-1}. This model also generated the highest gross returns from medicinal crops (₹4,85,750 ha^{-1}), resulting in a coconut equivalent yield of 24,287.50 nuts ha^{-1}. Consequently, the highest total CYEY of 42,122.50 nuts ha^{-1} was obtained under this cropping model.

In contrast, Cropping Model-3 (T13: Coconut + Kalmegh + Ashwagandha + Bhumi Amla) recorded a coconut yield of 141 nuts palm^{-1} year^{-1} and 17,343 nuts ha^{-1} year^{-1}. The medicinal crops generated gross returns of ₹80,040 ha^{-1}, contributing an additional 4,002.00 nuts ha^{-1} as coconut equivalent yield and resulting in a total CYEY of 21,345.00 nuts ha^{-1}.

Cropping Model-1 (T11: Coconut + Tulasi + Coleus + *Tribulus terrestris*) produced 136 nuts palm^{-1} year^{-1} and 16,728 nuts ha^{-1} year^{-1}. The medicinal component generated gross returns of ₹42,785 ha^{-1}, corresponding to a coconut equivalent yield of 2,139.25 nuts ha^{-1} and a total CYEY of 18,867.25 nuts ha^{-1}, which was the lowest among the three cropping models.

Overall, the results clearly indicate that the integration of medicinal plants in multi-tier cropping systems substantially enhanced overall productivity and profitability without significantly compromising coconut yield. Among the evaluated systems, Cropping Model-2 (Coconut + Cassia + *Solanum nigrum* + Peppermint) emerged as the most productive and economically viable model, recording the highest gross returns, coconut equivalent yield, CYEY, and benefit-cost ratio. The superior performance of this model demonstrates the potential of medicinal plant diversification for enhancing agro-economic viability and resource-use efficiency in coconut-based production systems under Telangana conditions.

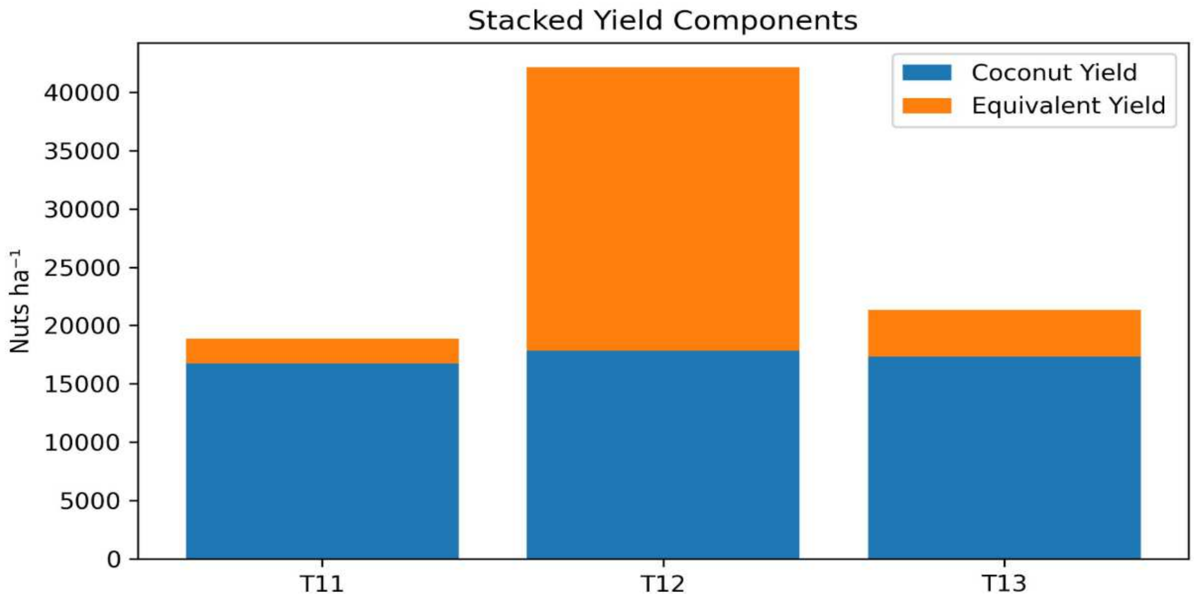

Figure 6. Coconut Yield and Coconut Equivalent Yield Derived from Medicinal Intercrops under Coconut-based Multi-tier Cropping Systems

Yield of Coconut and Economic Performance of Medicinal Crop-Based Multi-Tier Cropping Models

The yield of coconut and economic returns varied significantly among the sole crop, individual medicinal intercrops, and multi-tier medicinal cropping models (Table 3). Coconut yield under the experimental treatments ranged from 134 to 154 nuts palm^{-1} year^{-1}, indicating that the introduction of medicinal intercrops did not adversely affect coconut productivity.

Among all treatments, the sole coconut plantation (T1) recorded the highest coconut yield of 154 nuts palm^{-1} year^{-1}, followed by Coconut + Coleus (T5) with 149 nuts palm^{-1} year^{-1}**,** Coconut + Tulasi (T2) with 148 nuts palm^{-1} year^{-1}, and Coconut + Kalmegh (T4) with 147 nuts palm^{-1} year^{-1}. The lowest coconut yield was observed in Coconut + Bhumi Amla (T10), which produced 134 nuts palm^{-1} year^{-1}, followed by Coconut + Ashwagandha (T7) with 135 nuts palm^{-1} year^{-1}. However, the variation in coconut yield among treatments remained within the critical difference (CD = 11.24), indicating that medicinal crop integration did not cause any substantial reduction in coconut productivity.

Benefit-Cost Ratio

Economic analysis revealed a considerable improvement in profitability through medicinal crop integration. The highest benefit-cost ratio (2.46) was recorded in Cropping Model-2 (T12: Coconut + Cassia + *Solanum nigrum* + Peppermint), followed by Cropping Model-3 (T13) with a B ratio of 2.35. Among the individual medicinal crops, Coconut + *Solanum nigrum* (T6) recorded the highest B ratio (2.07), followed by Coconut + Ashwagandha (T7) (2.02), Cropping Model-1 (T11) (2.01), Coconut + Coleus (T5) (1.99), and Coconut + Cassia

(T3) and Coconut + Peppermint (T9) (both 1.98). The lowest B ratio was observed in Coconut + Bhumi Amla (T10) **(**1.65**)**, whereas sole coconut cultivation recorded a B ratio of 1.80. These findings clearly demonstrate that medicinal crop integration significantly enhanced economic returns compared to monocropped coconut plantations.

Treatments	**Yield of coconut/year/Palm**	**BC Ratio**
T_1	154	1.8
T_2	148	1.92
T_3	142	1.98
T_4	147	1.86
T_5	149	1.99
T_6	138	2.07
T_7	135	2.02
T_8	139	1.85
T_9	137	1.98
T_{10}	134	1.65
T_{11}	136	2.01
T_{12}	145	2.46
T_{13}	141	2.35
CD	11.24	-
SE.m	3.45	-

Table: 3 Yield of coconut as sloe crop and intercropped with medicinal crops and BC ratio of coconut as sole crop and medicinal plants as intercrops

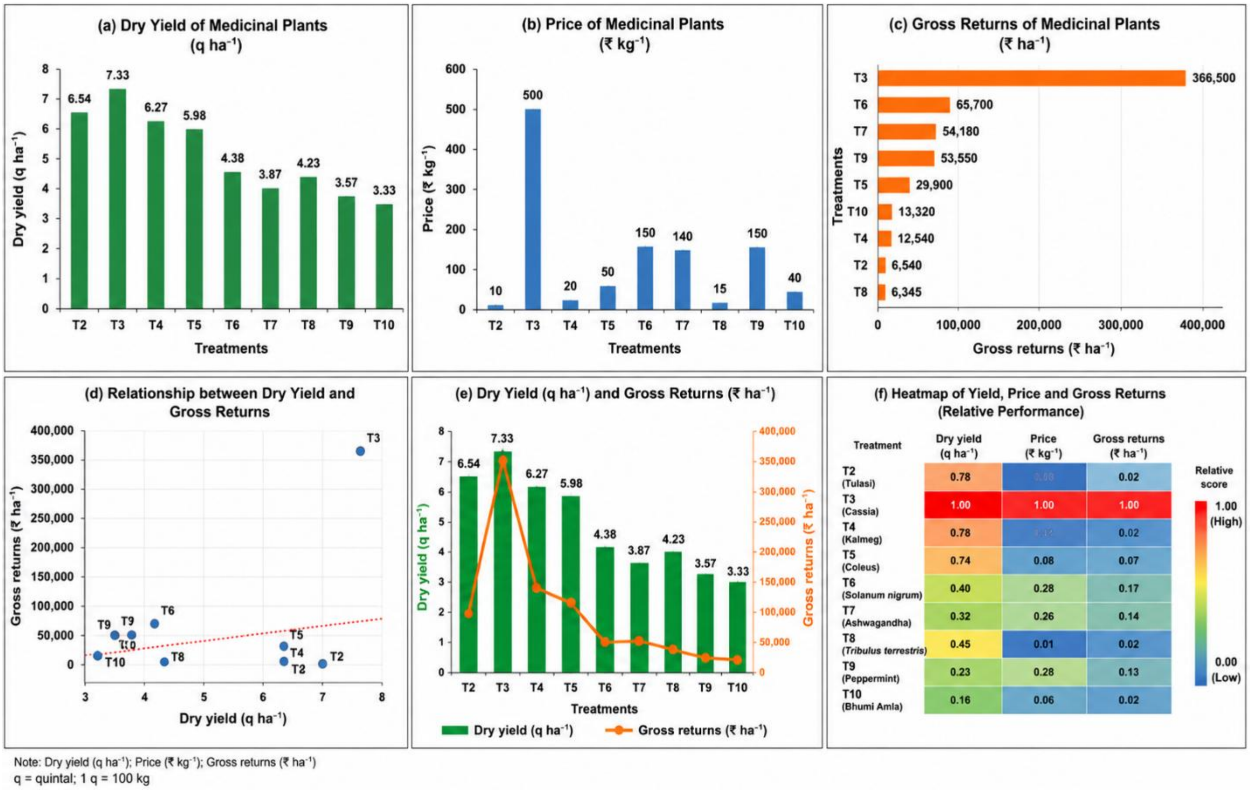

Figure 7. Economic Performance of Medicinal Intercrops under Coconut Plantation Based on Dry Yield, Market Price, and Gross Returns.

Fig.7.a represents the medicinal intercrops varied significantly under coconut plantation conditions. Cassia (T3) recorded the highest dry yield (7.33 q ha^{-1}), followed by Tulasi (T2) and Kalmeg (T4), indicating their superior biomass production potential in the coconut-based agroforestry system.

Fig.7.b characterizes medicinal intercrops showed substantial variation among treatments. Cassia (T3) commanded the highest market price (₹500 kg^{-1}), followed by *Solanum nigrum* (T6) and Peppermint (T9) (₹150 kg^{-1}), indicating their greater commercial value and profitability potential under coconut-based agroforestry systems.

Fig.7.c exemplifies Gross returns varied markedly among the medicinal intercrops, with Cassia (T3) recording the highest return (₹366,500 ha^{-1}) due to its combination of high dry yield and premium market price. In contrast, Tulasi (T2), *Tribulus terrestris* (T8), and Kalmeg (T4) generated comparatively lower returns, highlighting the significant influence of market value on overall profitability.

Fig.7.d revealed that dry yield alone was not a reliable indicator of economic returns. Cassia (T3) generated exceptionally high gross returns despite having a dry yield comparable to other treatments, highlighting the dominant role of market price in determining profitability.

Fig.7.e showed noticeable differences between biological yield and economic performance among medicinal intercrops. While several treatments produced moderate to high dry yields, Cassia (T3) achieved substantially greater gross returns, emphasizing the importance of integrating yield and market value for crop selection.

Fig.7.f provided a clear visual comparison of the economic traits across treatments. Cassia (T3) exhibited the highest intensity values for market price and gross returns, identifying it as the most economically viable medicinal

intercrop, whereas Tulasi (T2), Kalmeg (T4), and *Tribulus terrestris* (T8) showed comparatively lower profitability despite reasonable yields.

Discussion

Growth and Yield Performance of Medicinal Intercrops under Coconut-Based Cropping System

The present investigation demonstrated significant differences in growth, biomass accumulation, and yield among medicinal plant species cultivated under coconut plantations, indicating species-specific adaptation to the modified microenvironment of coconut-based multi-tier systems. Coconut plantations create a unique ecological niche characterized by moderated temperature, reduced evapotranspiration, improved soil moisture conservation, and partial shade, which collectively influence intercrop performance. Coconut-based intercropping systems are known to improve resource-use efficiency by utilizing otherwise underexploited vertical and horizontal spaces beneath the palm canopy (Basavaraju et al. 2018; Nuwarapaksha et al. 2022; Selva Rani et al. 2024; Sundaram et al. 2024). Among the medicinal crops evaluated, Tulasi recorded the highest plant height, plant spread, and leaf area index, reflecting its vigorous vegetative growth under coconut shade conditions. The enhanced canopy development may be attributed to its ability to efficiently utilize diffused light and available soil moisture under the coconut ecosystem. Similar observations have been reported in agroforestry-based medicinal plant production systems, where moderate shade promoted vegetative growth and leaf area expansion through improved microclimatic conditions (Gupta et al. 2020). The higher leaf area index observed in Tulasi suggests greater photosynthetic surface area, which contributes to increased biomass production and improved adaptation to shaded environments.

Cassia exhibited superior biomass accumulation and produced the highest dry matter yield. Greater dry matter production indicates efficient conversion of intercepted radiation into plant biomass. The improved growth of Cassia may also be associated with enhanced nutrient cycling and soil biological activity commonly observed in diversified coconut-based systems. Intercropping under coconut has been shown to improve soil microbial diversity, nutrient availability, and soil organic carbon status, thereby enhancing crop productivity and sustainability (Tong et al. 2024). Enhanced biomass accumulation under perennial tree-based systems has also been linked to improved soil fertility and favorable rhizosphere interactions (Jose, 2009).

Kalmeg recorded the highest herbage yield among all medicinal crops it suggests that the crop is highly compatible with the partial shade and moderated environmental conditions prevailing under coconut plantations. Medicinal plants grown under agroforestry systems frequently benefit from reduced heat stress and improved water-use efficiency leading to greater biomass production. Similar responses have been reported for several medicinal and aromatic plants cultivated under tree-based production systems, where moderated light intensity improved overall growth and yield performance (Kumar et al. 2021; Gupta et al. 2020). The high herbage productivity of Kalmeg highlights its potential as a profitable component in coconut-based medicinal plant diversification models.

Coleus produced the highest tuber yield among the root-producing medicinal crops. Root and tuber crops generally benefit from improved soil structure, moisture retention, and moderated soil temperature under perennial plantation systems. Coconut-based intercropping has been reported to enhance belowground productivity through improved soil physical conditions and greater organic matter accumulation (Malek et al. 2020; Bhalerao et al. 2021). The substantial tuber yield observed in Coleus indicates that the species effectively exploits belowground resources while remaining compatible with coconut root architecture.

The comparatively lower growth and herbage yields recorded in *Tribulus*, Peppermint, and Bhumi Amla may be attributed to their relatively higher light requirements and reduced competitive ability under shaded conditions. Crop response in agroforestry systems largely depends on the extent of shade tolerance and resource sharing mechanisms among component species. Species that are less adapted to reduced light environments generally exhibit lower biomass accumulation and productivity due to limitations in photosynthetic efficiency (Nair et al. 2021).

From a system perspective, the integration of medicinal plants within coconut plantations represents an effective strategy for sustainable intensification. Coconut monocropping utilizes only a fraction of the available land area, canopy space, and incident solar radiation. Multi-tier cropping systems improve land-use efficiency by exploiting vertical stratification and complementary resource utilization among component crops (Nuwarapaksha et al. 2022; Selva Rani et al. 2024). Such systems not only increase biological productivity but also enhance overall farm profitability through diversification of outputs. The findings further support the role of coconut-based medicinal plant systems in enhancing climate resilience. Diversified agroforestry systems contribute to improved soil health, greater carbon sequestration, enhanced biodiversity, and increased resilience against climatic variability compared with monocropping systems. Recent studies have highlighted that intercropping and agroforestry under coconut significantly improve soil carbon storage and ecosystem sustainability while reducing vulnerability to climate-induced production risks (Namitha et al. 2025; Khopade et al. 2025). Coconut-based diversified systems therefore provide an effective pathway for simultaneously improving productivity, profitability, and environmental sustainability.

Dry matter content

Dry matter content, an important indicator of biomass accumulation and medicinal yield quality, varied considerably among the medicinal crops grown under coconut-based multi-tier systems. Cassia and Ashwagandha recorded the highest dry matter content (32%), indicating superior biomass accumulation and efficient partitioning of photosynthates under the partially shaded conditions of coconut plantations. Such enhanced dry matter production may be attributed to improved microclimatic conditions, including moderated temperature, better soil moisture, and enhanced nutrient availability commonly observed in agroforestry systems (Singh et al. 2021; Jose et al. 2024). Kalmegh (28%) and *Tribulus terrestris* (26%) also exhibited relatively high dry matter accumulation, reflecting their adaptability to shaded environments and efficient resource utilization. Similar improvements in biomass production under agroforestry conditions have been reported by Gupta et al. (2020).

Coleus recorded 25% dry matter content, likely due to greater assimilate allocation to storage organs, particularly tubers, supported by favorable soil moisture and physical conditions under coconut-based systems (Namitha et al. 2025). Intermediate values observed in Tulasi (23%) and Bhumi Amla (24%) may be attributed to balanced biomass production and moisture retention, consistent with species-specific growth and biochemical characteristics reported in medicinal herbs (Dissanayaka et al. 2023).

The lowest dry matter content was recorded in *Solanum nigrum* (18%) and Peppermint (19%), which may be associated with their succulent tissues, higher moisture content, and greater allocation of assimilates towards metabolic activities rather than structural biomass. In Peppermint, maintenance of higher tissue moisture is often linked to physiological processes involved in essential oil biosynthesis (Selva Rani et al. 2024). Higher dry matter accumulation is advantageous for medicinal crops owing to reduced post-harvest drying requirements, improved storage stability, and greater recovery of marketable biomass. Moreover, enhanced biomass production contributes to carbon sequestration, nutrient cycling, and overall system resilience (Nair et al. 2021; Namitha et al. 2025). The superior dry matter accumulation observed in Cassia, Ashwagandha, Kalmegh, and *Tribulus terrestris* highlights their suitability for coconut-based multi-tier cropping systems aimed at improving profitability and sustainability.

Proximate Composition and Biochemical Characteristics of Medicinal Plants

The medicinal plant species evaluated under the coconut-based multi-tier cropping system exhibited substantial variation in proximate composition, antioxidant properties, and phytochemical constituents, indicating differential physiological adaptation and metabolic responses under the modified microclimatic conditions created by coconut plantations. Agroforestry environments are known to influence the biosynthesis of secondary metabolites through alterations in light intensity, temperature, humidity, and nutrient availability, thereby affecting both the nutritional and medicinal quality of intercrops (Pandey et al. 2020; Patil et al. 2024; Intharuksa et al. 2024).

The lower moisture content observed in Cassia (69.5%) compared to other medicinal plants suggests greater dry matter accumulation and biomass stability. Plants with lower tissue moisture generally possess improved post-harvest keeping quality and higher recovery of marketable dry biomass. In contrast, *Solanum nigrum* (85.3%), Bhumi Amla (81.3%), and Kalmegh (81.2%) maintained higher moisture levels, indicating active physiological metabolism and enhanced water retention capacity. Such variation in moisture content has been attributed to species-specific differences in cellular structure and water-use efficiency.

Ash content serves as an indicator of total mineral accumulation in plant tissues. The significantly higher ash content recorded in *Solanum nigrum* (12.3%) and Bhumi Amla (10.1%) suggests superior mineral uptake and nutrient assimilation under coconut-based cultivation. Enhanced nutrient recycling through litter decomposition and soil organic matter enrichment in coconut-based systems may contribute to increased mineral availability and uptake by intercrops, thereby improving nutritional quality.

Crude fiber content was highest in *Tribulus terrestris* (19.9%) and Ashwagandha (17.6%), indicating greater deposition of structural carbohydrates. Higher fiber accumulation is generally associated with improved plant structural integrity, stress tolerance, and nutraceutical value. Fiber-rich medicinal plants are increasingly recognized for their role in promoting digestive health and reducing metabolic disorders, thereby enhancing their functional food potential.

The most remarkable variation was observed in total phenolic and flavonoid contents. Bhumi Amla recorded the highest total phenolic content (95.3 mg GAE g^{-1} DW) and flavonoid content (71.6 mg QE g^{-1} DW), followed by Kalmegh, Peppermint, and Tulasi. Phenolic compounds represent one of the most important classes of plant secondary metabolites and play critical roles in antioxidative defense, environmental stress adaptation, and pharmacological activity. Recent reviews have emphasized that phenolics and flavonoids contribute significantly to antioxidant, anti-inflammatory, antimicrobial, cardioprotective, and anticancer activities in medicinal plants (Intharuksa et al. 2024; Zhang et al. 2022). Furthermore, phenolic compounds function as natural stress alleviators by protecting cellular components against oxidative damage and improving plant resilience under environmental stress conditions (Saini et al. 2024). The exceptionally high phenolic and flavonoid concentrations observed in Bhumi Amla therefore indicate its superior phytochemical richness and medicinal potential.

The DPPH radical scavenging activity closely followed the trend observed for phenolic and flavonoid accumulation. Bhumi Amla and Tulasi exhibited the highest antioxidant activity (80.3%), followed by *Solanum nigrum* (75.3%) and Coleus (71.3%). Numerous studies have demonstrated a strong positive relationship between phenolic concentration and antioxidant capacity because phenolic compounds effectively neutralize reactive oxygen species through hydrogen donation and electron transfer mechanisms. The superior antioxidant activity observed in Bhumi Amla may therefore be attributed to its elevated phenolic and flavonoid content. Similar observations have been reported for Phyllanthus species, which are recognized as rich sources of antioxidant phytochemicals with significant therapeutic applications.

Alkaloid concentration was highest in Kalmegh and *Solanum nigrum* (2.4%), followed by Bhumi Amla and Ashwagandha. Alkaloids constitute an important group of nitrogen-containing secondary metabolites known for their antimicrobial, anti-inflammatory, antidiabetic, and anticancer activities. Higher alkaloid accumulation in Kalmegh may be associated with its inherent genetic potential and adaptation to the shaded agroforestry environment. The elevated alkaloid concentration further enhances the pharmaceutical value of these species and supports their inclusion in diversified medicinal cropping systems.

A notable variation was also observed in total saponin content, with *Tribulus terrestris* recording the highest concentration (7.59%), followed by Ashwagandha (4.67%) and *Solanum nigrum* (3.67%). *Tribulus terrestris* is well known for its richness in steroidal saponins, which contribute to its adaptogenic, antioxidant, anti-inflammatory, and reproductive health-promoting properties. The high saponin concentration observed in the present study confirms the suitability of *Tribulus* as a high-value medicinal crop for integration into coconut-based production systems.

Overall, the biochemical profiling revealed that Bhumi Amla emerged as the richest source of phenolics, flavonoids, and antioxidant activity, whereas Kalmegh and *Solanum nigrum* accumulated the highest alkaloid concentrations. *Tribulus terrestris* exhibited exceptional saponin content, while Cassia combined lower moisture content with greater dry matter accumulation. These findings demonstrate that coconut-based multi-tier cropping systems not only enhance agro-economic viability but also support the production of phytochemically rich medicinal plants with significant pharmaceutical and nutraceutical value, thereby contributing to both climate-resilient agriculture and sustainable medicinal plant production.

Yield of Coconut and Economic Performance of Medicinal Crop-Based Multi-Tier Cropping Models

The integration of medicinal plants into coconut-based production systems significantly improved system productivity and profitability without adversely affecting coconut yield, demonstrating their ecological compatibility and economic complementarity. These findings support the role of multi-tier agroforestry systems in enhancing resource-use efficiency through complementary utilization of light, water, nutrients, and growing space (Nair et al. 2021; Dissanayaka et al. 2023). Although sole coconut recorded the highest nut yield, yields under diversified systems remained statistically comparable, indicating minimal competition between component crops. This suggests efficient partitioning of above- and below-ground resources, consistent with earlier reports on coconut-based multistoried systems where suitable intercrops enhanced overall productivity without affecting palm performance (Maheswarappa et al. 2018; Nuwarapaksha et al. 2022). The maintenance of coconut productivity under intercropping conditions can be attributed to the efficient utilization of underexploited ecological niches within the coconut ecosystem. Coconut palms intercept only a portion of the incident solar radiation, leaving considerable amounts of light, soil moisture, and nutrients available for intercrop utilization. The medicinal crops evaluated in the present study effectively occupied these ecological niches and converted otherwise unutilized resources into economically valuable biomass. Such complementary interactions are considered a fundamental ecological principle underpinning the productivity advantages of agroforestry systems (Jose et al. 2004; Nair et al. 2021).

The substantial improvement in benefit-cost ratio observed under medicinal crop integration highlights the economic advantages of diversification in perennial plantation systems. The highest B:C ratio recorded in Cropping Model-2 (2.46) indicates superior economic efficiency resulting from the combined contribution of Cassia, *Solanum nigrum*, and Peppermint. The enhanced profitability may be attributed to the higher market demand and economic value of these medicinal crops, coupled with their ability to produce substantial biomass under the modified microclimatic conditions of the coconut plantation. Diversification of production components is widely recognized as an effective strategy for reducing economic risks and improving income stability in smallholder agroforestry systems (Dagar and Tewari, 2017).

Among the evaluated systems, Cropping Model-2 produced the highest coconut equivalent yield (42,122.50 nuts ha^{-1}), which was approximately 2.2 times greater than that of Cropping Model-1 and nearly double the actual coconut yield achieved under the system. Coconut equivalent yield provides a comprehensive measure of biological and economic productivity by converting the value of intercrop outputs into equivalent coconut yield units. The remarkably high CYEY recorded under Cropping Model-2 indicates greater overall resource-use efficiency and stronger economic synergy among component crops. Similar increases in equivalent yield have been reported in diversified coconut-based systems incorporating high-value intercrops, where efficient utilization of available resources substantially enhanced total system productivity (Namitha et al. 2025).

The superior performance of Cropping Model-2 also demonstrates the importance of species composition in determining agroforestry system efficiency. Cassia, *Solanum nigrum*, and Peppermint differ considerably in canopy architecture, rooting depth, nutrient demand, and growth dynamics, thereby reducing interspecific competition and promoting complementary resource utilization. Such functional diversity among component species is considered a key driver of productivity enhancement in agroforestry systems because it enables more complete exploitation of available environmental resources (Jose et al. 2024). The combination of species with contrasting growth habits likely improved light interception, nutrient capture, and temporal resource use, thereby contributing to greater economic returns and system productivity.

The comparatively lower CYEY observed in Cropping Models-1 and -3 does not necessarily indicate poor performance but rather reflects differences in the economic value and biomass productivity of component medicinal crops. Nevertheless, all three cropping models generated higher economic returns than sole coconut cultivation, demonstrating the inherent advantage of diversification. The findings further support the concept that productivity in agroforestry systems should be evaluated not only in terms of the principal crop yield but also through aggregate measures of biological and economic output (Nair et al. 2021).

From a climate-resilience perspective, medicinal crop diversification enhances the adaptive capacity of coconut-based systems by increasing species diversity, reducing dependence on a single commodity, and improving system-level stability. Diverse agroforestry systems are known to buffer climatic variability through improved soil cover, enhanced nutrient cycling, greater carbon sequestration, and increased biological resilience (Dissanayaka et al. 2023; Khopade et al. 2025). The inclusion of medicinal plants additionally provides alternative income streams during periods of market or climatic uncertainty, thereby reducing vulnerability of farming households.

The economic superiority of medicinal plant-based multi-tier systems observed in the present study is consistent with reports that diversified coconut agroforestry systems enhance productivity, profitability, nutrient cycling, soil organic carbon accumulation, and overall environmental sustainability (Tong et al. 2024; Namitha et al.

2025). The results demonstrate that medicinal plant integration improves land-use efficiency and economic returns without affecting coconut productivity. Among the systems evaluated, Cropping Model-2 (Coconut + Cassia + *Solanum nigrum* + Peppermint) exhibited the highest productivity and profitability, indicating more efficient utilization of available ecological resources. Therefore, medicinal plant diversification offers a promising strategy for improving agro-economic viability, climate resilience, and sustainability of coconut-based production systems in Telangana and similar agroecological regions.

Conclusion

The present study demonstrates that integration of medicinal plants into coconut-based multi-tier cropping systems significantly enhances system productivity, profitability, and resource-use efficiency without compromising coconut yield. The diversified systems effectively utilized underexploited light, soil, and ecological resources beneath mature coconut canopies, thereby improving overall system performance and sustainability. Considerable interspecific variation was observed among medicinal crops, with Tulasi exhibiting superior vegetative growth, Kalmegh producing the highest biomass yield, Cassia accumulating the greatest dry matter, and Coleus recording the highest root yield. Several species, particularly Bhumi Amla, Tulasi, Peppermint, and Kalmegh, also exhibited enhanced phytochemical quality, characterized by higher phenolic, flavonoid, and antioxidant contents, indicating their potential as high-value medicinal raw materials. Among the evaluated systems, the Coconut + Cassia + *Solanum nigrum* + Peppermint model emerged as the most efficient and economically viable, achieving the highest Coconut Yield Equivalent Yield (42,122.5 nuts ha^{-1}) and benefit–cost ratio (2.46). The superior performance of this system highlights the importance of complementary crop interactions and efficient resource partitioning in maximizing productivity and profitability. Overall, medicinal plant diversification represents a promising strategy for sustainable intensification of coconut-based agroecosystems, contributing to enhanced farm income, improved land-use efficiency, climate resilience, and long-term ecological sustainability. Therefore, the Coconut + Cassia + *Solanum nigrum* + Peppermint multi-tier system may be recommended as a scalable agroforestry model for coconut-growing regions of Telangana and other tropical environments with similar agroecological conditions.

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Author Contribution

Neelima Palagani, D. Sravanthi, I.V.S. Reddy, K. G. K. Murthy, R. Ramesh, and B. Deepak Reddy: Conceptualization, Investigation, Data curation, Methodology, and Writing—original draft.

B. Balakrishna and I. Krishna Teja: Formal analysis, Statistical analysis, Validation, and Data interpretation.

J. Hemantha Kumar: Supervision, Project administration, Review and editing, and Final approval of the manuscript. All authors have read and agreed to the published version of the manuscript.

Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request. All relevant data supporting the findings of this study are presented within the article and its supplementary materials.

Conflict of Interest

The authors declare no conflict of interest

Ethical Approval: Not applicable.

Consent to Participate: Not applicable.

Consent for Publication

All authors have read and approved the manuscript for publication

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