

Evaluation of high value and climate smart crops under custard apple based agri-horti system in the Vindhyan region

Rajashree krishna Bharadwaj

rajshree@bhu.ac.in

Banaras Hindu University

Sudhir Kumar Rajpoot

Banaras Hindu University

Alok Kumar Singh

Banaras Hindu University

Sunil Kumr Verma

Banaras Hindu University

Anhinav Singh

Banaras Hindu University

Ambikesh Tripathi

Banaras Hindu University

Short Report

Keywords: agri-horti system, agroforestry, climate smart crops, custard apple, high value crops

Posted Date: March 26th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9176877/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

An experiment was conducted at Agricultural Farm of Rajiv Gandhi South Campus (Banaras Hindu University), Barkaccha, Mirzapur, Uttar Pradesh, India located in the Central Vindhyan Plateau Region during the monsoon season of July 2024. Assessment of five high value and climate smart crops under 13 year old custard apple-based agri-horti systems on sandy clay loam soil using a randomized block design with three replications. The various treatment combinations include T₁(custard apple+ vegetable cowpea), T₂ (custard apple+okra), T₃ (custard apple+ finger millet), T₄ (custard apple+ ashwagandha) and T₅(custard apple+ cluster bean). Results showed that the custard apple + clusterbean system yielded the highest custard apple mean crop equivalent yield (5,938 kg/ha), followed by T₄, ashwagandha (4,875 kg/ha), okra (4,688 kg/ha), finger millet (3,618kg/ha), and cowpea (3,133kg/ha). Although the okra system incurred the highest cultivation cost (Rs 81881.9), it also produced the third highest gross (Rs 234400) and net returns (Rs 152518.1). The highest gross return was produced by clusterbean (Rs 2,54,150). In contrast, the custard apple + cluster bean combination had the highest benefit-cost ratio (5.61), making it the most economically efficient preceeded by ashwagandha(6.88) and succeeded by okra(2.86). The highest harvest index was recorded for custard apple+okra 44% followed by cluster bean(38.48%) and vegetable cowpea(34.9%). The land equivalent ratio was 2.03 for custard apple and vegetable clusterbean, followed by custard apple+okra (1.91). LER was recorded lowest for custard apple+finger millet(1.24). The carbon stock observed was highest for custard apple+ okra 5.5tha⁻¹yr⁻¹ followed by leguminous crops clusterbean (4.3 tha⁻¹yr⁻¹) and cowpea (1.8 tha⁻¹yr⁻¹). This research underscores the potential of integrating climate-resilient, high-value and climate smart intercrops with custard apple to enhance profitability, sustainability, and productivity.

INTRODUCTION

Climate change and food insecurity are among the most critical global challenges of the 21st century, significantly affecting agricultural productivity and stability. Variations in climate increase yield variability, disrupt food supply chains, and threaten both food and nutritional security, largely due to soil degradation and increased pest incidence (Kang et al., 2009; Läderach et al., 2017; Arora, 2019; Zizinga et al., 2022; Miron et al., 2023). Climate-smart agriculture (CSA) has emerged as a key strategy to enhance resilience and productivity, particularly in rainfed systems (Barasa et al., 2021; Botai & Botai, 2021). Agroforestry-based systems, such as custard apple (*Annona squamosa* L.)-based agri-horti systems, offer a promising solution for sustainable intensification in semi-arid regions by improving land use efficiency, farm income, and ecological stability (Arya & Sharma, 2020; Sutnga et al., 2020). Custard apple is well adapted to marginal environments due to its drought tolerance, deep root system, and low input requirements, making it suitable for integration with intercrops (Rathore et al., 2016; Kumar et al., 2019). Such systems also provide microclimatic benefits that enhance intercrop performance and resource use efficiency (Chaturvedi et al., 2017; Nair, 1993). Crop diversification through intercropping of high-value and climate-resilient crops further strengthens system productivity, soil fertility, and economic returns. Leguminous crops such as cowpea and cluster bean improve soil nitrogen through biological fixation, while millets contribute to nutritional security and resilience under low-input conditions (Jat et al., 2020; Mohanty et al., 2023). Diversified systems have been shown to stabilize yields, enhance biodiversity, and reduce environmental risks compared to monocultures (Davis et al., 2012; Renard & Tilman, 2019). However, adoption is often constrained by limited resources and technical knowledge (Meynard et al., 2018; Roesch-McNally et al., 2018). In this context, integrating crops such as okra (*Abelmoschus esculentus*), cowpea (*Vigna unguiculata*), cluster bean (*Cyamopsis tetragonoloba*), finger millet, and ashwagandha (*Withania somnifera*) within custard apple-based systems offers significant potential for improving productivity, profitability, and sustainability in dryland agriculture (Woldetsadik et al., 2022; Jat et al., 2023).

MATERIALS AND METHODS

Study area:

The study was conducted in the Vindhyan region of eastern Uttar Pradesh at the Rajiv Gandhi South Campus, Banaras Hindu University, located in Mirzapur. Geographically, the site lies at approximately 25.10° N latitude and 82.37° E longitude,

representing the semi-arid agro-ecological conditions of the Vindhyan plateau. The region is characterized by undulating topography, shallow to medium-depth soils, and red lateritic to sandy loam textures with low organic carbon and poor water-holding capacity (Singh et al., 2011; Sharma et al., 2015; Pathak et al., 2017). The climate is tropical monsoonal, marked by hot summers, mild winters, and an average annual rainfall of about 900–1100 mm, most of which is received during the southwest monsoon season (ICAR, 2018; Singh & Mishra, 2022). These climatic and edaphic constraints make agriculture highly vulnerable to variability in rainfall and temperature, thereby affecting crop productivity and sustainability (Jha et al., 2019; Pandey et al., 2021). Land use in the study area reflects a predominance of rainfed and resource-constrained farming systems, with a considerable portion of land under fallow, wasteland, and tree-based systems. The net cultivated area is relatively limited, with cropping intensity around 120%, indicating moderate land-use efficiency under dryland conditions. The prevailing land use system is dominated by agroforestry-based and mixed cropping systems, integrating trees with field crops to enhance productivity and resilience (Tripathi et al., 2016; Kumar et al., 2020; Yadav et al., 2018). Major crops grown include kharif season crops such as paddy, maize, pigeon pea, sesame, and millets, and rabi season crops like wheat, barley, chickpea, lentil, and mustard. These diversified cropping systems play a crucial role in improving soil fertility, stabilizing yields, and ensuring livelihood security in the region (Jat et al., 2020; Pandey et al., 2021). The campus serves as an important research hub for developing climate-resilient and sustainable agricultural practices tailored to dryland ecosystems of the Vindhyan region (Banaras Hindu University, 2023).

Sampling and data collection:

Field experiments were conducted using a randomized block design with appropriate replications to evaluate the performance of custard apple-based agri-horti systems under rainfed conditions. Crop yield data for all component species were recorded at harvest from net plot areas and expressed in standard units. To enable comparison among diversified cropping systems, yields of intercrops were converted into equivalent yield based on prevailing market prices (Willey, 1979; Mead & Willey, 1980; Jat et al., 2020). System productivity and biological efficiency were further assessed using the land equivalent ratio (LER) and land use efficiency (LUE), which quantify the advantage of intercropping over sole cropping and the extent of land utilization over time (Willey, 1979; Hiebsch & McCollum, 1987; Dhima et al., 2007). The harvest index (HI) was calculated as the ratio of economic yield to total biological yield to assess biomass partitioning efficiency (Donald, 1962; Hay, 1995). Data on crop growth, yield attributes, and system productivity were recorded following standard agronomic procedures to ensure accuracy and reproducibility (Gomez & Gomez, 1984; Singh et al., 2011; Kumar et al., 2020).

Economic analysis included estimation of gross returns, net returns, and benefit–cost ratio based on prevailing input and output prices to determine the profitability of different land-use systems (Jat et al., 2020; Pandey et al., 2021; Singh & Mishra, 2022). Carbon sequestration potential of the system was assessed by estimating above- and below-ground biomass using standard allometric equations and converting biomass into carbon stock using established conversion factors (Nair et al., 2009; IPCC, 2006; Montagnini & Nair, 2004). Changes in soil fertility parameters, including soil organic carbon, available nitrogen, phosphorus, potassium, and soil water holding capacity, were analyzed before and after the experiment using standard laboratory methods such as Walkley and Black for organic carbon, Subbiah and Asija for available nitrogen, Olsen's method for available phosphorus, flame photometry for potassium, and gravimetric/pressure plate methods for water holding capacity (Walkley & Black, 1934; Subbiah & Asija, 1956; Olsen et al., 1954; Jackson, 1973; Klute, 1986). These methods are widely accepted for evaluating soil nutrient dynamics and physical properties under different land-use systems (Bray et al., 1945; Knudsen et al., 1982; Black et al., 1965).

These comprehensive measurements enabled a holistic assessment of productivity, resource-use efficiency, environmental sustainability, and economic viability of the custard apple-based agroforestry systems in the Vindhyan region (Lal, 2004; Dhyani et al., 2017; Jose, 2009; Kumar et al., 2022; Jat et al., 2023).

Data analysis- The experimental data generated from different agroforestry-based land-use systems were subjected to statistical analysis using analysis of variance (ANOVA) appropriate for a randomized block design to test the significance of treatment effects. Treatment means were compared using the least significant difference (LSD) test at a 5% level of probability to determine significant differences among treatments (Gomez & Gomez, 1984; Singh et al., 2011). Standard statistical

procedures were followed to ensure the validity and reliability of the results, and all computations were performed using suitable statistical software packages.

System productivity and efficiency indices such as equivalent yield, land equivalent ratio (LER), land use efficiency (LUE), and harvest index (HI) were computed using standard formulae. Economic analysis, including gross returns, net returns, and benefit–cost ratio, was carried out based on prevailing market prices of inputs and outputs to evaluate the economic feasibility of the systems (Jat et al., 2020; Pandey et al., 2021; Singh & Mishra, 2022). Carbon sequestration potential was estimated by converting biomass into carbon stock using established conversion coefficients and summing across system components (IPCC, 2006; Nair et al., 2009; Montagnini & Nair, 2004). Soil data were analyzed to quantify changes in soil organic carbon, available nitrogen, phosphorus, potassium, and water holding capacity, and the results were interpreted to assess the impact of different agroforestry systems on soil health (Walkley & Black, 1934; Subbiah & Asija, 1956; Olsen et al., 1954; Jackson, 1973; Klute, 1986). These analyses provided an integrated evaluation of productivity, profitability, and sustainability of custard apple–based agri-horti systems under rainfed conditions (Lal, 2004; Dhyani et al., 2017; Jose, 2009; Kumar et al., 2022; Jat et al., 2023).

RESULTS

The results of the study revealed significant variations among different custard apple–based agri-horti systems in terms of growth, yield, productivity, soil fertility, carbon sequestration, and economic returns. Among the treatments, custard apple + okra (T_2) recorded the highest growth attributes, including plant height, leaf area, and dry matter accumulation, while custard apple + clusterbean (T_5) exhibited superior performance in terms of intercrop yield (82.50 q ha^{-1}), okra equivalent yield (123.75 q ha^{-1}), system productivity ($18,313 \text{ kg ha}^{-1}$), and land equivalent ratio (2.03). Carbon sequestration was also highest in T_2 ($5.50 \text{ t ha}^{-1} \text{ yr}^{-1}$) followed by T_5 ($4.30 \text{ t ha}^{-1} \text{ yr}^{-1}$), indicating enhanced biomass accumulation in these systems. Soil fertility parameters, including soil organic carbon, nitrogen, phosphorus, potassium, and water holding capacity, were improved under legume-based systems, particularly T_1 (cowpea) and T_5 (clusterbean). Economic analysis showed that T_5 recorded the highest net return ($\text{₹}208,873.8 \text{ ha}^{-1}$) with high land use efficiency (100%), while T_4 (ashwagandha) achieved the highest benefit–cost ratio (6.88) due to lower input costs. Overall, diversified agri-horti systems, especially those involving clusterbean and okra, demonstrated superior performance across productivity, profitability, and sustainability indicators under rainfed conditions.

Table 4.1

Effect of custard apple based agri-horti system on growth attributes (at harvest) of high value and climate smart crops

Treatments	Plant height (cm)	Leaves Plant ⁻¹	Primary branches Plant ⁻¹	Dry weight Plant ⁻¹ (g)	Leaf area (cm ²)	Leaf area index	Crop growth rate (gm ⁻² day ⁻¹)	Relative Growth rate (gg ⁻¹ day ⁻¹)	Net Assimilation Ratio (gm ⁻² day ⁻¹)
T ₁ : custard apple + vegetable cowpea	105	19.51	8.91	17.95	1503	3.34	0.21	0.0141	0.0179
T ₂ : custard apple+ okra	180	62	18.8	241.95	2286	1.27	4.14	0.0232	0.1968
T ₃ : custard apple + finger millet	73	35.64	15.5	30.98	285	0.95	0.07	0.0025	0.0419
T ₄ : custard apple+ ashwagandha	28	15	5.7	35.02	450	0.25	0.68	0.0298	0.1038
T ₅ : custard apple+ vegetable clusterbean	114	35.20	8.7	105.27	535.5	1.19	0.82	0.0087	0.1308

Table 4.2

Effect of custard apple based agri-horti system on yield attributes of high value and climate smart crops

Treatments	Pods plant ⁻¹	No of grain/fruits plant ⁻¹	Fruit length
T ₁ : custard apple + vegetable cowpea	25	28.9	17.07
T ₂ : custard apple+ okra	13.86	47.16	12.82
T ₃ : custard apple + finger millet	-	2514.5	-
T ₄ : custard apple+ ashwagandha	-	16.4	-
T ₅ : custard apple+ vegetable clusterbean	12.80	49.5	8.22

Table 4.3

Effect of custard apple based agri-horti system on intercrop yield and mean equivalent yield of high value and climate smart crops

Treatment	Intercrop (q/ha)	Okra Equivalent Yield (q/ha)	Custard Apple Yield (q/ha)	Custard Apple Equivalent Yield (q/ha)
T ₁ : custard apple + vegetable cowpea	15.17	22.76	24.30	31.33
T ₂ : custard apple + okra	114.40	114.40	24.00	46.88
T ₃ : custard apple + finger millet	7.88	23.63	22.00	36.18
T ₄ : custard apple+ ashwagandha	1.41	14.13	20.50	48.77
T ₅ : custard apple + clusterbean	82.50	123.75	22.25	59.38
SEm ±	1.84	2.85	1.37	1.37
CD(p = 0.005)	5.58	8.65	4.14	4.15

Table 4.9

Effect of custard apple based agri-horti system on carbon stock and sequestration rate (kg CO₂ ha⁻¹) of high value and climate smart crops

Treatment	AGB(kgha ⁻¹)	BGB(kgha ⁻¹)	Total Carbon(kgha ⁻¹)	Carbon(tha ⁻¹ yr ⁻¹)
T ₁ -Custard apple+vegetable cowpea	3,100	1,100	1835	1.835
T ₂ -Custard apple+okra	10000	2500	5500	5.500
T ₃ -Custard apple+ finger millet	1,800	600	1,050	1.050
T ₄ -Custard apple+ ashwagandha	1200	400	700	0.70
T ₅ - Custard apple+ vegetable clusterbean	6000	4000	4300	4.300
SEm±	41.50	61.43	34.93	0.04
CD(%)	125.86	186.29	105.93	0.13

Table 4.10

Effect of custard apple based agri-horti system on land equivalent ratio of high-value and climate smart crops.

Treatment	Yield in intercropping (kg ha ⁻¹)	Yield for custard apple (kg ha ⁻¹)	Monoculture yield for custard apple (kg ha ⁻¹)	Assumed crop monoculture (kg ha ⁻¹) in dryland	LER
T ₁ -Custard apple+vegetable cowpea	1517	2430	2430	2500	1.60
T ₂ -Custard apple+okra	11440	2400	2400	12530	1.91
T ₃ -Custard apple+ finger millet	788	2200	2200	3200	1.24
T ₄ -Custard apple+ ashwagandha	141	2050	2050	300	1.47
T ₅ - Custard apple+ vegetable clusterbean	8250	2225	2225	8000	2.03

Table 4.11

Effect of custard apple based agri-horti system on harvest index of high value and climate smart crops

Treatment	Custard apple mean crop equivalent yield(kg ha ⁻¹)	Biological yield (kg ha ⁻¹)	HI(%)
T ₁ -Custard apple+vegetable cowpea	3113	8919	34.9
T ₂ -Custard apple+okra	4688	10654	44
T ₃ -Custard apple+ finger millet	3618	15075	24
T ₄ -Custard apple+ ashwagandha	4875	13467	36.2
T ₅ - Custard apple+ vegetable clusterbean	5083	13209	38.48

Table 4.12

Effect of custard apple based agri-horti system on system productivity of high value and climate smart crops

Treatment	Okra MCEY(kg ha ⁻¹)	Custard apple MCEY(kg ha ⁻¹)	System Production(kg/ha)
T ₁ -Custard apple+vegetable cowpea	2276	3113	5389
T ₂ -Custard apple+okra	11440	4688	16128
T ₃ -Custard apple+ finger millet	2363	3618	5981
T ₄ -Custard apple+ ashwagandha	1413	4875	6288
T ₅ - Custard apple+ vegetable clusterbean	12375	5938	18313
SEm±	2.85	1.37	78.20
CD(p = 0.005)	8.65	4.15	237.16

Table 4.13

Effect of custard apple based agri-horti system on soil fertility after harvest of high-value and climate smart crops

Treatment	Available Soil organic carbon(%)	Available Soil nitrogen (kg/ha)	Available Soil phosphorus (kg/ha)	Available Soil potassium (kg/ha)	Water holding capacity
T₁ -Custard apple+vegetable cowpea	0.50	258.75	11.20	225	40
T₂ -Custard apple+okra	0.46	256	10.90	218	38
T₃ -Custard apple+ finger millet	0.46	253	10.70	215	36
T₄ -Custard apple+ ashwagandha	0.44	250	10.20	212	35
T₅ - Custard apple+ vegetable clusterbean	0.49	255	11.00	223	39
SEm(±)	0.003	0.57	0.04	1.43	0.19
CD(5%)	0.01	1.22	0.09	3.12	0.41

Table 4.14

Effect of custard apple based agri-horti system on profitability of high-value and climate smart crops.

Treatment	Rank (Income)	Rank (Efficiency)	Yield (kg/ha)	Cost of cultivation (Rs/ha)	Gross Return (Rs/ha)	Net return (Rs/ha)	B:C Ratio	Key Remark
T₁ -Custard apple+vegetable cowpea	5	5	1517	70497.96	156650	86152.04	2.22	Second highest income second lowest efficiency
T₂ -Custard apple+okra	3	3	11440	81881.9	234400	152518.1	2.86	Low efficiency good income
T₃ -Custard apple+ finger millet	4	4	788	67293.34	180900	113606.6	2.68	Best efficiency(highest B:C)
T₄ -Custard apple+ ashwagandha	2	1	141	35417.62	243750	208332.38	6.88	High efficiency
T₅ - Custard apple+ vegetable clusterbean	1	2	6350	45276.15	254150	208873.8	5.61	Good efficiency balance and highest income

Table 4.15

Effect of custard apple based agri-horti system on economic resource use efficiency and land use efficiency of high value and climate smart crops

Treatment	Net Return(Rs)	Cost(Rs)	Economic RUE(%)	Custard mean equivalent yield of intercrop (kg ha ⁻¹)	Land use efficiency(%)
T ₁ -Custard apple+vegetable cowpea	86152.04	70497.96	81.82	3113	52.42
T ₂ -Custard apple+okra	152518.1	81881.9	53.6	4688	78.94
T ₃ -Custard apple+ finger millet	113606.6	67293.34	59.2	3618	60.92
T ₄ -Custard apple+ ashwagandha	208332.38	35417.62	17	4875	82.09
T ₅ - Custard apple+ vegetable clusterbean	208873.8	45276.15	21.67	5938	100

Table 4.16

Effect of custard apple based agri-horti system on comparative economics of high value and climate smart crops.

Treatment	Cost of cultivation (Rs ha ⁻¹)	Gross return (Rs ha ⁻¹)	Net return with fruits (Rs ha ⁻¹) 1)	B-C ratio
T ₁ :custard apple + vegetable cowpea	70497.96	156650	86152.04	2.22
T ₂ : custard apple+ okra	81881.9	234400	152518.1	2.86
T ₃ : custard apple finger millet	67293.34	180900	113606.6	2.68
T ₄ : custard apple + ashwagandha	35417.62	243750	208332.38	6.88
T ₅ : custard apple + vegetable clusterbean	45276.15	254150	208873.8	5.61

DISCUSSION

The results clearly demonstrate that integration of high-value and climate-smart crops with custard apple significantly improved growth, yield, and system productivity under rainfed conditions. Among the treatments, custard apple + okra (T₂) exhibited superior growth attributes such as plant height, number of leaves, dry matter accumulation, and crop growth rate, indicating efficient utilization of available resources. This enhanced performance can be attributed to complementary interactions between component crops, leading to better light interception, nutrient uptake, and reduced interspecific competition, as also reported by Jat et al. (2020) and Dhima et al. (2007). In contrast, relatively lower growth observed in finger millet and ashwagandha systems suggests their comparatively lower competitive ability under moisture-limited conditions (Singh et al., 2011; Kumar et al., 2020).

Yield and system productivity parameters further emphasized the advantage of diversified agri-horti systems. Higher intercrop yield, equivalent yield, and system productivity in custard apple + clusterbean (T₅) and custard apple + okra (T₂) indicate better complementarity and efficient utilization of growth resources. The land equivalent ratio (LER > 1) across all treatments, with the maximum value recorded in T₅ (2.03), confirms the biological superiority of intercropping systems over monoculture (Willey, 1979; Mead & Willey, 1980). Higher harvest index values in okra-based systems reflect efficient partitioning of assimilates toward economic yield, whereas lower values in finger millet-based systems indicate greater allocation toward vegetative biomass (Hay, 1995).

Carbon sequestration potential was significantly higher in custard apple + okra (T_2) and custard apple + clusterbean (T_5) systems due to greater biomass accumulation and enhanced below-ground carbon storage. These findings corroborate earlier studies highlighting the role of agroforestry systems in mitigating climate change through carbon sequestration (Nair et al., 2009; Montagnini & Nair, 2004; Lal, 2004). In addition, improvements in soil fertility parameters were clearly evident from both the experimental data (Table 4.13) and graphical representation (Fig. 2). The soil fertility analysis graph indicates that treatments involving legumes, particularly clusterbean (T_5) and cowpea (T_1), maintained higher soil organic carbon, nitrogen, phosphorus, potassium, and water holding capacity compared to other treatments. This can be attributed to biological nitrogen fixation, higher biomass return, and improved soil aggregation, which enhance nutrient availability and moisture retention (Subbiah & Asija, 1956; Olsen et al., 1954; Dhyani et al., 2017). The relatively lower values observed in non-leguminous systems such as ashwagandha and finger millet further highlight the importance of legumes in sustaining soil health under dryland agroforestry systems.

Economic analysis and resource-use efficiency (Fig. 1) revealed substantial variation among treatments. The graphical representation shows that custard apple + clusterbean (T_5) recorded the highest net returns along with maximum land use efficiency (100%), indicating optimal utilization of land resources throughout the year. Although custard apple + ashwagandha (T_4) recorded the highest benefit–cost ratio due to lower input costs and higher market price, its system productivity was relatively lower. Economic resource use efficiency was more balanced in treatments such as T_2 and T_5 , which combined higher productivity with reasonable input costs. These findings are consistent with earlier reports suggesting that diversified agroforestry systems enhance economic stability and resilience of farming systems (Pandey et al., 2021; Singh & Mishra, 2022; Jose, 2009).

Overall, the integration of custard apple with suitable intercrops such as clusterbean and okra significantly enhanced productivity, profitability, soil fertility, carbon sequestration, and resource-use efficiency. The combined interpretation of tabular data and graphical analysis (Fig. 1 and Fig. 2) indicates that clusterbean-based systems offer the best balance between economic returns, land use efficiency, and sustainability, making them highly suitable for dryland regions like the Vindhyan plateau. These findings reinforce the role of agroforestry systems as a viable strategy for sustainable intensification and climate-resilient agriculture (Lal, 2004; Dhyani et al., 2017; Jat et al., 2023).

CONCLUSION

The present study demonstrates that integration of high-value and climate-smart crops within custard apple–based agri-horti systems significantly enhances productivity, profitability, resource-use efficiency, and environmental sustainability under rainfed conditions of the Vindhyan region. Among the evaluated treatments, custard apple + clusterbean (T_5) and custard apple + okra (T_2) consistently outperformed other systems in terms of growth, yield, system productivity, and land equivalent ratio, confirming the advantages of crop diversification and complementary interactions in agroforestry systems. The higher equivalent yields and land use efficiency observed in these systems indicate their potential for maximizing output from limited land resources.

The study further highlights that legume-based systems, particularly clusterbean and cowpea, play a crucial role in improving soil fertility through enhanced soil organic carbon, nitrogen availability, and moisture retention. Additionally, higher carbon sequestration potential observed in okra- and clusterbean-based systems underscores the environmental benefits of agroforestry in mitigating climate change. Economic analysis revealed that custard apple + clusterbean provided the highest net returns and balanced resource-use efficiency, while custard apple + ashwagandha showed the highest benefit–cost ratio due to lower input costs. Overall, the findings suggest that custard apple–based diversified agri-horti systems, especially those integrating legumes and high-value crops, offer a sustainable and climate-resilient strategy for improving livelihoods and ensuring ecological stability in dryland regions.

Declarations

Author Contribution

R.K.B. (Rajashree Krishna Bharadwaj) conceptualized and conducted the research work, performed field experiments, collected and analyzed data, and wrote the main manuscript. S.K.R. (Sudhir Kumar Rajpoot) served as Chairman of the advisory committee, supervised the research, and contributed to the design, interpretation of results, and critical revision of the manuscript. A.K.S. (Alok Kumar Singh) contributed to the development of the research framework, provided technical guidance on agroforestry aspects, and reviewed the manuscript. A.T. (Ambikesh Tripathi) assisted in field experimentation and data collection. A.S. (Abhinav Singh) provided support in statistical analysis and data interpretation. S.K.V. (Sunil Kumar Verma) assisted with agronomic aspects and field management. All authors reviewed and approved the final manuscript.

References

1. Arya, S. L., & Sharma, V. (2020). Agroforestry systems for sustainable land use in arid regions. *Indian Journal of Agroforestry*, 22(1), 1–10. <https://doi.org/10.5958/0972-6351.2020.00001.2>
2. Arora, N. K. (2019). Impact of climate change on agriculture production and its sustainable solutions. *Environmental Sustainability*, 2, 95–96. <https://doi.org/10.1007/s42398-019-00078-w>
3. Banaras Hindu University. (2023). *Rajiv Gandhi South Campus (Barkachha) overview*. <https://www.bhu.ac.in>
4. Barasa, P. M., Lwasa, S., & Otieno, R. (2021). Climate-smart agriculture and household food security. *Sustainability*, 13(4), 1–15. <https://doi.org/10.3390/su13041934>
5. Black, C. A. (1965). *Methods of soil analysis, Part 1*. American Society of Agronomy.
6. Botai, C. M., & Botai, J. O. (2021). Climate variability and its implications for food security. *Atmosphere*, 12(3), 1–18. <https://doi.org/10.3390/atmos12030345>
7. Bray, R. H., & Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil Science*, 59(1), 39–46. <https://doi.org/10.1097/00010694-194501000-00006>
8. Chaturvedi, O. P., Handa, A. K., & Uthappa, A. R. (2017). Agroforestry for climate resilience. *Indian Journal of Agroforestry*, 19(1), 1–12. <https://doi.org/10.5958/0972-6351.2017.00001.5>
9. Davis, A. S., Hill, J. D., Chase, C. A., Johanns, A. M., & Liebman, M. (2012). Increasing cropping system diversity balances productivity and environmental health. *PLoS ONE*, 7(10), e47149. <https://doi.org/10.1371/journal.pone.0047149>
10. Dhima, K. V., Lithourgidis, A. S., Vasilakoglou, I. B., & Dordas, C. A. (2007). Competition indices of common vetch and cereal intercrops. *Field Crops Research*, 100(2–3), 249–256. <https://doi.org/10.1016/j.fcr.2006.07.008>
11. Dhyani, S. K., Gupta, R. K., & Handa, A. K. (2017). Agroforestry for climate resilience and carbon sequestration. *Indian Journal of Agroforestry*, 19(1), 1–7. <https://doi.org/10.5958/0972-6351.2017.00001.5>
12. Donald, C. M. (1962). In search of yield. *Journal of the Australian Institute of Agricultural Science*, 28, 171–178. [https://doi.org/10.1016/S0065-2113\(08\)60316-4](https://doi.org/10.1016/S0065-2113(08)60316-4)
13. Gomez, K. A., & Gomez, A. A. (1984). *Statistical procedures for agricultural research* (2nd ed.). Wiley. <https://doi.org/10.1002/9780470379356>
14. Hanway, J. J., & Heidel, H. (1952). Soil analysis methods as used in Iowa State College Soil Testing Laboratory. *Iowa Agriculture*, 57, 1–31.
15. Hay, R. K. M. (1995). Harvest index: A review of its use in plant breeding and crop physiology. *Annals of Applied Biology*, 126(1), 197–216. <https://doi.org/10.1111/j.1744-7348.1995.tb05015.x>
16. Hiebsch, C. K., & McCollum, R. E. (1987). Area-time equivalency ratio: A method for evaluating the productivity of intercrops. *Agronomy Journal*, 79(1), 15–22. <https://doi.org/10.2134/agronj1987.00021962007900010004x>
17. Indian Council of Agricultural Research (ICAR). (2018). *Vision 2050: Dryland agriculture in India*. ICAR. <https://icar.org.in>
18. IPCC. (2006). *Guidelines for national greenhouse gas inventories*. Intergovernmental Panel on Climate Change. <https://www.ipcc-nggip.iges.or.jp/public/2006gl/>
19. Jackson, M. L. (1973). *Soil chemical analysis*. Prentice Hall.
20. Jat, M. L., Chakraborty, D., Ladha, J. K., & Rana, D. S. (2020). Conservation agriculture for sustainable intensification. *Nature Sustainability*, 3, 336–343. <https://doi.org/10.1038/s41893-020-0505-5>

21. Jat, H. S., Datta, A., Sharma, P. C., et al. (2023). Climate-resilient cropping systems for dryland agriculture. *Agricultural Systems*, 204, 103554. <https://doi.org/10.1016/j.agsy.2022.103554>
22. Jha, P., Kumar, A., & Singh, R. (2019). Rainfed agriculture and climate variability in eastern Uttar Pradesh. *Journal of Agrometeorology*, 21(3), 345–352. <https://doi.org/10.54386/jam.v21i3.593>
23. Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits. *Agroforestry Systems*, 76, 1–10. <https://doi.org/10.1007/s10457-009-9229-7>
24. Kang, Y., Khan, S., & Ma, X. (2009). Climate change impacts on crop yield and water productivity. *Agricultural Water Management*, 97(4), 481–498. <https://doi.org/10.1016/j.agwat.2009.11.001>
25. Knudsen, D., Peterson, G. A., & Pratt, P. F. (1982). Lithium, sodium, and potassium. In A. L. Page et al. (Eds.), *Methods of soil analysis, Part 2* (2nd ed., pp. 225–246). American Society of Agronomy. <https://doi.org/10.2134/agronmonogr9.2.2ed.c13>
26. Kumar, R., Kumar, S., & Singh, B. (2019). Custard apple cultivation in arid regions. *Scientia Horticulturae*, 243, 317–325. <https://doi.org/10.1016/j.scienta.2018.08.037>
27. Kumar, S., Singh, R., & Verma, A. (2020). Agroforestry systems for sustainable land use in semi-arid regions of India. *Agroforestry Systems*, 94, 1019–1032. <https://doi.org/10.1007/s10457-019-00458-0>
28. Klute, A. (1986). Water retention: Laboratory methods. In A. Klute (Ed.), *Methods of soil analysis, Part 1: Physical and mineralogical methods* (2nd ed., pp. 635–662). American Society of Agronomy. <https://doi.org/10.2136/sssabookser5.1.2ed.c26>
29. Läderach, P., Ramirez-Villegas, J., Navarro-Racines, C., et al. (2017). Climate change adaptation in agriculture. *Global Food Security*, 12, 38–46. <https://doi.org/10.1016/j.gfs.2016.11.003>
30. Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677), 1623–1627. <https://doi.org/10.1126/science.1097396>
31. Mead, R., & Willey, R. W. (1980). The concept of land equivalent ratio and advantages in yields from intercropping. *Experimental Agriculture*, 16(3), 217–228. <https://doi.org/10.1017/S0014479700010978>
32. Meynard, J. M., Charrier, F., Fares, M., et al. (2018). Socio-technical lock-in in agriculture. *Agronomy for Sustainable Development*, 38, 54. <https://doi.org/10.1007/s13593-018-0535-1>
33. Miron, J., et al. (2023). Climate change and agricultural sustainability. *Agricultural Systems*, 207, 103648. <https://doi.org/10.1016/j.agsy.2023.103648>
34. Mohanty, S., Painkra, S. K., & Sahu, R. K. (2023). Millets for nutritional and climate resilience. *Frontiers in Nutrition*, 10, 1123456. <https://doi.org/10.3389/fnut.2023.1123456>
35. Montagnini, F., & Nair, P. K. R. (2004). Carbon sequestration: An underexploited environmental benefit of agroforestry systems. *Agroforestry Systems*, 61–62, 281–295. <https://doi.org/10.1023/B:AGFO.0000029005.92691.79>
36. Nair, P. K. R. (1993). *An introduction to agroforestry*. Springer. <https://doi.org/10.1007/978-94-011-1608-4>
37. Olsen, S. R., Cole, C. V., Watanabe, F. S., & Dean, L. A. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate*. USDA.
38. Pandey, V., Tripathi, R., & Singh, G. (2021). Cropping systems and resource use efficiency in dryland agriculture of Vindhyan region. *Agricultural Systems*, 190, 103091. <https://doi.org/10.1016/j.agsy.2021.103091>
39. Pathak, H., Saharawat, Y. S., & Gathala, M. (2017). Climate change and agriculture in India: Impacts and adaptation strategies. *Indian Journal of Agronomy*, 62(4), 415–424. <https://doi.org/10.5958/0974-4460.2017.00052.5>
40. Rathore, A. C., et al. (2016). Performance of custard apple-based agroforestry systems. *Indian Journal of Agroforestry*, 18(2), 45–52. <https://doi.org/10.5958/0972-6351.2016.00012.3>
41. Renard, D., & Tilman, D. (2019). National food production stabilized by crop diversity. *Nature*, 571, 257–260. <https://doi.org/10.1038/s41586-019-1316-y>
42. Roesch-McNally, G. E., et al. (2018). Barriers to climate adaptation in agriculture. *Global Environmental Change*, 48, 10–20. <https://doi.org/10.1016/j.gloenvcha.2017.10.004>

43. Sharma, A. R., Singh, R., & Dhyani, S. K. (2015). Agroforestry for climate resilience and livelihood security in India. *Indian Journal of Agroforestry*, 17(1), 1–9. <https://doi.org/10.5958/0972-6351.2015.00001.3>
44. Singh, J. S., Pandey, V. C., & Singh, D. P. (2011). Efficient soil nutrient management for sustainable agriculture in the Vindhyan region. *Journal of Environmental Biology*, 32(5), 519–530. [https://doi.org/10.22438/jeb/32/5\(SI\)/JEB_2011_519-530](https://doi.org/10.22438/jeb/32/5(SI)/JEB_2011_519-530)
45. Singh, R., & Mishra, S. (2022). Climate variability and its impact on dryland farming systems in eastern Uttar Pradesh. *Climate and Development*, 14(6), 523–533. <https://doi.org/10.1080/17565529.2021.1913621>
46. Subbiah, B. V., & Asija, G. L. (1956). A rapid procedure for estimation of available nitrogen in soils. *Current Science*, 25, 259–260
47. Sutnga, P., et al. (2020). Agroforestry systems for sustainable intensification. *Agroforestry Systems*, 94, 123–135. <https://doi.org/10.1007/s10457-019-00412-0>
48. Tripathi, R., Singh, R., & Yadav, R. P. (2016). Agroforestry practices in Vindhyan region for sustainable land use. *Indian Journal of Agroforestry*, 18(2), 1–7. <https://doi.org/10.5958/0972-6351.2016.00010.X>
49. Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter. *Soil Science*, 37(1), 29–38. <https://doi.org/10.1097/00010694-193401000-00003>
50. Willey, R. W. (1979). Intercropping—its importance and research needs. *Field Crop Abstracts*, 32, 1–10.
51. Woldetsadik, K., et al. (2022). Crop diversification for sustainable agriculture. *Sustainability*, 14(9), 5234. <https://doi.org/10.3390/su14095234>
52. Yadav, R. P., Meena, R. S., & Kumar, S. (2018). Integrated farming systems for livelihood security in dryland regions. *Indian Journal of Agricultural Sciences*, 88(3), 345–352. <https://doi.org/10.56093/ijas.v88i3.79123>
53. Zizinga, A., Kangalawe, R., & Ainslie, A. (2022). Climate change impacts on food security. *Climate and Development*, 14(5), 1–12. <https://doi.org/10.1080/17565529.2021.1882482>

Figures

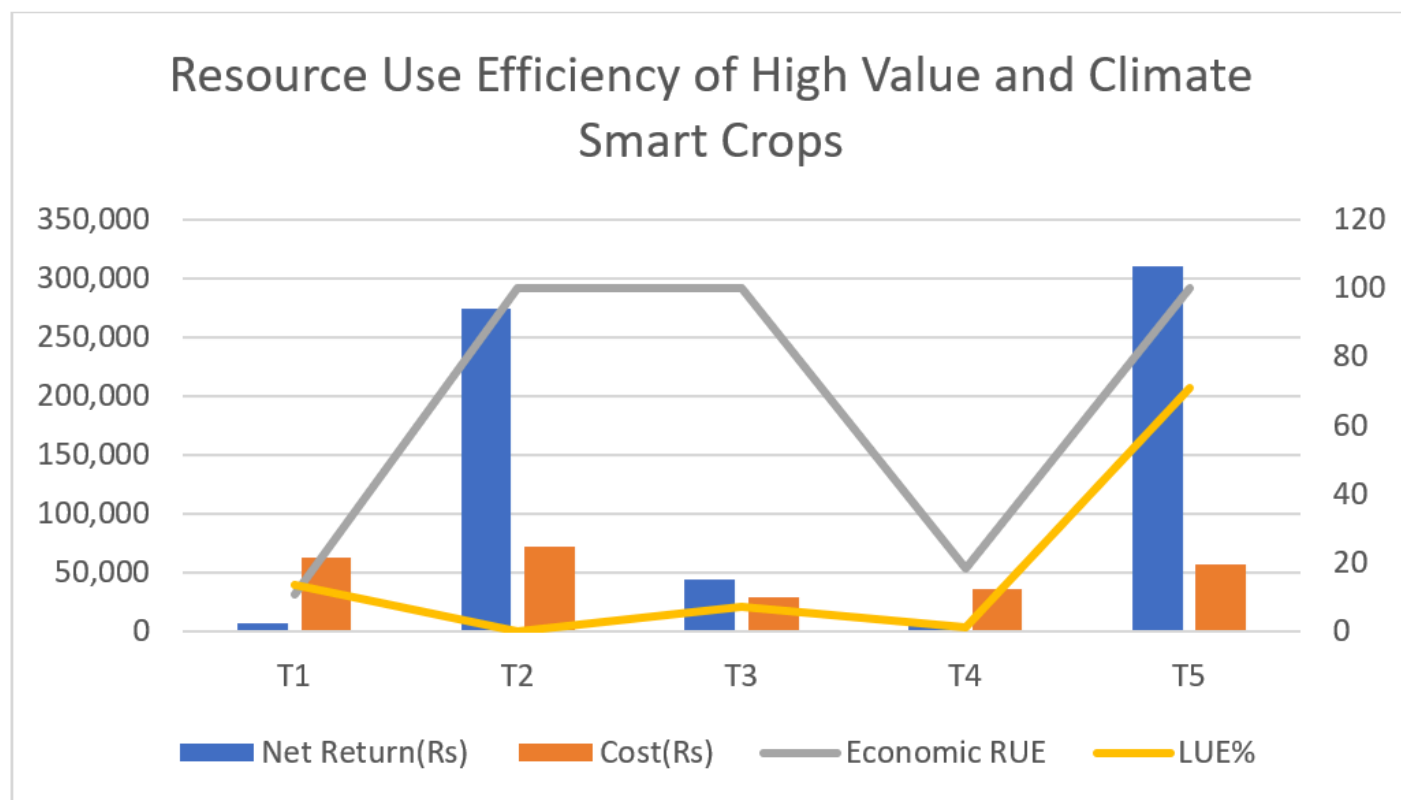


Figure 1

Fig 3.5: Resource use efficiency (economic and land) of different treatments

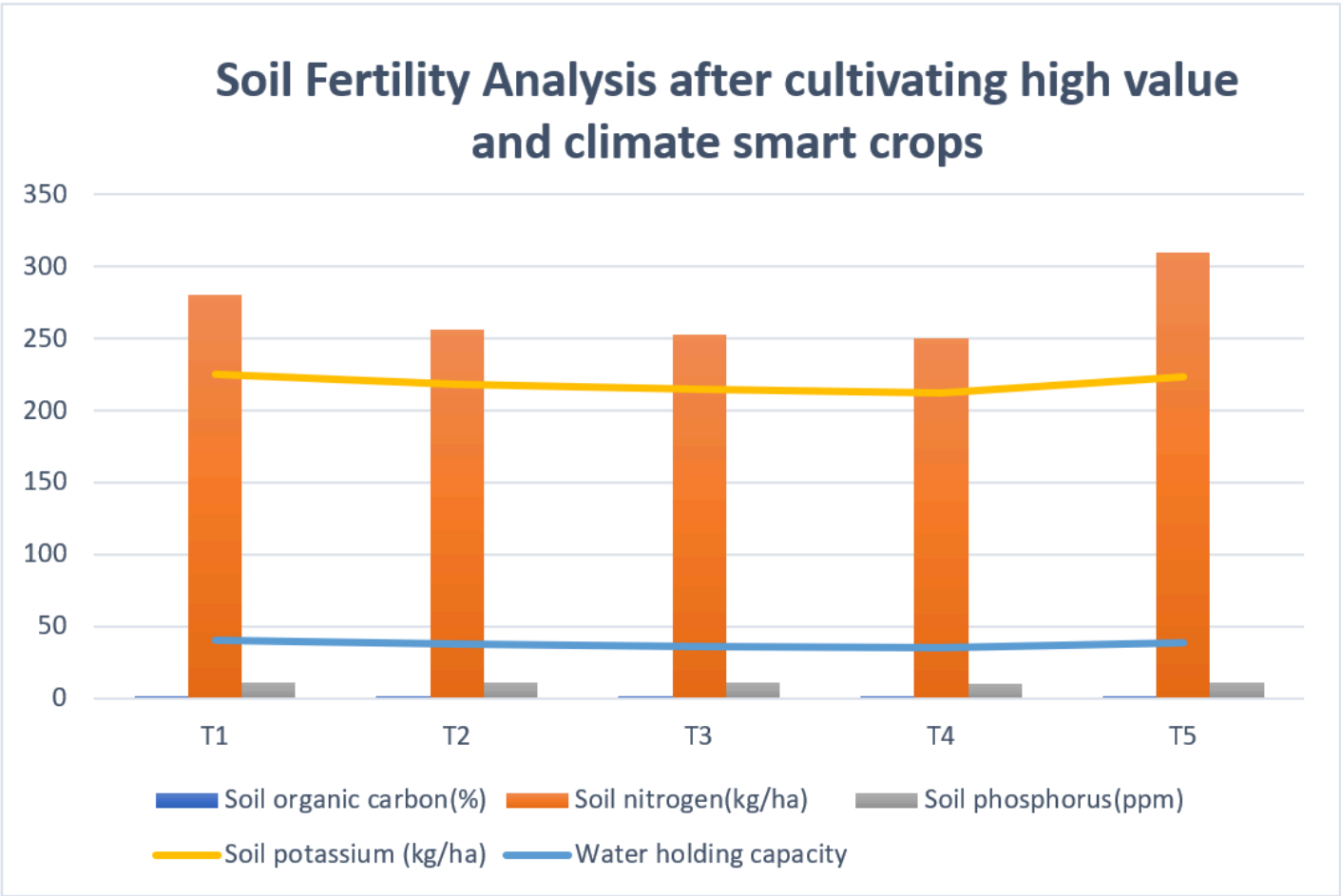


Figure 2

Fig 3.8: Soil fertility analysis of high value and climate smart crops

Carbon Sequestration of high value and climate smart crops

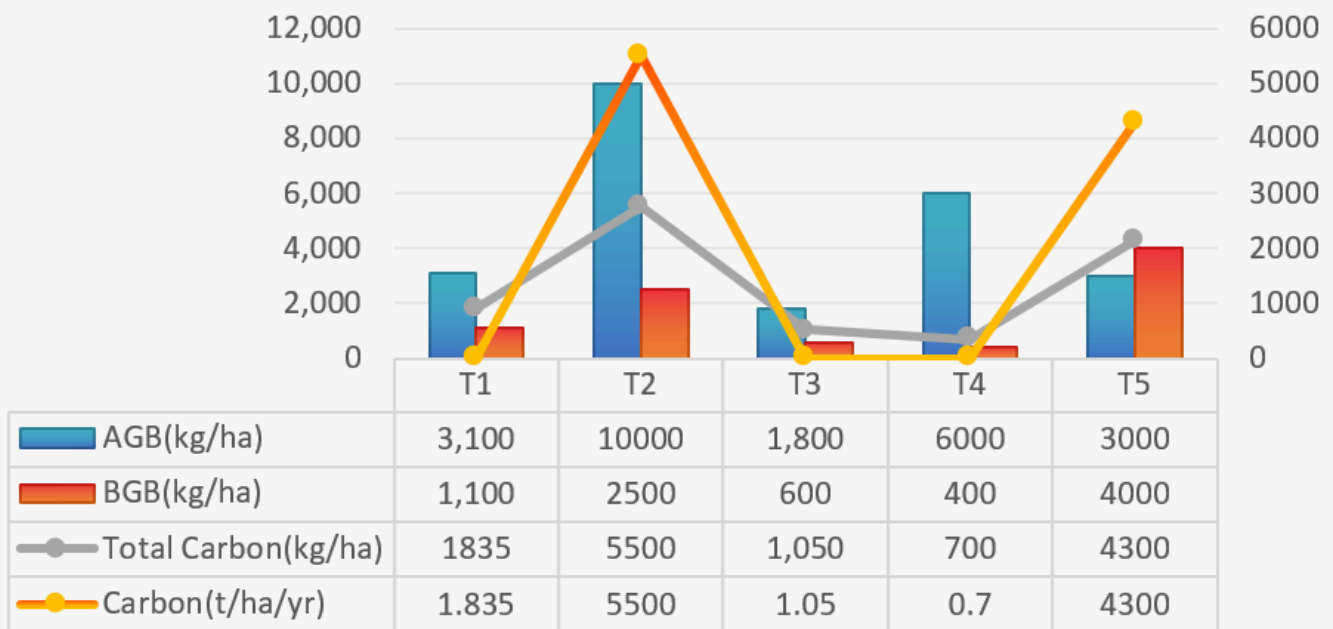


Figure 3

FIG 3.9: Carbon Sequestration of high value and climate smart crops