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Sapota (*Achras zapota*) based bio-engineering measures for slope stabilization and sustainable productive utilization in Mahi ravines, Gujarat

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ABSTRACT

A long-term field experiment (2010-2022) was conducted on 14% sloped ravine lands along the Mahi River in Gujarat to evaluate agroforestry systems integrated with bio-engineering techniques for runoff conservation, soil loss reduction, and productivity enhancement. Five treatments were tested on 72 × 24 m plots: (i) cowpea + castor on bench terraces (CCBT), (ii) sapota + cowpea + castor on bench terraces (SCCBT), (iii) sapota on bench terraces (SBT), (iv) sapota with staggered trenches on slope (SSTS) and (v) sapota on untreated slope (SS - control). Bench terraces were subdivided to reduce slope length; staggered trenching involved 96 trenches (2 × 0.5 × 0.5) m. Tree spacing was 8 × 8 m; Cowpea and Castor were intercropped at 0.3 m spacing. Data on plant growth, yield, runoff, and soil loss were collected using a randomized block design with four replications for crop components, while runoff and soil loss were monitored in a single replication. Results showed that SCCBT achieved the best outcomes: maximum sapota height (4.58 m), stem diameter (13.06 cm), fruit count (256/plant), fruit yield (3672 kg ha^{-1}), and crop equivalent yield (3953 kg ha^{-1}). It also recorded the highest energy efficiency (362%), lowest runoff (96.83% reduction), and soil loss within permissible limits (9.27 t ha^{-1}yr^{-1}). Water productivity peaked at 6.54 kg^{-1}ha^{-1}mm, with a net return of ₹ 41,726 ha^{-1}yr^{-1}. These results demonstrate that the sapota + cowpea + castor system on bench terraces is the most effective bio-engineering solution for slope stabilization and sustainable land use in the Mahi ravines.

1 | INTRODUCTION

Ravine ecosystems, characterized by deep gullies and highly eroded landscapes, pose significant environmental challenges in semi-arid regions like the Mahi ravines of Gujarat, India (Singh *et al.,* 2020b). In Gujarat, ravines spread across 0.4 million hectares in the major river systems of Mahi, Narmada, Vatrak, Tpi, and Sabarmati and their tributaries (Kumar *et al.,* 2020a). These ravine areas are highly susceptible to soil erosion, leading to a loss of agricultural productivity and land degradation, severely impacting local livelihoods (Singh *et al.,* 2020b). Bio-engineering measures offer a sustainable and cost-effective approach to address these issues by utilizing vegetation and natural systems to stabilize slopes and rehabilitate degraded lands (Singh *et al.,* 2020a; Jinger *et al.,* 2022). In regions like the Mahi ravines of Gujarat, traditional farming often becomes unviable without effective soil conservation and land management practices due to high rates of soil erosion and the poor water holding capacity of the soil (Kumar et al., 2021a; Kumar *et al.,* 2021b). Sapota cultivation covers about 14,037 ha in the state of Gujarat, and the state's sapota production reached 166,163 mt in the year 2020, according to the statistics of the Directorate of Horticulture, Gujarat (Pakwar *et al.,* 2021). Agroforestry, a land-use system that integrates trees with crops, offers a promising solution for both ecological restoration and enhanced agricultural productivity in degraded ravine areas (Jinger *et al.,* 2023).

Among various agroforestry species, Achras zapota (sapota) has proven to be a suitable tree for slope stabilization and productive land use due to its deep-rooted system, drought tolerance, and high economic value as a fruit crop (Rashmi *et al.,* 2021; Kumar *et al.,* 2021a; Singh *et al.,* 2020). In combination with appropriate soil conservation techniques such as terracing and trenching, sapota can help reduce soil erosion, improve water retention, and contribute to long-term soil health (Verma *et al.,* 2021; Kumar *et al.,* 2021b). However, to further enhance the economic viability and sustainability of these agroforestry systems, intercrops such as Castor (*Ricinus communis*) and Cowpea (*Vigna unguiculata*) can be introduced. Castor, a drought-tolerant oilseed crop, and cowpea, a nitrogen-fixing legume, are well-suited for intercrop systems with Sapota (Jinger *et al.,* 2022). Both crops can thrive on treated ravine slopes, contributing to soil fertility, providing additional income through crop diversification, and improving overall land productivity (Jinger *et al.,* 2022). Moreover, the integration of these crops with Sapota on terraced and trenched slopes enhances water conservation and reduces runoff, further stabilizing the ravines (Ali *et al.,* 2020; Meena *et al.,* 2023). Therefore, to test the potential of the agroforestry system alongside bio-engineering measures for the conservation of runoff, soil loss, and productivity of sloped ravine lands of the mahi river in gujarat, this study was initiated in the year 2010 with the objective of assessing the potential of Sapota-based agroforestry systems with Castor (*Ricinus communis*) and Cowpea (*Vigna unguiculata*) as intercrops on treated ravine slopes with trenching and terracing in the mahi ravines of gujarat. The data generated on runoff conservation, soil conservation, crop production, and economic viability in this study aims to provide insights into sustainable ravine land management practices for productive utilisation through these bio-engineering measures.

HIGHLIGHTS

- Sapota plantation intercropped with castor and cow pea on bench terrace is the best bio-engineering measure for reclaiming degraded ravine land.
- This combination maximizes crop productivity, resource efficiency, runoff management, and soil conservation.
- The sapota-based measures can yield a net return of ₹ 41726 per hectare annually from reclaimed land.

2 | MATERIALS AND METHODS

2.1 | Study Area and Site Characteristics

A long-term field experiment was conducted from 2010 to 2022 in the Mahi ravine region of Anand district, Gujarat, to enhance the productivity of degraded ravine lands through sapota (*Achras zapota*, locally known as Kalipatti) plantation and intercropping systems (*Fig. 1*). The study site, located near Vasad in western India, lies along the right bank of the Mahi River in a semi-arid landscape (25 m above mean sea level; Latitude 22°16′ N, Longitude 72°58′ E). The region experiences a tropical semi-arid climate with an

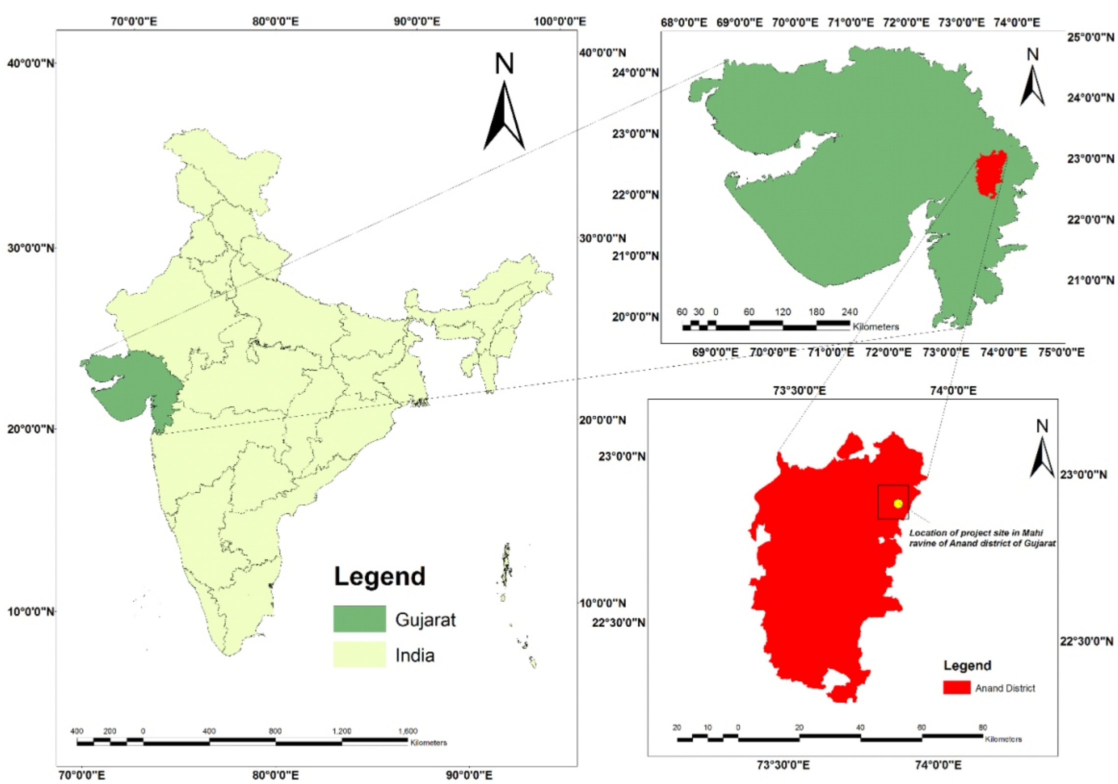

FIGURE 1 Location of project site in Mahi ravine of Anand District, Gujarat

average annual temperature of 25.4°C and mean annual rainfall of 850 mm. The monsoon season (July-September) accounts for nearly 90% of the annual precipitation. During the study period, notable climatic variations were observed, with exceptionally high rainfall in 2013 (1611 mm) and drought conditions in 2015 (475 mm). Average monthly temperatures ranged from 17.4°C in January to 33.5°C in May (Singh *et al.,* 2019).

Soils in the area are predominantly alluvial, derived from sediment deposition by the Mahi River. According to soil survey staff (2014), the soils are classified as fine-loamy, mixed calcareous, hyperthermic fluventic ustochrepts (Inceptisols). The topsoil is mostly sandy loam, interspersed with calcareous patches, and is deep, well-drained, and moderately fertile. Due to low water-holding capacity, effective moisture conservation practices are essential for sustainable cultivation. Soil pH ranges from 7.5 to 8.5, indicating slightly to moderately alkaline conditions. Available nitrogen levels are low (<280 kg ha^{-1}), while organic carbon content ranges between 0.4% and 0.6%, indicating low to moderate fertility. In contrast, phosphorus levels are moderate (25-50 kg ha^{-1}), and potassium levels are high (>300 kg ha^{-1}), providing a favourable nutrient base for diversified cropping systems when supplemented with appropriate conservation measures.

2.2 | Treatment details and experiment layout

Field treatments were initiated in 2010 on a 14% slope of ravine land along the mahi river using five treatments: (i) Cowpea + Castor on bench terraces (CCBT), (ii) Sapota + Cowpea + Castor on bench terraces (SCCBT), (iii) Sapota on bench terraces (SBT), (iv) Sapota with staggered trenches on slope (SSTS), and (v) Sapota on slope without treatment (SS – control). Each treatment was implemented on a 72 m × 24 m plot. Bench terrace plots were subdivided into three terraces to reduce slope length, while two plots remained at the original 14% slope - one with staggered trenches (96 trenches of 2 × 0.5 × 0.5 m) and one as control. Tree spacing was 8 m × 8 m, with cowpea and castor intercropped in a 2:1 ratio at 0.3 m line spacing, following local agronomic practices. The experimental layout of the study in ravine slope of mahi river in gujarat is shown in *Fig. 2*. Data on plant growth, yield, runoff, and soil loss were collected from 2010 to 2022 under a randomized block design with four replications, though runoff and soil loss were monitored in only one replication.

2.3 | Sapota Plantation and Crop Cultivation

The six-month-old sapota (*Achras zapota*) seedlings were planted in each of the four treatments in March 2010 in uniform numbers (27 per treatment) with an 8 m x 8 m spacing. Standard practices were followed to sustain sapota growth and productivity. To assess the effects of crop cultivation and tillage practices on runoff, soil loss, and tree growth, Castor (*Ricinus communis*) and Cowpea (*Vigna unguiculata*) crops were grown alongside sapota in the SCCBT treatment. Every year, the crops were produced in a ratio of 1 (Castor) to 2 (Cowpea), using conventional tillage

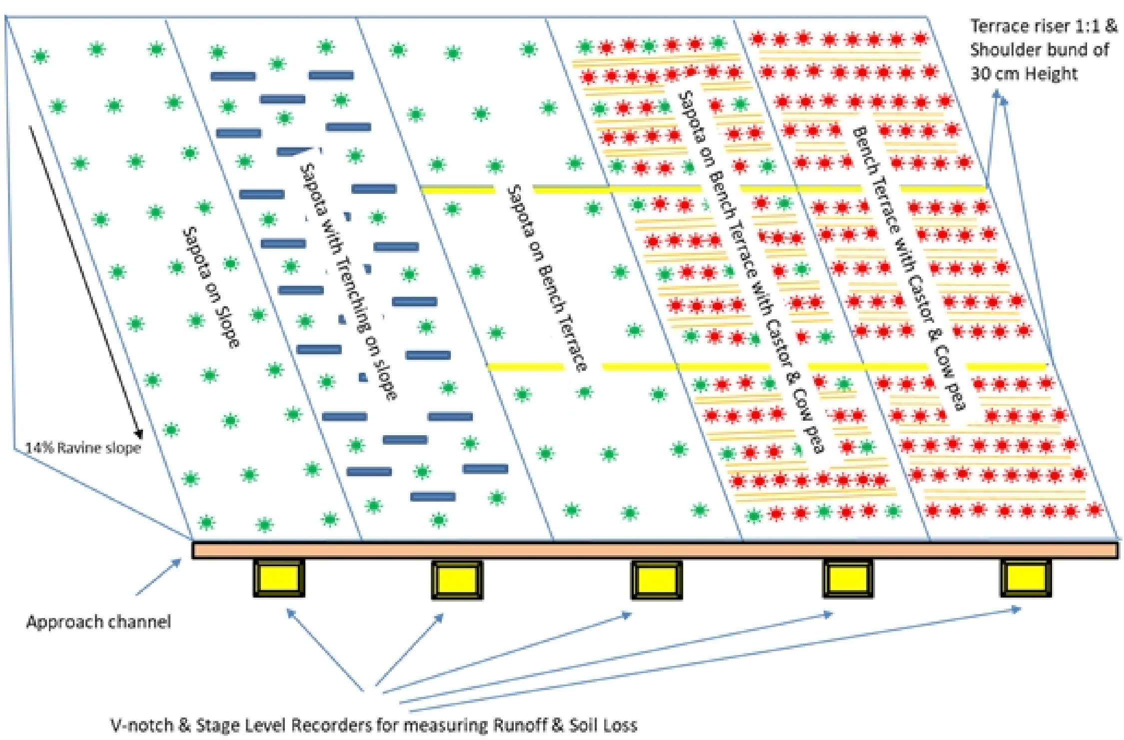

FIGURE 2 Experiment layout of the study in ravine slope of Mahi river in Gujarat

with a power tiller, following the standard agronomic techniques recommended for crop cultivation. Eight trees per treatment (two per replication) were chosen randomly and assessed every three months from 2010 to 2022 to evaluate sapota productivity and growth. The standard methods outlined by Jinger et al. (2024) were utilized to measure the sampled trees' basal diameter, total tree height, crown width, and fruit output.

2.4 | Runoff and Soil Loss Measurements

To monitor runoff and soil loss in each treatment, each plot's outlet was equipped with a stage level recorder and a V-notch to quantify runoff and soil loss, respectively. During every rainy event between 2010 and 2022, sediment samples were taken at each plot's outflow. The samples were then examined in a lab to ascertain the amount of sediment and soil loss (Meena *et al.,* 2023). By following the method used by Ali *et al.* (2020), runoff was measured from the charts fixed in the stage level recorders. The runoff coefficient, expressed as a percentage, was calculated as the ratio of runoff to precipitation. Runoff and air-dried sediment samples were analysed to determine the concentration of N, P, K, and organic carbon (OC) in the runoff water using standard laboratory methods (e.g., colourimetry for P, Kjeldahl for N, flame photometry for K, and Walkley-Black for OC).

2.5 | Water use efficiency (WUE)

The WUE is expressed as the amount of sapota yield or sapota equivalent yield produced per unit of water used by the crop and calculated as:

$$\text{WUE} = \frac{\text{Sapota Equivalent Yield } (\frac{\text{kg}}{\text{ha}})}{\text{Seasonal Rainfall (mm)}}$$

2.6 | Statistical analysis

To assess the effects of different agroforestry and bioengineering treatments, statistical analyses were conducted on the observed parameters, including runoff, soil loss, rainwater use efficiency (RWUE), post-harvest soil moisture, and crop yields. A one-way analysis of variance (ANOVA) was employed to evaluate the significance of treatment differences for parameters with replicated observations (e.g., crop and tree yield components), using a randomized block design. For runoff and soil loss, which were recorded from a single replication due to logistical constraints, the data across multiple years (2010-2022) were treated as repeated observations. Repeated measures analysis was used to estimate the error variance and assess year-wise variability, treating year as the replication unit. A correlation matrix was developed to examine the interrelationships among key variables such as rainfall, runoff, soil loss, RWUE, and yield attributes. To visualize treatment effects and variability in key parameters, box plots were generated for runoff, soil loss, RWUE, and post-harvest soil moisture content. All statistical analyses were performed using standard procedures, with significance evaluated at $p \leq 0.05$ unless otherwise stated.

3 | RESULTS AND DISCUSSION

3.1 | Agronomic Performance & System Productivity

The integration of sapota with cowpea and castor on bench terraces (SCCBT) consistently outperformed other treatments across agronomic, environmental, and economic indicators (Table 1). SCCBT recorded the highest tree height (4.58 m), stem diameter (13.06 cm), fruit count per plant (269), and sapota yield (3672 kg ha^{-1}), reflecting enhanced vegetative and reproductive performance. The sapota equivalent yield (SEY) was highest in SCCBT (3953 kg ha^{-1}), highlighting the advantage of intercropping over monocropping on slopes (SS), which showed the lowest values across parameters.

This improvement is attributed to enhanced soil moisture and nutrient cycling due to diversified cropping and better soil structure. The highest canopy spread in SCCBT (EW: 4.80 m; NS: 4.65 m) also facilitated better microclimatic conditions and intercrop compatibility. These findings align with earlier reports (Kumar *et al.,* 2021a; Jinger *et al.,* 2022).

3.2 | Crop and System Productivity

CCBT and SCCBT yielded 720 and 450 kg ha^{-1} of cowpea and 1500 and 1200 kg ha^{-1} of castor, respectively. Grass yields were highest in SBT (13.51 t ha^{-1}), followed by SSTS and SS. The highest crop equivalent yield (SEY) and rainwater use (781 mm) were recorded in SCCBT, driven by

TABLE 1 Growth parameters of sapota plants (Kalipatti) in different bio-engineering measures

Treatments	Tree height (m)	Stem Dia (cm)	Fruits / Plant	Sapota Yield (kg ha^{-1})	Sapota Equivalent Yield (kg ha^{-1})
CCBT	...	...	...	...	2204 ± 107b
SCCBT	4.58 ± 0.22a	13.06 ± 0.45a	269 ± 12a	3672 ± 255a	3953 ± 231a
SBT	3.24 ± 0.20b	8.76 ± 0.52b	164 ± 11b	3133 ± 196b	2143 ± 196c
SSTS	3.27 ± 0.20b	7.67 ± 0.54c	136 ±8c	2790 ± 168c	1928 ± 185d
SS	2.91 ± 0.21c	7.71 ± 0.50c	122 ± 6d	2368 ± 131d	1674 ± 165e

CCBT- Cowpea + Castor on bench terraces, SCCBT-Sapota + Cowpea + Castor on bench terraces, SBT-Sapota alone on bench terraces, SSTS - Sapota + Staggered trench on slope, and SS - Sapota alone on slope.

optimized use of rainfall and cropping intensity. Water use efficiency peaked at 6.54 kg ha^{-1}mm^{-1} in SCCBT, significantly surpassing all other treatments (Table 1, *Fig. 3*).

3.3 | Resource Conservation and Rainwater Use Efficiency

SCCBT achieved the highest energy use efficiency (361.92%), lowest runoff (96.82 mm), and substantial reduction in soil loss (9.27 t ha^{-1}yr^{-1}). Improved infiltration due to terracing and intercrop biomass input improved rainwater utilization and moisture conservation. Conversely, monocropping on slopes (SS) showed the highest runoff (334.07 mm) and one of the highest soil losses (10.25 t ha^{-1}yr^{-1}), indicating poor resource conservation (Table 2, Fig. 4). Although SBT exhibited the lowest soil loss (8.24 t ha^{-1}yr^{-1}), its limited system productivity and moderate runoff reduction make SCCBT the more balanced option for ravine land restoration. These trends match the observations reported by Jinger *et al.* (2022).

3.4 | Soil Nutrients and Moisture Dynamics

Nutrient loss through runoff varied significantly across treatments (Table 3). The CCBT treatment, though without sapota, exhibited the highest loss of N (7.71 kg ha^{-1}), P (1.63 kg ha^{-1}), K (8.38 kg ha^{-1}), and organic carbon (108.17 kg ha^{-1}), likely due to intensive tillage and fertilization. SCCBT showed moderate nutrient loss but retained higher soil organic carbon (86.07 kg ha^{-1}) and post-harvest soil moisture (14.17%). SBT and SSTS had better moisture at 0-15 cm due to trenching and terracing, while CCBT and SCCBT had higher moisture at 15-30 cm, reflecting soil loosening from tillage and organic matter accumulation. At 30-45 cm, moisture content equalized across treatments due to minimal disturbance at depth. SCCBT produced the highest litter fall (252 kg ha^{-1}) from sapota trees, with additional biomass from intercrops contributing 52-70 kg ha^{-1}. The increased canopy also improved rainfall interception, reducing kinetic energy and enhancing infiltration, thereby reducing runoff and soil erosion.

3.5 | Correlation Analysis

The correlation matrix (Table 4) revealed strong negative associations between runoff, soil loss, and system productivity, underscoring the detrimental effects of unchecked erosion on yield. Organic carbon also showed inverse relationships with yield, suggesting a trade-off between long-term soil health and short-term productivity in some systems. Notably, treatments enhancing water retention and nutrient cycling (e.g., SCCBT) balanced these trade-offs effectively. Phosphorus and potassium losses correlated negatively with hydrological parameters, indicating nutrient leaching under poor management.

TABLE 2 Mean runoff, soil loss, energy use efficiency, water use efficiency and net returns in different bio-engineering measures

Treatments	Runoff (mm)	Soil Loss (t ha^{-1}yr^{-1})	Energy use efficiency (%)	Water use efficiency (kg ha^{-1}mm^{-1})	Net Return (₹ ha^{-1}yr^{-1})
CCBT	143.73±12.94d	10.33± 0.19a	327.00±4.61b	3.20 ±1.14e	9880.76±1645.83e
SCCBT	96.82 ±10.75e	9.27±0.18b	361.92 ±6.45a	6.54 ±3.40a	41725.99±1677.87a
SBT	174.22±12.50c	8.24±0.19c	183.92 ±5.54c	4.21 ±2.95b	28679.07±1325.38b
SSTS	234.52±18.65b	9.32±0.20b	163.84 ±4.19d	4.13 ±3.01c	25467.30±1313.41d
SS	334.07±21.71a	10.25±0.22a	137.30 ±3.83e	3.83 ±2.82d	26871.53±4147.19c

CCBT- Cowpea + Castor on bench terraces, SCCBT-Sapota + Cowpea + Castor on bench terraces, SBT-Sapota alone on bench terraces, SSTS - Sapota + Staggered trench on slope, and SS - Sapota alone on slope.

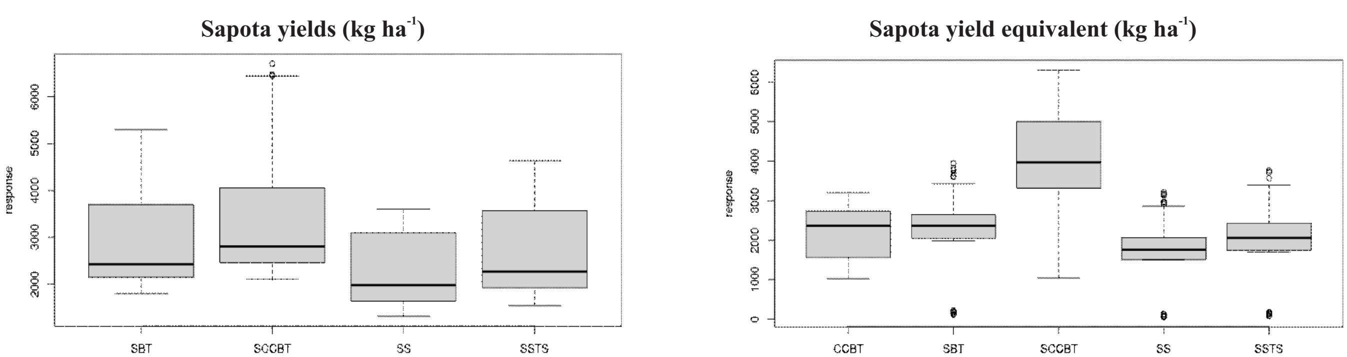

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FIGURE 3 Sapota yields and Sapota yield equivalent (kg ha^{-1}) on ravine slopes treated with different bio-engineering measures

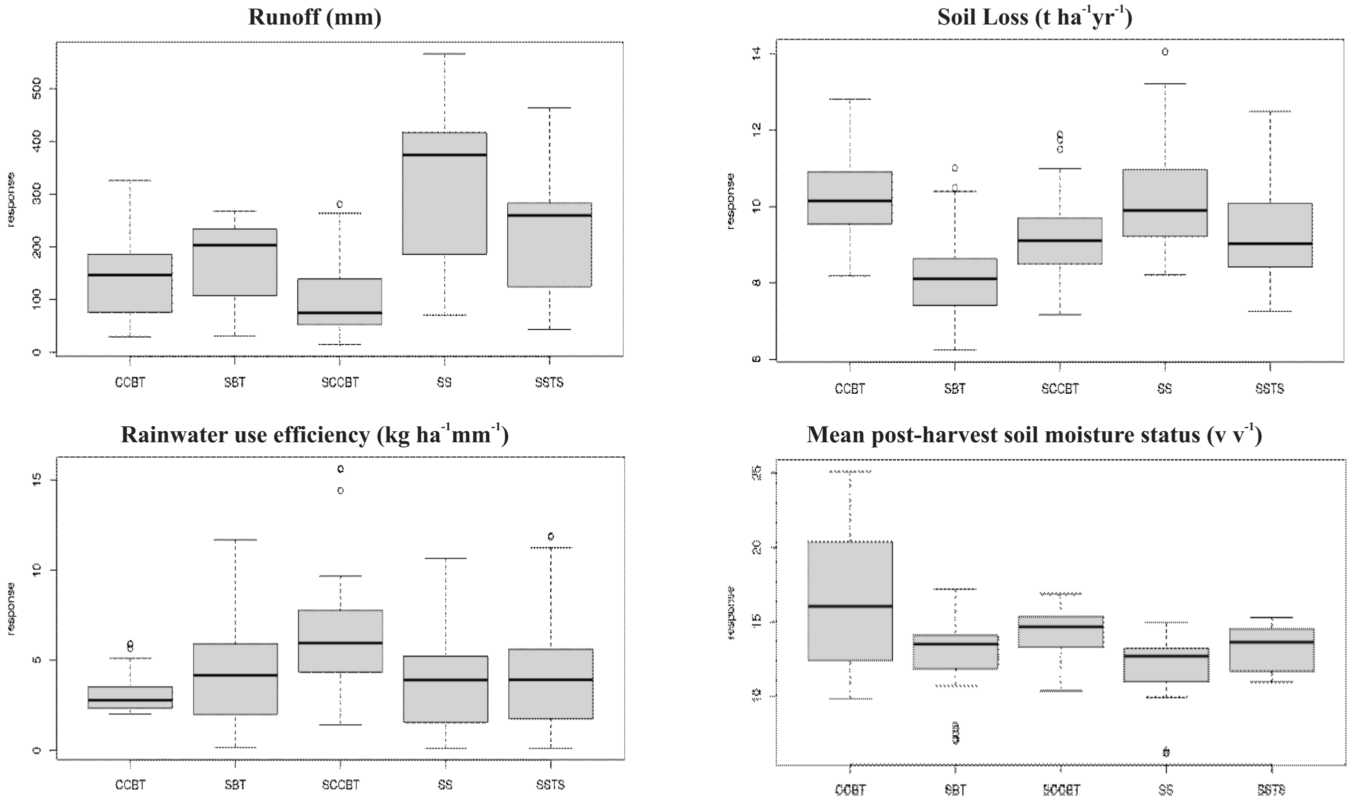

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FIGURE 4 Runoff, Soil loss, Rainwater use efficiency and post-harvest soil moisture under different bio-engineering measures

TABLE 3 Mean nutrient loss (kg ha^{-1}) through runoff and mean soil moisture (v v^{-1}) in different bio-engineering measures

Treatments	N	P	K	OC	SM
CCBT	7.71±0.12a	1.63 ±0.05a	8.38±0.07a	108.17±1.56a	16.50±0.75a
SCCBT	4.88±0.13b	1.38±0.05c	5.62±0.05c	86.07±1.50b	14.17±0.29b
SBT	2.71±0.04e	1.36±0.06cd	4.66±0.06e	39.73±0.55e	12.71±0.43d
SSTS	3.36±0.02d	1.47±0.06b	4.79±0.06d	65.88±0.69d	13.24±0.22c
SS	3.51±0.03c	1.35±0.07d	5.71±0.05b	76.22±0.87c	11.93±0.33e

CCBT- Cowpea + Castor on bench terraces, SCCBT-Sapota + Cowpea + Castor on bench terraces, SBT-Sapota alone on bench terraces, SSTS - Sapota + Staggered trench on slope, and SS - Sapota alone on slope.

3.6 | Net Returns from Different Bio-Engineering Measures in Ravine Land

The annual cost of each treatment was estimated by summing the costs of seed, fertilizers (as per regional recommendations), labor, agrochemicals, diesel for mechanized operations, and implementation of soil and water conservation structures. Among all treatments, the *Sapota + Castor + Cowpea on Bench Terrace* (SCCBT) system provided the highest net return of ₹ 41,726 ha yr^{-1}, followed by *Sapota on Bench Terrace* (SBT) at ₹ 28,679 ha^{-1} and *Sapota on Slope* (SS) at ₹ 26,871 ha^{-1} (Table 2). These findings are consistent with those reported by Jinger *et al.* (2023). The annual return included yields from intercrops (castor and cowpea), naturally growing grasses in non-intercropped treatments, and sapota fruit harvested from the third year onward. These results indicate that integrating high-value annual crops and fruit trees on bench terraces significantly enhances economic viability on ravine lands.

4 | CONCLUSIONS

The findings of this long-term study highlight that the unchecked expansion of ravine lands is primarily a consequence of unsustainable agricultural practices on marginal lands, particularly the cultivation of annual crops without suitable soil and water conservation measures. Sole cropping

TABLE 4 Correlation matrix of observed parameters in different bio-engineering measures

	Q (mm)	R	S (t $ha^{-1}yr^{-1}$)	CEY (kg ha^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	OC (kg ha^{-1})
Q (mm)	1.00							
R	0.79	1.00						
S (t/ha)	0.77	0.77	1.00					
CEY (kg/ha)	-0.90	-0.93	-0.93	1.00				
N (kg/ha)	-0.40	-0.17	-0.03	0.20	1.00			
P (kg/ha)	-0.01	-0.62	-0.24	-0.36	0.16	1.00		
K (kg/ha)	-0.57	-0.27	0.09	-0.22	-0.67	-0.25	1.00	
OC (kg/ha)	-0.87	-0.89	-0.96	-0.98	-0.03	0.31	0.13	1.00

Q is Runoff in mm, R is Runoff coefficient, S is Soil loss in t $ha^{-1}yr^{-1}$, CEY is Sapota yield equivalent in kg ha^{-1}, N is Nitrogen in kg/ha, P is Phosphorus in kg ha^{-1}, K is Potassium in kg ha^{-1}, OC is Organic Carbon in kg ha^{-1}.

on slopes accelerates erosion and land degradation, thereby contributing to the advancement of ravines into adjacent cultivable areas. The integrated use of soil conservation engineering interventions, such as bench terracing, in combination with agroforestry systems that include perennial fruit trees and compatible intercrops, proved to be a more sustainable approach for ravine land rehabilitation.

Among all the bio-engineering treatments evaluated, the Sapota + Castor + Cowpea on Bench Terrace (SCCBT) system demonstrated superior economic returns, crop productivity, and ecological stability. It achieved the highest net returns and fruit yields while significantly reducing soil loss and surface runoff. The SCCBT system also enhanced energy use efficiency, water use efficiency, and carbon sequestration, underscoring its potential to serve both as a productive land-use strategy and a climate change mitigation measure.

Despite these promising outcomes, several research gaps persist. The long-term effects of agroforestry systems on soil health dynamics, particularly beyond a decade of implementation, are not fully understood. Additionally, the nutrient and water interactions between sapota and intercrops under different slope gradients require further investigation. Socio-economic factors, such as farmers' willingness to adopt these systems, access to capital and markets, and institutional support, also merit deeper study. Moreover, the potential inclusion of native or drought-resilient multipurpose tree species in similar systems could enhance biodiversity and reduce input requirements, but this aspect remains underexplored.

The evidence generated from this study provides a strong foundation for scaling up sapota-based agroforestry systems in ravine-prone regions such as the Mahi ravines of Gujarat. With appropriate policy support, including integration into existing watershed development and rural employment schemes, these systems can be widely adopted. Upscaling efforts should also prioritize capacity building, access to planting material, and financial incentives for initial establishment. Overall, sapota-based agroforestry on engineered landforms offers a replicable and resilient model for sustainable ravine land management, combining ecological restoration with improved livelihoods and long-term productivity.

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DATA AVAILABILITY

The data related to the manuscript is available with ICAR-Indian Institute of Soil and Water Conservation, Research Centre-Vasad, District-Anand, Gujarat.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript. All authors have approved the manuscript and agree with its submission to the Indian Journal of Soil Conservation. The authors confirm that this manuscript is an original work and has not been published previously or under consideration for publication elsewhere.

AUTHOR'S CONTRIBUTION

GS: Conceptualization, data curation, formal analysis, investigation, methodology, writing - original draft; DD: Writing - original draft, Conceptualization, data curation, formal analysis, investigation; DJ: Writing - original draft, Conceptualization, data curation, formal analysis, investi-gation; RK: Writing - original draft, Conceptualization, data curation, formal analysis, investigation; VDK: Writing-original draft, Conceptualization, data curation, formal analysis, investigation; BKR: Writing - review and editing, conceptualization, formal analysis, SKK: Writing-review and editing, conceptualization, formal analysis, NKN: Writing-review and editing, Conceptualization, data curation, formal analysis, investigation; AKS: Writing - review and editing, MJK: Writing-review and editing, MM: Project administration, resources, software, supervision.

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