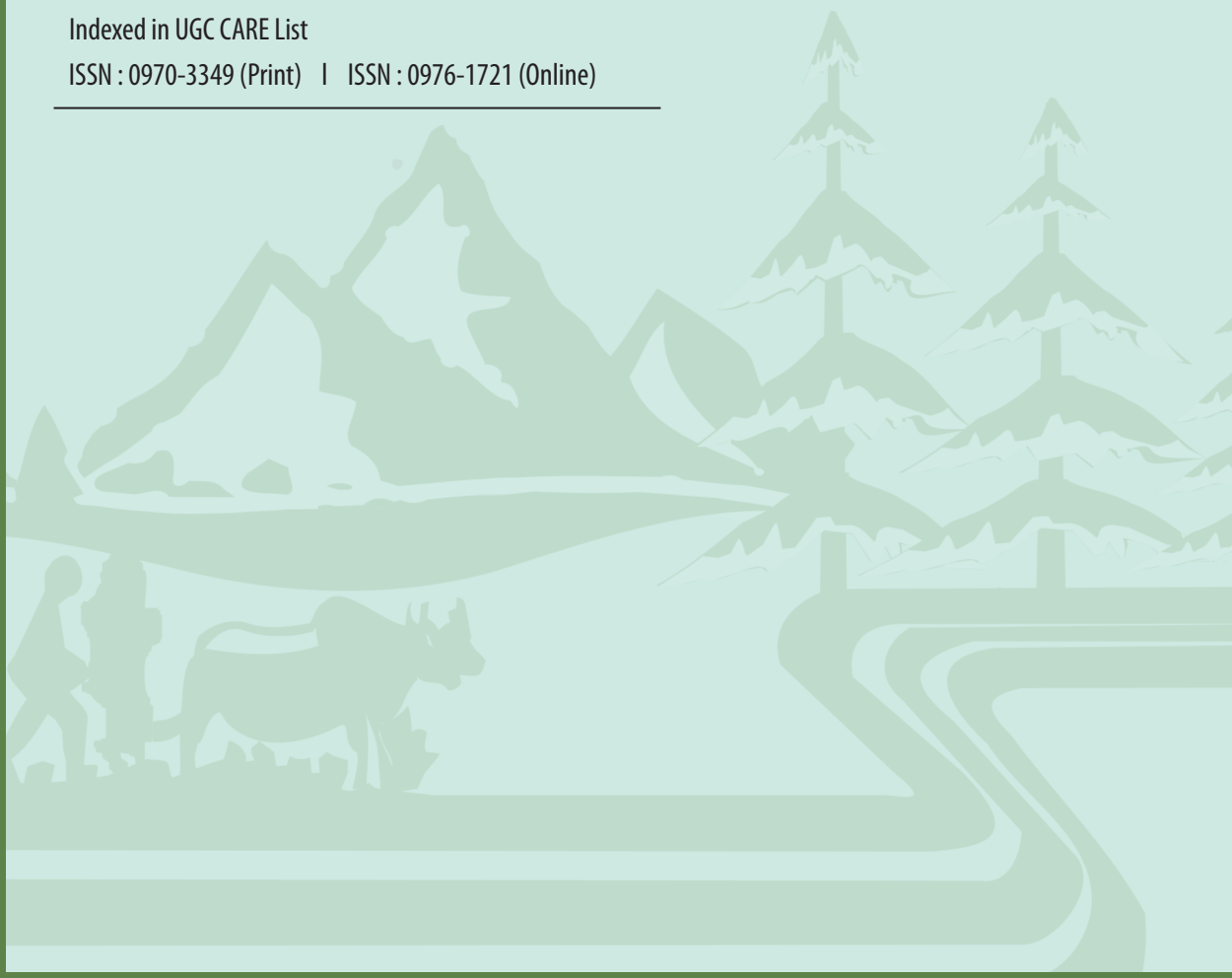
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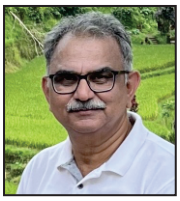
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CONTENTS

Morphometric Analysis-based Prioritization of Sub-watersheds for Conservation Planning in Purna River Basin, Maharashtra 89
Gayatri Wani, Pranita Mhaiske, S.A. Chaware, Ch. Jyotiprava Dash, Sirisha Adamala, M.R. More, P. Pakhare and H. Biswas

Groundwater Quality Assessment for Sustainable Water Management in Semi-Arid Chitradurga District, Karnataka 103
M. Chandrakala, Ranabir Chakraborty, Gizachew Ayalew Tiruneh, Shreyasi Gupta Choudhury, Parvathy S, S. Harshithareddy, M.V. Parvathi and Ramamurthy V.

Optimum Designing and Field Validation of a Multi-Objective Integrated Farming System in Indian North-Western Himalayas 117
Pradeep Dogra, Avinash Chandra Rathore, Sridhar Patra, Muthiah Muruganandam and Narinder Kumar Sharma

Sustainable Intensification of Rice-Fallow Areas through Strategic Crop Selection and Fertilizer Management in Lower Indo-Gangetic Plains 132
Chandan Baskey, Sarbajoya Goswami, Ramyajit Mondal, Sanjib Kumar Mandi and SB Goswami

Biomass and Nutrient Accumulation of Green Manure Species in Humid Tropical Subsistence Cropping Systems of Papua New Guinea 142
Paula Kaupa and Rajashekhar Rao Bangady Killur

Optimizing Soilless Growing Media for Red Amaranthus (*Amaranthus tricolor*) Production 150
Rohith P, Shavitha Sri, V., Ruban Kumar, D., Adithya, I., Elakiya, N

Potential Grass Species for Soil Conservation and Fodder Production in the Nilgiri Hills of the Western Ghats 162
K. Kannan, C.Babu, P. Sundarambal, K. Rajan and P. Raja

Economic Viability of Underground Pipeline Irrigation System Projects in Punjab: Evidences from Randomized Control Trails 170
Pankaj Panwar, Sharmistha Pal, Pradeep Dogra, OP Premi, Manoj Kumar and OPS Khola

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Study the Socio-Economic Dynamics of Farming Communities Practicing Agroforestry in upstream Catchment area of Gobind Sagar Reservoir 179
S. Sarvade, B. Gupta, D.R. Bhardwaj, Prem Prakash, Dhirender Kumar, Chaman Lal and Prashant Sharma

Short Communications

Efficacy of Foliar Nutrient Applications on Growth, Yield and Economics of Mung Bean (*Vigna radiata L.*) under Hot Arid Conditions of Rajasthan 189
Rohitash Bajiya

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ORIGINAL ARTICLE

Indian Journal of Soil Conservation

Morphometric Analysis-based Prioritization of Sub-watersheds for Conservation Planning in Purna River Basin, Maharashtra

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ABSTRACT

Watershed studies provide a critical framework for understanding hydrological responses to environmental and developmental activities, enabling effective planning for resource optimization. This study focuses on prioritizing sub-watersheds according to their vulnerability to soil erosion, based on morphometric, topographic-hydrological parameters, land use, and land cover in the Purna River basin of the Marathwada region, Maharashtra, India. The Purna basin is of 7th order and contains 22 sub-watersheds (SW). The slope in the study area ranges from 0 to 117%. The mean bifurcation ratio values for various sub-watersheds in the river basin range from 1.96 (SW-22) to 5.98 (SW-13). The drainage density values of sub-watersheds in the Purna river basin vary from 0.78 (SW-13) to 0.92 km/km² (SW-22), reflecting the presence of poor and coarse drainage texture. The channel maintenance constant shows that, on average, 1.20 km² of basin area is required to develop and maintain a 1 km long stream channel. The prioritization indicates that SW-13 (Cp=3.91), SW-5 (Cp=4.10), and SW-16 (Cp=4.79) are high-priority sub-watersheds needing structural interventions (check dams, contour bunding) and vegetative measures based on their elevated bifurcation ratios (>4.17), low drainage density (<0.81 km/km²), and intensive agricultural land use (>85%). Since the prioritization relies solely on GIS-based DEM-derived empirical models and land use and land cover analysis, it can serve as an initial framework for resource allocation. These rankings should be viewed as indicative rather than definitive. Consequently, the operational implementation of this prioritization should involve a comprehensive validation process to align model predictions with field conditions and long-term watershed management goals.

1 | INTRODUCTION

The expansion in urbanization, industrial, and agricultural sectors, driven by a high population, along with climate change, has created tremendous pressure on land and water resources, leading to land degradation. Soil erosion is one of the most prominent forms of land degradation. In India, soil erosion due to water and wind affects approximately 71% of the total geographic area of the country. Being an agrarian country, India needs sustainable land and water management for its food and nutritional security. Sustainable use of land and water is even more important in semi-arid regions, as this ecology faces constraints due to water availability and high evaporative demand. Hence, in a semi-arid environment, watershed management has been proven to be one of the best approaches for natural resource management. Numerous researchers have emphasized the importance of prioritizing sub-watersheds for effective planning and implementation of appropriate conservation measures, as it aids in identifying vulnerable areas and enhancing the overall impact of watershed management efforts (Ahirwar *et al*., 2019; Dahipale *et al.,* 2022; Fenta *et al*., 2024; Sekhar and Mathew, 2022).

The weighted sum analysis (WSA) method is one of the most efficient for prioritizing sub-watersheds in ungauged or data-scarce regions (Adam *et al*., 2024). It uses only the digital elevation model (DEM) to compute various morphometric parameters of sub-watersheds for their prioritization. Morphometric parameters describe the shape, configuration, and dimensions of a watershed (Strahler, 1964), and their measurement and characterization are carried out through morphometric analysis (Adhikary and Dash, 2018). The integration of topo-hydrological indices such as the Sediment Transport Index (STI), Stream Power Index (SPI), and Topographic Wetness Index (TWI) helped

to clarify the watershed hydrological behavior (Singh and Singh, 2022). Both topo-hydrological and morphometric features are generated using Geographic Information Systems (GIS) platforms to analyse terrain features, which in turn help in understanding erosion patterns, predicting flood-prone areas, and assessing the overall hydrological response of a landscape (Sanchez and Alvarez, 2024).

While morphometric analysis has been applied globally, the Purna River basin, Maharashtra, characterized by erratic monsoon rainfall (750-900 mm), frequent droughts, black cotton soils with poor drainage, and intensive cotton-sorghum agriculture, presents a unique hydrogeological setting. Previous studies on Purna tributaries (Ingle, 2022; Chaudhari *et al*., 2023) conducted only basic morphometric analysis without integrating topo-hydrological indices or LULC dynamics. The present study aims to integrate morphometric parameters with topo-hydrological indices (TWI, SPI, and STI) and high-resolution (10 m) land use and land cover (LULC) data for comprehensive sub-watershed prioritization across the entire Purna River basin. The integration of these datasets will enable assessment of erosion susceptibility, hydrological response, and sediment transport potential, providing a replicable framework for watershed management and conservation planning in data-scarce semi-arid regions.

HIGHLIGHTS

- Integration of morphometric parameters with topo hydrological and land use land cover analysis allowed for a comprehensive assessment of watershed condition.
- Novel integration of topo-hydrological indices (TWI, SPI, STI) with high-resolution LULC data provides a replicable framework for data-scarce semi-arid regions.
- Positive Stream Power Index values (4.85-5.49) coupled with 86 % agricultural dominance indicate high basin-wide erosion susceptibility in Marathwada's drought-prone landscape.

2 | MATERIALS AND METHODS

2.1 | Study Area

The Purna river basin is a major tributary of the Godavari river and flows from north to southeast , covering an area of 15,864.2 km². The basin lies between latitudes 19° 11' 08.43" to 20° 24' 51.41" N and longitudes 75°13' 33.41" to 77° 00' 2.61" E in Maharashtra, India (*Fig.1*). The river originates in the Ajanta hill range. The basin outlet is located just before the Purna river merges with the Godavari near Purna village. The elevation of the study area ranges between 361 to 933 m. The region experiences a tropical climate with three distinct seasons: winter (November to February), summer (March to May), and southwest monsoon season (June to September). The annual rainfall ranges between 750 and 900 mm, and is predominantly received during the south-west monsoon. The average rainy days are of 65 days. The mean minimum temperature is 13 °C, whereas the mean maximum temperature is 39.8 °C. The study area is characterized by diverse soil types and geomorphological features shaped by its semi-arid climate and Deccan plateau geology. The predominant soil type is black cotton soil, derived from basaltic parent material, which is highly fertile but has poor drainage and shrink-swell properties. Other soil types, such as red soils and laterites, are found on elevated terrains, often associated with weathered and eroded landforms. Geomorphologically, the region features undulating plains, isolated hills, and river valleys, with the Purna river and its tributaries playing a crucial role in shaping the landscape. The cropping pattern in the area is influenced mainly by its semi-arid climatic conditions, soil types, and irrigation availability. Major crops include cotton (*Gossypium hirsutum*), sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), pigeon pea (*Cajanus cajan*), and chick pea (*Cicer arietinum*). Additionally, a few horticultural crops, such as pomegranate and mango, are extensively cultivated. In irrigated areas, sugarcane (*Saccharum officinarum*) and wheat (*Triticum aestivum*) are also cultivated. The cropping pattern exhibits seasonal variability, with rainy season crops dominating due to reliance on rainfall, and limited winter season crops grown in regions with assured irrigation facilities. Overall, it's cropping pattern highlights the interplay of agro-climatic factors and the resourcefulness of farmers adapting to challenging environmental conditions.

2.2 | Data Source and Pre-Processing of Data

In this study, the Shuttle Radar Topography Mission (SRTM) DEM from the United States Geological Survey (USGS) Earth Explorer, with a resolution of 30 m, was used to delineate the Purna river basin and its sub-watersheds. The SRTM DEM (30 m resolution) was selected because: (i) it provides consistent global coverage essential for large basin analysis (15,864 km²), (ii) it's 30 m resolution adequately captures terrain variability in gently undulating Deccan plateau topography (slope ranges 0 to 117%, with a mean value of 5%), and (iii) previous validation studies for basaltic terrain of Central India show SRTM vertical accuracy of less than 10 m, suitable for drainage network delineation (Zade *et al.*, 2022). The processing of DEM was done with a sequence of operations such as fill, flow direction, flow accumulation, stream definition, stream to feature, along with stream outlet point and sub-watersheds delineation. Google Earth Pro based satellite data was utilized to support watershed delineation, locating outlet, verify stream networks and other terrain features. ArcGIS software (version 10.7.1), along with the ArcSWAT extension, was employed to delineate the watershed and extract relevant parameters for geospatial analysis. Further, the WSA was conducted to assess and prioritize the sub-watersheds.

To ensure reliability of morphometric parameters, SRTM DEM elevation values were validated against: (i) Survey of India topographic sheets (1:50,000 scale) at 50

reference points distributed across elevation gradients, and (ii) 25 ground control points collected using Differential GPS (DGPS) with vertical accuracy of ±0.5 m. The root mean square error (RMSE) was calculated as:

$$RMSE = \sqrt{[\Sigma(ZDEM - ZGPS)^2/n]}$$

Where ZDEM is DEM elevation, ZGPS is reference elevation, and n is number of points.

2.3| Morphometric and Topo-hydrological parameters

The two sets of factors, including morphometric and topographic-hydrological factors, were computed for all sub-watersheds using an integrated approach involving Remote Sensing (RS) and Geographic Information Systems (GIS). High-resolution satellite imagery and SRTM DEM datasets were used to delineate sub-watershed boundaries and extract the drainage network. Sub-watershed delineation followed a systematic workflow: (1) DEM conditioning through sink filling (depth threshold: 5 m), (2) flow direction computation using D8 algorithm, (3) flow accumulation with minimum threshold of 500 cells (45 ha) to define channel initiation, (4) stream network extraction and ordering following Strahler's method, (5) outlet point placement at coordinates (77° 01' 34.07" E and 19° 6' 55.49" N) before Purna-Godavari confluence, and (6) automated watershed segmentation using ArcSWAT's watershed delineator tool. The 45 ha threshold was selected based on Google Earth validation to match observable drainage channels in the field. Morphometric factors include a) linear parameters [stream order (So), bifurcation ratio (Rb)], b) areal parameters [stream frequency (Fs), drainage density (Dd), drainage texture (Dt), constant channel maintenance (Cm), compactness coefficient (Cc)] and c) relief parameters [form factor (Rf), circularity ratio (Rc), elongation ratio (Re)], whereas TWI, STI and SPI were estimated as topo-hydrological parameters. The formula or equations used for the calculation of these parameters are presented in Table 1. The present approach to prioritizing the sub-watersheds allows for a detailed characterization of the watershed's topography and hydrological behavior, facilitating improved understanding of runoff processes, erosion potential, and watershed management strategies (*Fig.2*).

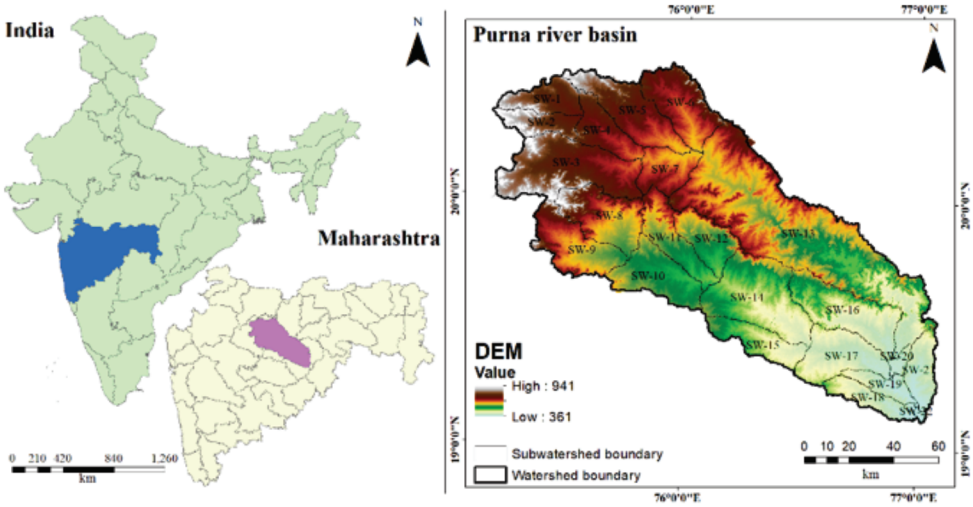


FIGURE 1 Map showing the study area with its elevation and sub-watersheds

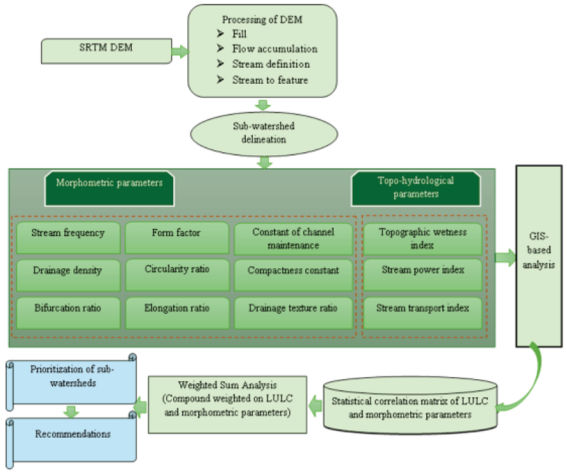


FIGURE 2 Flow chart showing process followed for prioritizing sub-watersheds

TABLE 1 Equation/formula used morphometric and topo-hydrological parameters computation

Sl. No	Parameters	Defination/formula	Reference
1	Dt, per km	Dt=Nu/P; Ratio of total stream number of all orders and basin perimeter (P)	Horton, 1945
2	Rc	$Rc=4\pi A/P^2$; Ratio of basin area to the area of a circle having the same perimeter as that of basin	Miller, 1953
3	Re	$Re= 2(A/\pi)^{0.5}/Lb$; Ratio between the diameter of a circle having same area as that of basin and the maximum basin length	Schumm, 1956
4	Cc	$Cc= P/2\times(\pi A)^{0.5}$; Ratio of perimeter of the watershed to the circumference of circle having same area as that of the watershed	Gravelius, 1914
5	Cm, km^2/km	Cm=1/Dd; Reciprocal of drainage density	Schumm,1956
6	TWI	$TWI=\ln(As/\tan\beta)$; As is the local upslope area draining through a certain point per unit contour length and $\tan\beta$ is the local slope	Beven, 1986
7	SPI	$SPI=As\times\tan\beta$	Rahmati *et al*., 2019
8	STI	$STI = (m+1) \times (As/22.13m) \times (\sin\beta/0{:}0896^n)$; where b is the local slope gradient in degrees, m is the contributing area exponent, and n is the slope exponent	Ahmad *et al*., 2019

*Other parameters include Rb, Dd, Fs, and Rf as per their standard definition (Horton, 1932; Strahler, 1964)

2.4| Land Use & Land Cover (LULC)

The LULC analysis for each sub-watershed of the study area was carried out using ESRI open-source data with a resolution of 10 m for the year 2024. Each sub-watershed was classified into six LULC categories, namely forest, open scrub, agriculture, water bodies, habitation, and wasteland. LULC classification accuracy was assessed using 150 randomly distributed validation points (25 points per class) generated through stratified random sampling. Reference data were collected from: (i) Google Earth Pro high-resolution imagery (2024), (ii) field photographs from 35 accessible locations, and (iii) the BHUVAN portal imagery. A confusion matrix was constructed, and overall accuracy, producer's accuracy, user's accuracy, and Kappa coefficient were calculated. The overall accuracy of 87.3% and the Kappa coefficient of 0.83 indicated substantial agreement, meeting USGS Level II classification standards.

2.5| Correlation Analysis

Inter-parameter correlation analysis was conducted to identify redundant variables and understand parameter interactions. The weighting scheme was based on (i) established erosion-parameter relationships from literature (Rahmati *et al.,* 2019; Sekhar and Mathew, 2022), (ii) correlation strength among parameters (*Fig. 5*), and (iii) physical significance of each parameter in the semi-arid black cotton soil environment. Parameters with direct erosion linkages (Rb, Dd, STI, SPI) received higher weights.

2.6| Weighted sun analysis (WSA) & Prioritization of sub-watersheds

The WSA method is one of the effective techniques for prioritizing sub-watersheds. It is a multi-criteria decision-making technique used to combine several input layers by assigning relative importance or weights to them (Aher *et al.*, 2014; Rahmati *et al.,* 2019). The relative importance or weights of each parameter was estimated through the statistical correlation (Rahmati *et al.,* 2019). This allows prioritization of sub-watersheds based on their overall suitability for a specific purpose, in this case, mitigation of soil erosion. In this study, each of these factors was considered based on its contribution to surface runoff, infiltration, erosion susceptibility, and overall watershed sensitivity.

Some morphometric factors have a linear or direct association with soil erosion, while others have an indirect relationship. Linear parameters such as Rb, Fs, Dd, and Dt have a direct relationship with soil erodibility, whereas areal parameters (Rf, Rc, Re, Cc) have an inverse relationship with soil erodibility (Sujatha *et al.*, 2015). Even though constant of channel maintenance is an areal parameter, it exhibits a direct relationship with soil erodibility. Similarly, all three topo-hydrological parameters (TWI, SPI, and STI) have a direct relationship with soil erodibility. Hence, the sub-watershed with the highest value in these linear parameters was rated as 1st rank, the second-highest value was rated as second rank, and so on. On the contrary, a sub-watershed showing the lowest value in areal parameters was rated as 1st rank, the next lower value rated as 2nd rank, and so on.

Similarly, forests and open scrub have an inverse relationship with soil erosion, while wasteland, habitation, and agricultural land have a direct relationship with erosion. Hence, the sub-watershed with the maximum area under waste land, agriculture, and habitation was rated as 1st rank, the second-highest value was rated as 2nd rank, and so on. In the contrary, a sub-watershed having minimum area under forest and open scrub was rated as 1st rank, the next lower value rated as 2nd rank and so on.

The compound value was calculated by summing the ranking values of all parameters for each sub-watershed and dividing by the number of parameters considered. The equation used to calculate the compound parameter (Cp) for prioritizing sub-watersheds is mentioned below (Rahmati *et al.,* 2019).

$$C_p = \sum_{i=1}^{n} r_i / n$$

Where r_i is the rank or weight of each morphometric/topo-hydrological/LULC parameter, and n is the no. of parameters. Further, the final cumulative compound values for sub-watershed prioritization were calculated by integrating topohydro-morphometric parameters with LULC data. In the prioritization, 75% and 25% weightage were given to topo-hydro-morphometric parameters and LULC, respectively, as morphometric parameters represent the permanent physiographic controls on runoff and erosion, which remain stable over time and are essential for long-term watershed behaviour, while LULC, being transient and variable, is assigned lower weight as it fine-tunes rather than defines the fundamental hydrological response. Nevertheless, incorporating sensitivity analysis in future research could help refine and validate the relative weights of these parameters. The sub-watershed with the least value of the compound parameter was considered the most susceptible sub-watershed and ranked as 1, the next higher value was ranked as 2, and so on. Ultimately, the sub-watershed with the highest Cp value was assigned the lowest priority. This implies that the highest priority indicates the risk of runoff occurrence, with subsequent soil erosion being maximum in that sub-watershed.

2.7 | Assumptions of the Study

The present study primarily relies on secondary geospatial data and has certain assumptions; hence may affect the precision and reliability of the findings. Those are presented below:

- SRTM DEM (30m) may not capture micro-relief features affecting localized erosion.
- LULC data (2024) represents a single temporal snapshot and does not account for seasonal variability or recent land use changes.
- Morphometric parameters are static and do not reflect dynamic processes such as rainfall intensity variations, soil moisture dynamics, or anthropogenic interventions (roads, check dams, mining).
- Prioritization rankings are DEM-based empirical model-derived and require field validation through erosion measurements, sediment yield monitoring, and ground reconnaissance before operational use.
- Weightage assignments (75:25 for morphometric-LULC integration) are based on expert judgment and may be refined through sensitivity analysis or stakeholder consultation.

Despite these limitations, the framework provides a cost-effective first-order assessment for prioritizing sub-watersheds for planning and execution of suitable conservation measures in data-scarce semi-arid basins.

3 | RESULTS AND DISCUSSION

3.1 | Basin Characteristics

The entire Purna river basin has been divided into 22 sub-watersheds as depicted in *Fig. 1*. The smallest sub-watershed is SW-22, having an area of 37.38 km^2, followed by SW-20 (80.52 km^2) and SW-19 (240.00 km^2) while the largest sub-watershed is SW-13 (3668.34 km^2), followed by SW-3 (1316.19 km^2) and SW-14 (1229.11 km^2) (Table 2). The elevation of the river basin ranges between 361 and 941 m (*Fig. 1*). The significant variation in sub-watershed size (37.38 to 3668.34 km^2) presents challenges for comparative analysis, as size influences several morphometric parameters. SW-13 accounts for 23.1% of the total basin area, while the smallest five sub-watersheds (SW-22, SW-20, SW-19, SW-21, SW-18) collectively represent only 6.5%. This size asymmetry necessitates the use of normalized parameters (Dd, Fs, Rb) rather than absolute values for prioritization. The elevation gradient of 580 m (361-941 m) across relatively short horizontal distances indicates moderate to steep terrain conducive to rapid runoff generation, consistent with the region's flash flood history during monsoon events.

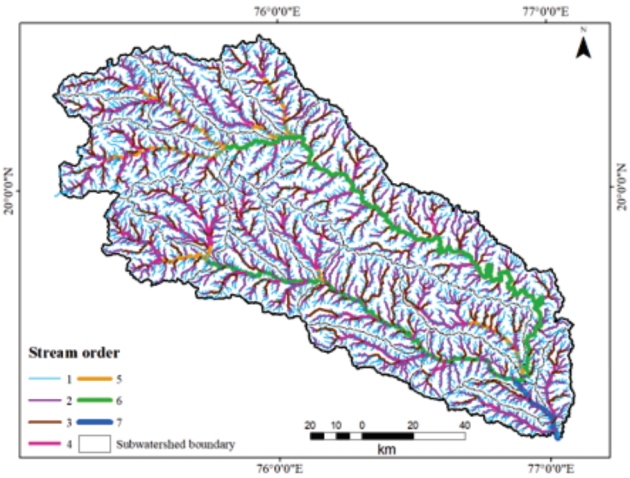


FIGURE 3 Stream order map of the river basin

3.2 | Slope Analysis

Slope analysis was performed by reclassifying DEM-derived slope maps into five categories following NBSS&LUP classification: nearly level (0-1%), very gently sloping (1-3%), gently sloping (3-5%), moderately sloping (5-10%), and steep (>10%). Results show that 68.3% of the Purna basin falls under gently to moderately sloping terrain (3-10%). In comparison, 12.7% exhibits steep slopes (>10%) primarily in the upper catchment areas of SW-1, SW-2, and SW-3 near the Ajanta hill range. Sub-watersheds SW-13, SW-16, and SW-17 contain significant areas (15-22%) with slopes exceeding 10%, where conventional agriculture without conservation measures accelerates soil erosion. The mean slope of the basin is 5.2%, with a standard deviation of 4.8%, indicating

moderate topographic heterogeneity. These slope characteristics directly influence the SPI and STI values discussed in Section 3.4.

3.3| Morphometric Parameters

3.3.1 | Linear Aspects

Stream order (So): It quantifies a stream's position within the hierarchical structure of its network, reflecting the connectivity between stream segments and the discharge contributions from upstream catchments (Strahler, 1964). The higher the stream order, the higher the basin area. The main and highest order (7th order) is shown at SW-22 (*Fig. 3*), whereas the maximum sub-watersheds are of 4th order. Stream order distribution across the basin follows Horton's law of stream numbers, with 1st order streams constituting 62.4% (3857 streams), 2nd order 23.1% (1429 streams), 3rd order 9.8%, and higher orders forming progressively smaller proportions. This hierarchical pattern indicates a well-developed, mature drainage network. However, sub-watersheds SW-5 and SW-13 deviate from this pattern with higher proportions of 1st order streams (68.2% and 71.3% respectively), suggesting active headward erosion and ongoing channel network expansion—both indicators of erosion vulnerability.

TABLE 2 Perimeter, basin length, area, no. of streams, stream length, and elevation of sub-watersheds

Sub-Watershed	Parameters						
	Perimeter (P), km	Basin length (Lb), km	Area (A), km^2	Minimum elevation (h), m	Maximum elevation (H), m	No. of streams (Nu)	Stream length, km
SW-1	170.59	42.31	417.81	599	907	172	359.24
SW-2	162.37	40.97	336.07	599	911	145	281.42
SW-3	317.71	69.22	1316.19	545	933	497	1088.41
SW-4	181.64	43.99	462.50	545	778	212	385.10
SW-5	264.59	68.10	811.72	528	898	598	635.11
SW-6	212.34	46.80	753.43	523	760	269	615.90
SW-7	161.88	35.36	437.83	523	667	168	368.99
SW-8	223.89	48.53	774.72	480	922	284	654.89
SW-9	231.86	53.42	745.88	480	930	298	673.63
SW-10	222.59	44.83	712.36	450	637	275	588.07
SW-11	229.57	56.90	561.09	438	669	221	454.49
SW-12	168.18	36.27	482.72	438	675	183	393.11
SW-13	689.82	156.13	3668.34	377	706	1374	2843.49
SW-14	268.73	51.93	1229.11	392	667	451	984.73
SW-15	202.58	49.74	481.09	392	524	184	399.60
SW-16	260.08	64.16	915.85	377	596	354	737.57
SW-17	219.38	49.14	698.46	369	476	272	584.33
SW-18	184.11	46.56	331.28	361	519	141	280.44
SW-19	160.15	36.20	240.00	365	450	101	204.49
SW-20	84.74	17.26	80.52	369	436	32	67.04
SW-21	157.37	38.40	369.82	365	544	166	318.51
SW-22	57.19	11.96	37.38	361	414	18	34.44

Bifurcation ratio (Rb)*:* In this study, the mean bifurcation ratio of sub-watersheds varied between 1.96 in SW-22 to 5.98 in SW-13 (Table 3). Ingle (2022) reported a mean Rb of 4.62 for the Morna river, whereas Chaudhari *et al.* (2023) found 5.09 for the Kasura river, both tributaries of the Purna river basin. Typically, Rb values within a range of 3.0 to 5.0 are common in river basins, which reflects the independence of the drainage pattern of the basin on its geological structure (Strahler, 1964). Low Rb values (< 4) indicate elongated drainage basins having high overland flow, increased infiltration rate, extended peak discharge durations, and reduced risks of flooding and soil erosion. In contrast, high Rb (> 5) values imply a circular drainage system with a low infiltration rate, sharp peak flow, limited groundwater recharge, and enhanced susceptibility to soil erosion and flooding (Adhikary and Dash, 2018). The sub-watersheds SW-4, SW-5, SW-13, SW-15, and SW-21,exhibiting high bifurcation ratio values (Rb > 5), are likely to experience concentrated runoff, resulting in increased soil erosion and sediment transport potential

3.3.2 | Areal Aspects

Stream frequency (Fs): Stream frequency (Fs) depends on lithology, drainage texture, climate, soils, vegetation, relief, infiltration, permeability, and runoff. Low Fs (< 3) indicates flat terrain with high infiltration and low erosion risk, while high Fs (> 6) suggests faster runoff and greater erosion potential. In the Purna river basin, Fs ranges from 0.36 to 0.78/km² (Table 3), indicating a poorly developed drainage network, low permeability, low relief, and reduced surface flow (Singh and Singh, 2022). Ingle (2022) reported a low Fs value of 2.11 km^{-2} for the Morna river.

TABLE 3 Morphometric and topohydrological parameters of the sub-watersheds

Sub-Watershed	Morphometric									Topo-hydrological		
	Rb	Fs	Dd	Dt	Cc	Cm	Rf	Re	Rc	TWI	SPI	STI
SW-1	4.15	0.41	0.86	1.01	2.37	1.16	0.23	0.55	0.18	11.16	5.21	16.86
SW-2	4.96	0.43	0.84	0.89	2.52	1.19	0.20	0.51	0.16	10.93	5.49	17.39
SW-3	4.49	0.38	0.83	1.56	2.49	1.21	0.27	0.59	0.16	11.17	5.21	17.49
SW-4	5.73	0.46	0.83	1.17	2.40	1.20	0.24	0.55	0.18	11.29	5.03	16.36
SW-5	5.26	0.74	0.78	1.04	2.64	1.28	0.18	0.47	0.15	11.27	5.07	17.24
SW-6	4.05	0.36	0.82	1.27	2.20	1.22	0.34	0.66	0.21	11.21	5.13	16.95
SW-7	3.73	0.38	0.84	1.04	2.20	1.19	0.35	0.67	0.21	11.38	4.94	15.96
SW-8	3.88	0.37	0.85	1.27	2.29	1.18	0.33	0.65	0.19	11.26	5.13	17.44
SW-9	3.54	0.40	0.90	1.29	2.41	1.11	0.26	0.58	0.17	11.45	4.89	16.50
SW-10	3.95	0.39	0.83	1.24	2.37	1.21	0.35	0.67	0.18	11.33	4.98	16.64
SW-11	3.73	0.39	0.81	0.96	2.75	1.23	0.17	0.47	0.13	11.28	5.03	16.84
SW-12	3.26	0.38	0.81	1.09	2.17	1.23	0.37	0.68	0.21	11.21	5.27	18.80
SW-13	5.98	0.37	0.78	1.99	3.24	1.29	0.15	0.44	0.10	11.41	4.96	16.92
SW-14	3.35	0.37	0.80	1.68	2.18	1.25	0.46	0.76	0.21	11.11	5.25	17.43
SW-15	5.29	0.38	0.83	0.91	2.62	1.20	0.19	0.50	0.15	11.41	4.94	16.62
SW-16	4.17	0.39	0.81	1.36	2.44	1.24	0.22	0.53	0.17	11.22	5.20	17.20
SW-17	3.84	0.39	0.84	1.24	2.36	1.20	0.29	0.61	0.18	11.42	5.01	16.78
SW-18	4.89	0.43	0.85	0.77	2.87	1.18	0.15	0.44	0.12	11.34	5.07	16.48
SW-19	3.58	0.42	0.85	0.63	2.94	1.17	0.18	0.48	0.12	11.34	5.07	15.57
SW-20	2.95	0.40	0.83	0.38	2.68	1.20	0.27	0.59	0.14	11.37	5.00	14.69
SW-21	5.11	0.45	0.86	1.05	2.32	1.16	0.25	0.57	0.19	11.40	4.98	16.20
SW-22	1.96	0.48	0.92	0.31	2.66	1.09	0.26	0.58	0.14	11.52	4.85	13.53

Drainage density (Dd): It reflects the extent of channel development and stream distribution within a basin, and also indicates a watershed's vulnerability to hydrological hazards, especially where hydro-meteorological data are scarce. Dd is classified into five categories: very fine (>4.97 km/km²), fine (3.73-4.97), moderate (2.49-3.73), coarse (1.24-2.49), and very coarse (<1.24 km/km²) (Sekhar and Mathew, 2022). High Dd suggests dense stream networks, typical of steep areas with rapid runoff. Low Dd indicates coarse drainage texture, low relief, permeable soil, dense vegetation, high infiltration, and greater groundwater recharge. In the Purna River basin, Dd ranges from 0.78 (SW-13) to 0.92 (SW-22) km/km² (Table 3), reflecting poor and very coarse drainage texture.

Drainage texture (Dt): Drainage texture depends on climate, soil, infiltration, elevation, and vegetation. Fine texture occurs in soft rocks with sparse vegetation, while resistant rocks lead to coarse texture. Dt is classified as: very coarse (<2/km), coarse (2-4), moderate (4-6), fine (6-8), and very fine (>8/km). Finer textures indicate higher erosion risk. In this study, the mean Dt is 1.15, indicating a very coarse drainage texture.

Compactness coefficient (Cc): It is slope-dependent but not related to watershed size. A Cc value of 1 indicates a circular shape, while values >1 show increasing elongation. In this study, the lowest Cc values are in SW-12 (2.17), SW-14 (2.18), and SW-6 (2.20), while SW-13 (3.24), SW-19 (2.94), and SW-18 (2.87) show the highest (Table 3). Thus, all sub-watersheds in the Purna river basin are elongated in shape.

Constant of channel maintenance (Cm): Constant of channel maintenance, the reciprocal of drainage density, indicates the drainage area required to develop and maintain one unit length of stream channel, reflecting basin infiltration and runoff characteristics (Singh and Singh, 2022). Classified into five erodibility categories (Sekhar and Mathew, 2022), the Cm values for the Purna river basin's sub-watersheds range from 1.09 to 1.29 km²/km, averaging 1.20 km²/km (Table 3). This suggests low erodibility and moderate surface runoff within the basin.

3.3.3 | Relief Aspects

Form factor (Rf): It indicates flow intensity and runoff characteristics within a basin. Lower Rf values suggest elongated watersheds with lower runoff and longer time of concentration, while higher values indicate more circular basins with higher runoff and shorter concentration times (Adhikary and Dash, 2018). In this study, Rf values ranged from 0.15 to 0.46 across sub-watersheds, with SW-13, SW-18, and SW-11 exhibiting lower values and SW-14, SW-12, and SW-10 showing higher values (Table 3). Ingle (2022) and Chaudhari *et al.* (2023) reported Rf values of 0.32 and 0.21 for the Morna river and Kasura river, respectively.

Elongation ratio (Re): It ranges theoretically from 0 to 1, but typically varies between 0.5 and 1.0. Watersheds are classified as circular (0.9-1.0), oval (0.8-0.9), less elongated (0.7-0.8), elongated (0.5-0.7), and more elongated (<0.5). Circular basins tend to have higher peak discharge and are more prone to erosion. In this study, Re values ranged from 0.44 to 0.76, indicating predominantly elongated sub-

Circulatory ratio (Rc): Influenced by geology, relief, climate, and land use, Rc ranges from 0 to 1 and reflects basin maturity: high values correspond to older basins, while low values indicate younger basins. In the Purna basin, Rc values ranged from 0.10 (SW-13) to 0.21 (SW-12), suggesting watersheds at an early stage of development with low runoff potential (Table 3).

3.4 | Topo-hydrological parameters

Topographic wetness index (TWI): It quantifies the influence of topography on hydrological processes and soil moisture distribution. It is determined by the slope and the contributing upstream area per unit width orthogonal to the flow direction. TWI correlates with soil properties such as organic matter, silt content, and soil depth (Singh and Singh, 2022). Higher TWI values (>10) reflect areas with greater potential for surface runoff and an elevated risk of soil erosion due to accumulation of water. Within the Purna river basin, TWI values vary from 10.93 (SW-2) to 11.52 (SW-22), indicating that the entire river basin is susceptible to saturation and erosion.

Stream Power Index (SPI): It indicates the potential erosive power of overland flow (Singh and Singh, 2022), influenced by slope, basin size, soil, vegetation, and climate. Positive SPI values highlight erosion-prone areas, while negative values indicate depositional zones. In the Purna river basin, SPI values range from 4.85 to 5.49, suggesting moderate erosive potential across the sub-watersheds.

Sediment Transport Index (STI): It quantifies the spatial dynamics of erosion and deposition within a watershed by representing the convergence and divergence of sediment fluxes along topographic gradients. It is strongly correlated with soil detachment and transport capacity, thereby serving as a proxy for erosion susceptibility and zones of potential sediment accumulation. In the Purna river basin, STI values range from 13.53 in SW-22 to 18.80 in SW-12 (Table 3). Elevated STI values correspond to steeply sloping terrain, deeply incised ravines, and dense drainage networks, collectively indicative of intensified erosion and sediment yield potential.

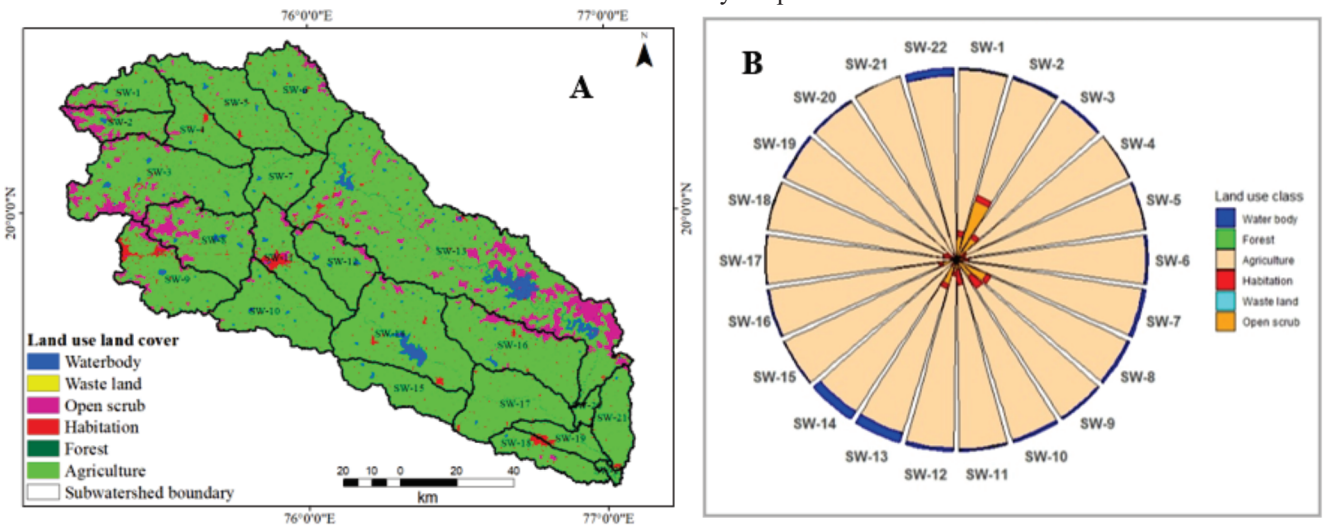


FIGURE 4 Land use and land cover map (A) and its percentage distribution (B) in study area

3.5 | Land use and Land cover of Purna river basin

The land use and land cover analysis is also a critical factor in prioritizing sub-watersheds. LULC categorization includes six classes, such as water bodies, forest, agriculture, habitation, waste lands, and open scrubs (*Fig. 4A*). The analysis highlights agriculture as the primary activity, spanning over 13733.17 km² (86.57% of total area), underscoring the region's agricultural reliance (*Fig. 4B*). Open scrub follows with an area of 1265.46 km². Water bodies constitute a tiny proportion of the area, covering 373.44 km² (2.35% of the area), highlighting limited aquatic resources and the probability of development of irrigation. The area under habitation accounts for 488.16 km², representing the space allocated for residential, industrial, and urban activities within the Purna river basin.

3.6 | Correlation Analysis

The correlation matrix for topo-hydro-morphometric parameters and LULC of sub-watersheds is presented in *Fig. 5*. The positive moderate association between Rb and Rf (r = 0.56) indicates that sub-watersheds with higher Rb tend to be more compact, favouring rapid runoff concentration and increased erosion susceptibility (*Fig. 5A*). In contrast, Rb has a negative correlation with the Dd (r=-0.24) and Dt (r=-0.32). Aside from its correlation with STI (r = 0.52), Fs shows no significant correlation with the other parameters. The strong positive correlation of Rf with Re (r = 0.84) and Rc (r = 0.63) indicates that more circular basins are hydrologically more responsive, exhibiting higher peak discharge and thus higher soil-erosion risk. Further, the strong TWI-SPI correlation (r = 0.72) emphasizes that zones with high water accumulation also exhibit greater erosive power of overland flow, making them hotspots of soil loss. LULC interactions reveal that declining forest cover (r = -0.48 with habitation) and agricultural expansion (r = 0.71 with habitation) increase

runoff potential by reducing infiltration and protective vegetative cover (Fig. 5B).

Overall, sub-watersheds with high Rb, compact shapes (high Rf/Re/Rc), elevated TWI-SPI values, and reduced forest cover are more prone to intense runoff and soil erosion. Based on correlation coefficient weights given to different parameters for prioritization of sub-watersheds, it can give insights for prioritization of erosion-prone sub-watersheds for targeted soil- and water-conservation interventions.

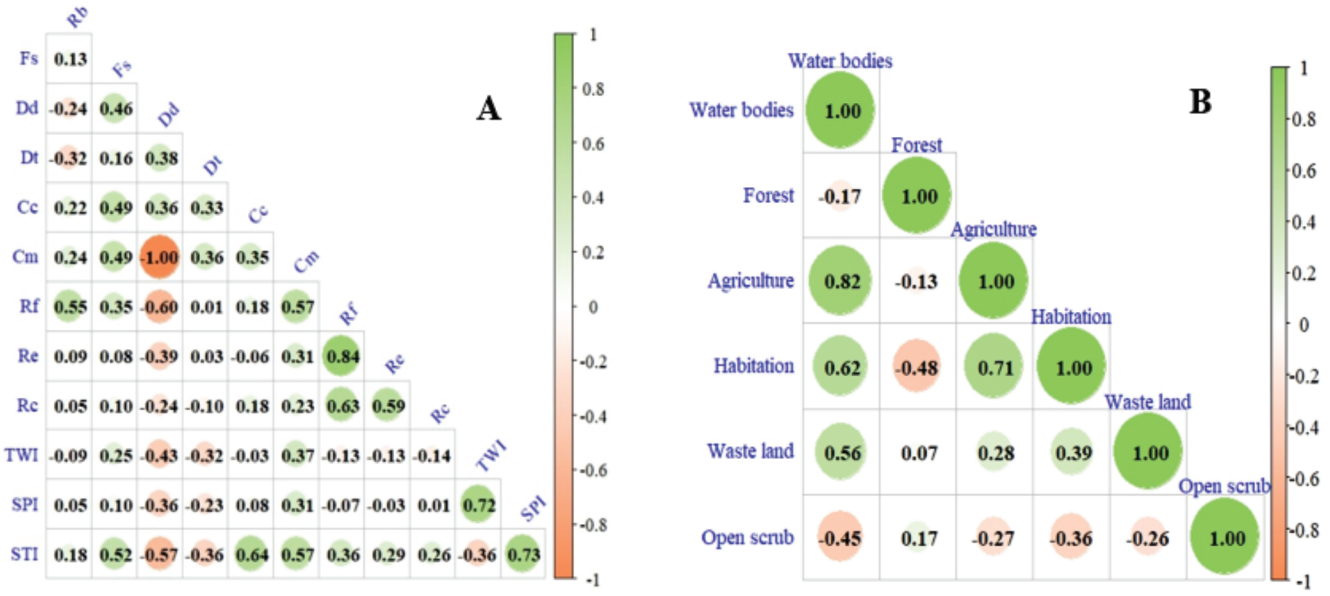


FIGURE 5 Correlation martrix of A) Topohydro-morphometric parameters B) LULC

3.7 | Prioritization of sub-watershed based on topohydro-morphometric parameters

Prioritizing sub-watersheds for conservation ensures efficient resource allocation and targeted interventions. Each morphometric and topohydrological parameter was weighted based on its influence on soil erosion. Linear parameters (Rb, Fs, Dd, Dt) show a direct relationship with erosion; hence, sub-watersheds with higher values were given higher priority (rank 1 being most erosion-prone). In contrast, areal/shape parameters (Rf, Rc, Re, Cc) exhibit an inverse relationship, so higher values received lower weights. Cm, along with TWI, SPI, and STI, shows a direct link to erosion risk and was accordingly assigned higher priority. The compound parameter value (Cpm) for each sub-watershed was calculated as the mean of all weights, reflecting cumulative susceptibility to erosion.

Based on Cpm, sub-watersheds were ranked (Table 4), in which SW-5 (Cpm = 7.50) and SW-13 (Cpm = 8.42) ranked 1st and 2nd while SW-7 ranked lowest. These were classified into four priority groups: high (1-5), medium to high (6-10), medium (11-16), and low (17-22) (*Fig. 6A*). High-priority sub-watersheds indicate greater erosion risk and require urgent soil and water conservation measures.

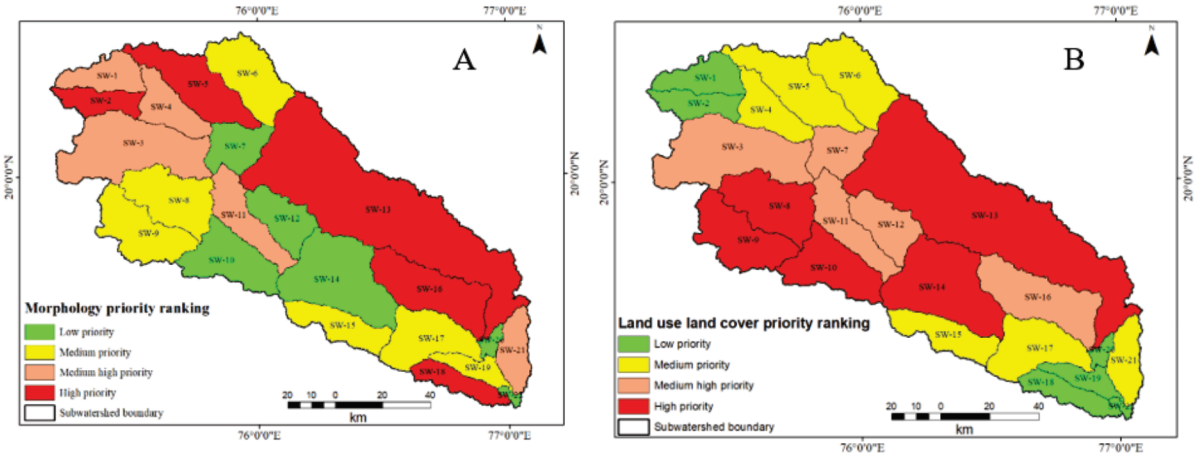


FIGURE 6 Priority ranking of sub-watersheds based on (A) topo-hydro-morphometric parameters and (B) LULC

TABLE 4 Weightage, compound parameter and rank of sub-watersheds based on topo-hydro-morphometric parameters

Sub-Watershed	Rb	Fs	Dd	Dt	Cc	Cm	Rf	Re	Rc	TWI	SPI	STI	Compound parameter (Cpm)	Rank
	Weightage assigned													
SW-1	10	8	4	15	9	19	9	9	14	20	4	10	10.92	7
SW-2	6	5	9	18	14	14	7	7	9	22	1	5	9.75	3
SW-3	8	18	14	4	13	9	15	15	10	19	5	2	11.00	10
SW-4	2	3	11	11	10	12	10	10	13	12	12	17	10.25	6
SW-5	4	1	21	1	16	2	4	4	7	14	10	6	7.50	1
SW-6	11	22	16	8	3	7	18	18	20	18	7	8	13.00	16
SW-7	16	15	8	14	4	15	19	19	19	7	20	19	14.58	22
SW-8	13	21	7	7	5	16	17	17	18	15	8	3	12.25	15
SW-9	18	9	2	6	11	21	13	13	12	2	21	15	11.92	14
SW-10	12	14	15	10	8	8	20	20	15	11	16	13	13.50	20
SW-11	15	11	18	16	19	5	3	3	4	13	13	11	10.92	8
SW-12	20	17	17	12	1	6	21	21	22	17	2	1	13.08	17
SW-13	1	19	22	2	22	1	1	1	1	4	18	9	8.42	2
SW-14	19	20	20	3	2	3	22	22	21	21	3	4	13.33	18
SW-15	3	16	13	17	15	10	6	6	8	5	19	14	11.00	11
SW-16	9	13	19	5	12	4	8	8	11	16	6	7	9.83	4
SW-17	14	12	10	9	7	13	16	16	16	3	14	12	11.83	13
SW-18	7	6	6	19	20	17	2	2	3	9	11	16	9.83	5
SW-19	17	7	5	20	21	18	5	5	2	10	9	20	11.58	12
SW-20	21	10	12	21	18	11	14	14	5	8	15	21	14.17	21
SW-21	5	4	3	13	6	20	11	11	17	6	17	18	10.92	9
SW-22	22	2	1	22	17	22	12	12	6	1	22	22	13.42	19

TABLE 5 Weightage, compound parameter and rank of sub-watersheds based on LULC

Sub-Watershed	Water bodies	Forest	Agriculture	Habitation	Waste lands	Open scrub	Compound parameter (Cpl)	Rank
SW-1	15	16	17	16	7	22	15.50	21
SW-2	13	21	20	18	10	21	17.17	22
SW-3	3	19	3	4	10	20	9.83	8
SW-4	18	1	14	10	10	19	12.00	16
SW-5	11	12	5	6	10	18	10.33	11
SW-6	6	17	6	7	10	17	10.50	12
SW-7	10	1	15	15	8	16	10.83	13
SW-8	4	7	9	9	2	15	7.67	4
SW-9	9	13	10	2	3	14	8.50	5
SW-10	5	1	8	13	5	13	7.50	3
SW-11	12	18	11	3	4	12	10.00	9
SW-12	8	1	13	17	6	11	9.33	7
SW-13	1	22	1	1	1	10	6.00	2
SW-14	2	8	2	5	9	9	5.83	1
SW-15	16	1	12	20	10	8	11.17	14
SW-16	7	14	4	11	10	7	8.83	6
SW-17	14	11	7	14	10	6	10.33	10
SW-18	20	20	18	8	10	5	13.50	18
SW-19	17	15	19	12	10	4	12.83	17
SW-20	21	10	21	21	10	1	14.00	20
SW-21	22	1	16	19	10	1	11.50	15
SW-22	19	9	22	22	10	1	13.83	19

3.8 | Prioritization of sub-watersheds based on land use land cover

The LULC-based prioritization of sub-watersheds is shown in *Fig. 6B*. The SW-14 (Cpl- 5.83) and SW-13 (Cpl- 6.00) ranked 1st and 2nd, while SW-2 ranked lowest (22nd) (Table 5). Sub-watersheds were grouped into four categories: high priority (1-5), medium-high (6-10), medium (11-16), and low (17-22) (Table 5). High-priority sub-watersheds reflect greater erosion and runoff risk and are key targets for soil and water conservation measures.

3.9 | Prioritization of sub-watersheds based on both LULC and topographic-hydro-morphometric parameters

The final prioritization of sub-watersheds for soil conservation was derived by integrating topo-hydro-morphometric (75% weight) and LULC (25% weight) parameters. A cumulative score was calculated for each sub-watershed, and the mean score determined their final ranking (Table 6). Sub-watersheds with lower scores (3.91), such as SW-13, indicate higher erosion susceptibility and thus require greater conservation attention, whereas SW-20, with the highest score (7.06), ranks lowest in priority (*Fig. 7*). High-priority sub-watersheds should be targeted for erosion control; reforestation, wetland restoration, and groundwater recharge initiatives. Collaborative efforts with local communities, NGOs, and government agencies can further strengthen sustainable watershed management.

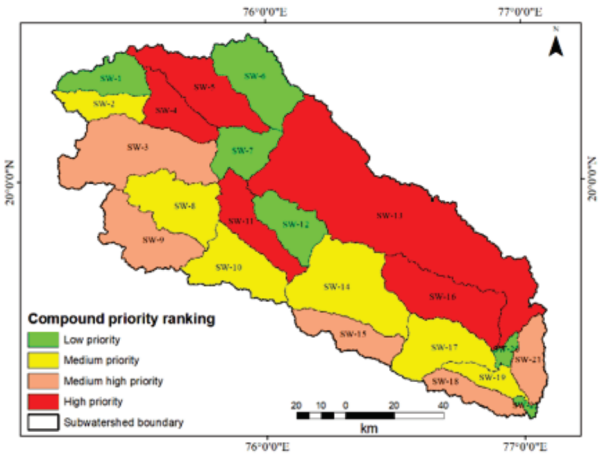


FIGURE 7 Priority ranking of sub-watersheds for SWC measures

TABLE 6 Cummulative weightages and rank of sub-watersheds based of Purna river basin

Sub-Watershed	Morphometric and topo-hydrologic parameter		LULC		Mean	Rank	Priority
	Cpm	On base 75%	Cpl	On base 25%			
SW-1	10.92	8.19	15.50	3.88	6.03	17	Low[#]
SW-2	9.75	7.31	17.17	4.29	5.80	14	Medium[@]
SW-3	11.00	8.25	9.83	2.46	5.35	6	Medium high[$]
SW-4	10.25	7.69	12.00	3.00	5.34	4	High
SW-5	7.50	5.63	10.33	2.58	4.10	2	High
SW-6	13.00	9.75	10.50	2.63	6.19	19	Low
SW-7	14.58	10.94	10.83	2.71	6.82	21	Low
SW-8	12.25	9.19	7.67	1.92	5.55	11	Medium
SW-9	11.92	8.94	8.50	2.13	5.53	9	Medium high
SW-10	13.50	10.13	7.50	1.88	6.00	16	Medium
SW-11	10.92	8.19	10.00	2.50	5.34	5	High
SW-12	13.08	9.81	9.33	2.33	6.07	18	Low
SW-13	8.42	6.31	6.00	1.50	3.91	1	High*
SW-14	13.33	10.00	5.83	1.46	5.73	12	Medium
SW-15	11.00	8.25	11.17	2.79	5.52	8	Medium high
SW-16	9.83	7.38	8.83	2.21	4.79	3	High
SW-17	11.83	8.88	10.33	2.58	5.73	13	Medium
SW-18	9.83	7.38	13.50	3.38	5.38	7	Medium high
SW-19	11.58	8.69	12.83	3.21	5.95	15	Medium
SW-20	14.17	10.63	14.00	3.50	7.06	22	Low
SW-21	10.92	8.19	11.50	2.88	5.53	10	Medium high
SW-22	13.42	10.06	13.83	3.46	6.76	20	Low

[*]High priority sub-watersheds considered combined effect of steeper slopes, higher Rb, finer Dt, higher STI, with more than 85% agriculture and minimal forest/scrub buffer, chance of active sheet-rill erosion, frequent gully formation, high sediment delivery, immediate action need for execution of conservation measures.

[$]Moderately high slope, with moderate SPI/STI, moderate-fine drainage texture with 70-85% agriculture and scattered scrub, pronounced sheet and rill erosion, localized gully along drainage lines.

[@] Gentler slopes, coarse drainage texture and agriculture still dominant land use, chance of sheet erosion during heavy rains, and minor rills

[#]Low slope, coarse Dt, lower Rb and SPI/STI, higher TWI in valley floors acting as depositional zones, agriculture present on flatter terrain, low-intensity sheet erosion only, limited sediment export.

3.10 | Possible soil and water conservation measures

In the Purna basin, effective soil and water conservation should target erosion mitigation, runoff regulation, and groundwater recharge through an integrated strategy combining (a) structural interventions-such as contour bunds, check dams, gabions, and terracing; (b) vegetative measures-including afforestation, vegetative barriers, and cover crops; and (c) water-harvesting structures-such as farm ponds, percolation tanks, and recharge pits (*Fig. 8*). Complementary practices, including mulching with locally available biomass, strip cropping, conservation tillage, and micro-irrigation, enhance soil moisture retention and

reduce surface runoff. Detailed specifications for these measures within the Purna basin are summarized in Table 7.

The watershed-based approach, which integrates conservation engineering, reforestation, and community participation, is most effective when supported by policy convergence across agencies and technologies such as Remote Sensing and GIS for site-specific planning and implementation. For instance, the SW-13, identified as potentially the most vulnerable sub-watershed with elevated SPI (4.96) and elongated morphology (Re = 0.44), exhibits concentrated flow erosion. This warrants the installation of check dams and gabions in 3rd and 4th order streams to dissipate energy and reduce sediment transport. Similarly, in SW-5, high stream frequency (0.74 km^{-2}) indicates susceptibility to sheet and rill erosion, making contour bunding and vegetative barriers the preferred interventions. The 3rd most vulnerable sub-watershed, SW-16, characterized by moderate STI (17.20) and intensive agricultural land use, requires farm ponds for runoff harvesting coupled with conservation tillage to minimize soil loss and enhance infiltration.

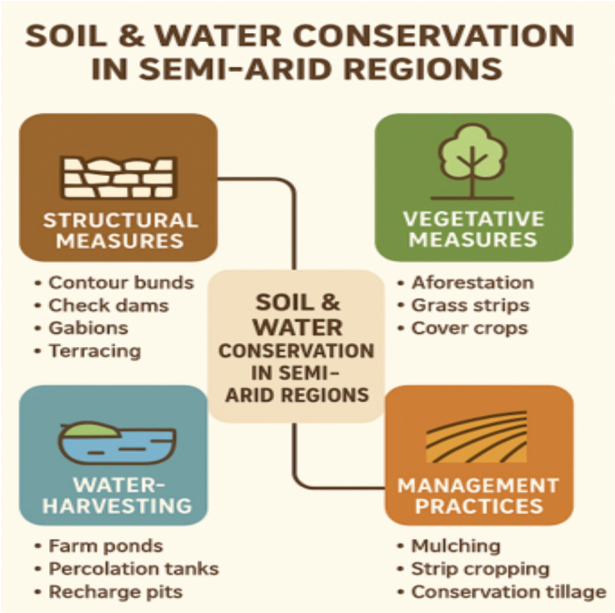


FIGURE 8 Conservation measures for semi-arid region

TABLE 7 Land use-wise possible measures and their specification for Purna river basin

Land use	Treatment	Cross section (m^2)	Unit ha^{-1}
Agriculture	Contour/farm bund, vegetative bund	0.45 -1.0	250 – 400 rm
	Stone outlets, earthen gully plugs	1.5 -.5	Site-specific
	Plantation on bund	Mango, guava, teak (variety: Brahma)	-
Forest/Open scrub	Water absorption trench (WAT)	1.0	300 rm
	Continuous contour trench (CCT)	0.18	1200 rm
	Refilling of CCT (RCT)	0.24	600 rm
	Stone bund	0.45-0.60	300 rm
	Gully plug	1.0	Site-specific
		1.0, 0.18, 0.24	Same as above
Waste land	WAT, CCT, RCT		
	Plantation (horticultural plant)	Pomegranate, grape, ber, custard apple	600 nos.
	Grass seeding	Buffel, Marvel, Vetiver	-
Gully control and water harvesting	Line cement gully plug	-	66 units ha^{-1}
	nala bund, farm pond, check dam	-	Site-specific

3.11 | Limitations of present study

The present study is focused chiefly on prioritizing sub-watersheds of the Purna river basin through a GIS-based framework, using only DEM and LULC. The topo-hydro-morphometric analysis is a useful, cost-effective and potential approach for sub-watershed prioritization, however, the method has its own limitations *(Fig. 9)*. It primarily relies on the geometric and topographic characteristics derived from DEMs or maps and does not account for dynamic factors such as rainfall variability, soil properties, and human interventions (construction of road, deforestation, mining etc.) that strongly influence erosion processes. The accuracy of prioritization is also constrained by the resolution and quality of input datasets (DEM), especially in areas with complex terrain. Furthermore, morphometric parameters alone cannot capture seasonal variations in runoff, sediment yield, or the effects of ongoing conservation measures. Similarly, sub-watershed rankings are governed exclusively by the output generated from the DEM-derived equations or empirical models. Therefore, the prioritization of watersheds in this study provides an initial framework for resource allocation. However, these rankings should be interpreted as indicative rather than definitive. To ensure reliability and practical

relevance, they require rigorous field validation through soil-loss measurements, sediment-yield monitoring, gully-density surveys, and consultations with local farmers. Such ground-truthing not only strengthens the accuracy of the top-hydo-morphometric outcomes but also enhances stakeholder acceptance and facilitates context-specific interventions. Consequently, operational implementation of these rankings should follow a comprehensive validation process to align model predictions with field realities and long-term watershed management objectives.

3.12 | Synthesis and Erosion Mechanism

The Purna basin's dominantly elongated, low-relief, coarse-textured sub-watersheds are better suited for infiltration-based water conservation, while localized high TWI, SPI, and STI zones require targeted structural and vegetative erosion-control measures. With respect to the high-priority sub-watersheds (SW-13, SW-5, SW-16), they have common characteristics that explain their erosion susceptibility. The SW-13 (rank 1, Cp=3.91), the largest sub-watershed (3668 km²), exhibits the highest bifurcation ratio (5.98), indicating structural control and rapid runoff concentration. Lowest drainage density (0.78 km/km²), suggesting coarse texture with inadequate channel network to distribute flows. Maximum agricultural land (86%), leaving soils exposed during monsoon onset. Form factor (0.15) indicates an elongated shape, yet high STI (16.92) and moderate SPI (4.96) suggest concentrated flow paths prone to incision. This combination creates a "flashy" hydrological response: sparse drainage channels concentrate runoff during intense monsoon events (typical 24-hr rainfall >100 mm), causing gully formation and bank erosion in agricultural lands with minimal vegetative cover. Similarly, the SW-5 exhibits high soil-erosion risk due to its almost complete agricultural land cover (94.5 %), negligible forest (<0.01%), and high topo-hydro-morphometric indices (Rb - 5.26, Dt - 2.26, STI - 17.2), which indicate concentrated runoff, fine drainage texture, and strong slope-driven erosive forces. Further, a lack of vegetative buffer can make it prone to intense sheet and rill erosion with significant sediment yield. The SW-16 (89.7 % agriculture, 7.3% scrub, Rb-4.67, Dt -1.9, STI-16.2) also exhibits high erosion susceptibility, due to extensive cropland.

4 | CONCLUSIONS

Optimum utilization and proper management of natural resources, particularly land and water, is utmost important for agricultural sustainability in the Marthawada region of Maharashtra, India, and agricultural sustainability depends on watershed-based management of natural resources. This present study developed and demonstrated a GIS-based framework integrating morphometric parameters, topo-hydrological indices (TWI, SPI, STI), and LULC data to prioritize 22 sub-watersheds in the Purna river basin (15,864 km²) for soil and water conservation. Based on weighted integration (75% morphometric-hydrological, 25% LULC), SW-13 (Cp=3.91) emerged as the highest priority sub-watershed, followed by SW-5 (Cp=4.10) and SW-16 (Cp=4.79). These sub-watersheds exhibit combined

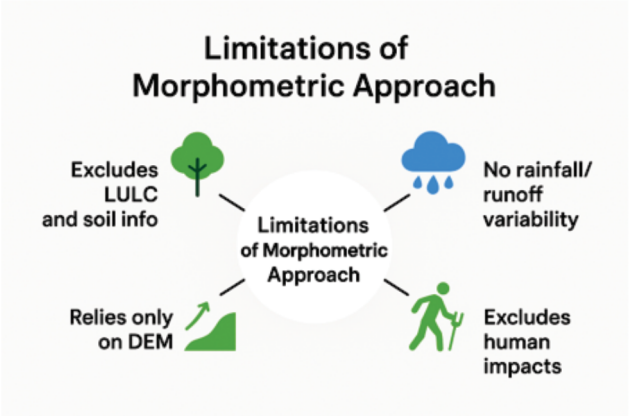


FIGURE 9 Limitation of morphometric approach

characteristics of high bifurcation ratios (4.17-5.98), low drainage density (0.78-0.81 km/km²), elevated stream power indices (4.96-5.20), and intensive agricultural land use (>85%), indicating heightened vulnerability to runoff concentration and soil erosion. The 7th order Purna basin displays coarse drainage texture (mean Dd=0.83 km/km², Dt=1.15/km), elongated sub-watershed morphology (mean Re=0.58), and positive SPI values (4.85-5.49), collectively indicating moderate-to-high erosion susceptibility across the basin.

Prioritization is based entirely on geospatial modeling without field validation. Rankings must be verified through ground-truth assessments, including: (i) erosion plot measurements in representative sub-watersheds, (ii) sediment yield monitoring at outlet points, (iii) participatory rural appraisal with farmers to confirm problem areas, and (iv) temporal LULC change analysis (2010-2024) to assess land degradation trends. This framework provides a replicable, cost-effective approach for preliminary sub-watershed prioritization in data-scarce semi-arid regions, but field validation remains essential before operational implementation. The methodology advances existing knowledge by integrating multiple parameters and can inform evidence-based watershed planning across Marathwada and similar geomorphological settings.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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DATA AVAILABILITY STATEMENT

The data presented in this study are available upon request

from the corresponding author.

DECLARATION

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

AUTHOR'S CONTRIBUTION

GW, PM & SAC: Formal analysis and writing – original draft; CJD: Conceptualization and writing – review & editing; SAC, CJD, SA & MRM: Writing – review & editing; PP: Visualization (land use map preparation); HB: Supervision.

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ORIGINAL ARTICLE

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Groundwater Quality Assessment for Sustainable Water Management In Semi-Arid Chitradurga District, Karnataka

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ABSTRACT

Groundwater pollution reduces water quality and negatively impacts human well-being, social and economic development, and agricultural land value. Therefore, to evaluate the pre-monsoon groundwater quality in Chitradurga district, Karnataka, 55 randomly collected pre-monsoon (February- March, 2023 & 2024) bore well water samples from farmlands across different villages in Hiriyur, Hosadurga, Challakere, Chitradurga, Molakalmuru, and Holalkere taluks were analyzed for pH, EC, Ca, Mg, Na, K, SO_4, CO_3, HCO_3, Cl, and B. The samples were also tested for Total Hardness (TH), Total Dissolved Salts (TDS), Soluble Sodium Percentage (SSP), Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC), Kelley' s Index (KI), Permeability Index (PI), Magnesium Hazard (MH), Potential Salinity (PS), and Water Quality Index (WQI). Results showed that WQI ranged from 30 to 81, with 87% of samples recording less than 50, indicating excellent water quality; 13% recorded between 51 and 81, indicating good quality for drinking. Similarly, irrigation suitability revealed that SAR indicates excellent to good. SSP indicates good to poor, RSC indicates good to bad, and PI indicates good. KI indicates permissible to non-permissible. The MH ranged from 60-98.65, indicates 100 % of water samples are non-acceptable. PS indicates excellent to good and to injurious. It was concluded that for drinking water samples are excellent to good. For irrigation, 66 % of water samples need to be treated before irrigation to cropland to control soil sodicity and salinity, sodium and sodium carbonates hazards, as it recorded RSC >2.5. Also, 100% of groundwater samples are found to have magnesium hazard, thus it leads to alkalinity/sodicity upon irrigation, which needs suitable irrigation water management practices, thereby elevating crop production and productivity and maintaining soil health and quality, besides controlling chemical land degradation.

1 | INTRODUCTION

Freshwater scarcity worsened by pollution, growth, urbanisation, industrialisation, and agriculture. Groundwater makes up 30% of the world's fresh water and 0.76% of total water, with 99% of fresh water stored underground (Upmanu *et al*., 2020). In India, groundwater is vital for drinking, irrigation, and industry, with about 230 km³ used annually (Kaliraj *et al*., 2019). It supplies 65% of irrigation needs (NDTV, 2019), mainly for its affordability and lower pollution risk. Over 2 billion people depend on groundwater (Famiglietti, 2014). In semi-arid regions, it is the main water source for drinking and farming. In arid areas like Chitradurga, deep aquifers supply irrigation. 70% of groundwater use is for agriculture (NGWA, 2021). Groundwater potential is declining, notably in drylands (Douville *et al.*, 2021).

Contamination of groundwater comes from various sources, including sanitation systems, landfill leachate, wastewater treatment effluents, leaking sewer systems, petrol stations, hydraulic fracturing (fracking), and the widespread use of chemical fertilizers in agriculture, as well as naturally occurring pollutants like arsenic and fluoride (Michael, 2014). Using this polluted groundwater for drinking or farming poses serious risks to human and animal health. Additionally, in coastal areas, groundwater is at risk of saltwater intrusion, which can cause land subsidence. These problems are worsened by rising sea levels and the diverse impacts of climate change, especially

on the water cycle. Furthermore, groundwater extraction has led to a shift in the Earth's axial tilt of up to 31 inches (Mindy, 2023; Davide, 2023). Therefore, assessing groundwater quality is essential, as pollution is often invisible and harder to clean up compared to surface water bodies like rivers and lakes.

When surface water undergoes significant evaporation, groundwater can become saline, either naturally in endorheic regions or artificially in irrigated agricultural areas. In coastal regions, extracting groundwater can lead to salinization. The variation of groundwater salinity across different locations results from diverse hydrogeological characteristics, which pose risks to groundwater in specific areas. Elevated salinity levels make water unsuitable for drinking and irrigation, especially in coastal regions like Bangladesh and parts of East and West Africa (Tanjila *et al.*, 2023). As water moves through the landscape, it accumulates soluble salts, mainly sodium chloride, which are left behind during evapotranspiration. In low-lying irrigated areas, poor soil and surface aquifer drainage can cause a shallow water table, sometimes reaching the surface. Waterlogging and increasing salt concentrations in surface waters contribute to soil salinity and land degradation (Anon, 2010), negatively impacting local economies and ecosystems (Ludwig *et al.*, 1993). In semi-arid regions like the Chitradurga district, aquifers with surface irrigation face higher salinisation risks due to excess irrigation water seeping into the ground from wells (ILRI, 1989).

The chemical composition of subterranean water is affected by the mineral components of the rocks and aquifer it traverses. Various hydrogeochemical processes modify the chemical makeup of groundwater as it moves from one aquifer to another, causing spatial and temporal variations in its hydrogeochemical characteristics. These variations depend on the geological and chemical properties of the aquifer (Hwang *et al.*, 2017). Understanding groundwater composition and evaluating it are essential for determining its suitability for various applications. Therefore, in this study, the groundwater from Hiriyur, Hosadurga, Challakere, Chitradurga, Molakalmuru, and Holalkere taluks of Chitradurga district, Karnataka, has been characterized and assessed for its suitability for drinking and irrigation purposes on a sustainable basis. The objectives are: i) to characterize the groundwater of Chitradurga district, Karnataka, by analyzing the concentrations of different major cations and anions; ii) to evaluate the groundwater for drinking suitability using the water quality index (WQI); iii) to assess its suitability for irrigation through parameters such as total dissolved salts (TDS), soluble sodium percent (SSP), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), total hardness (TH), Kelly's index (KI), potential salinity (PS), magnesium hazard (MH), and permeability index (PI); and iv) to discuss irrigation water management in Chitradurga district, Karnataka, India.

HIGHLIGHTS

- Water Quality Index ranged from 30-81, indicating that it's excellent to good quality for drinking.
- Magnesium Hazard ranged from 60-98.65, indicating that 100% of the groundwater is unacceptable for direct irrigation.
- Spatial analysis revealed Na^+-K^+-Cl^--HCO_3- dominated groundwater chemistry with high salinity requiring improved drainage and water management practices

2 | MATERIALS AND METHODS

2.1 | Study Area

Chitradurga district belongs to Central Karnataka, a hot, moist semi-arid eco-sub-region and a hot arid eco-sub-region, and as per the Planning Commission, Agro-Climatic Region is the Southern Plateau and Hills Region (10), covering a total geographical area (TGA) of 8.433 lakh ha. The district lies between north latitude of 13º 32' 20.721" to 15º 3' 27.178" N to east longitude of 75º 58' 55.046" to 77º 55' 57" E with an altitude of 732 m AMSL. It receives rainfall from June to September, primarily from the southwest monsoon, and from October to December, primarily from the northeast monsoon. Average yearly rainfall varies between 668 mm in Holalkere in the west to 457 mm in Chellakere in the northeast. The temperature varies between 17 to 41 ^{0}C and may fall up to 12 – 9 ^{0}C during the winter season. Geology is granite, gneiss & schist. Storage of groundwater in hard rock terrain and its movement control by the lineaments and fractures of the area (Basavarajappa *et al.*, 2015). The land is used for coconut, areca nut, maize, finger millet, Bengal gram, jowar, sunflower, cotton, tomato, onion, banana, mango, sapota, mulberry, pomegranate, and chrysanthemum cultivation. The vegetation consists of Prosopis sp., Lantana, tamarind, Acacia sp., neem, and cacti. Agriculture is a significant economic activity in rural livelihoods using water sources from canals, tanks, borewells, rivers, and rainfall.

2.2 | Water Sample Collection and Analysis

A total of 55 random bore well water samples were collected from different farmlands of Hiriyur and Hosadurga (27 samples collected during February-March, 2023) and Challakere, Chitradurga, Molakalmuru and Holalkere taluks (28 samples collected during February-March, 2024) during the pre-monsoon period (*Fig. 1*). Collected water samples were labelled with coordinates and stored in polyethylene bottles, which were brought to the laboratory, refrigerated, and used for further laboratory characterization. Major cation and anion concentrations were determined in all the water samples using standard protocols outlined by APHA et al. (2012). pH and EC were analyzed using a pH meter (Hanna make) and an EC meter (Toshniwal make), respectively. The Ca^{2+}, Mg^{2+}, Na^+, and K^+ were analyzed by an atomic absorption spectrophotometer (Pinnacle 900 F by PerkinElmer). The CO_3^{2-} and HCO_3^- were estimated via acid titration, and Cl^- by the Mohr technique of silver nitrate titration. The BaCl method was

applied for SO_4^{2-} determination using a UV-VIS spectrophotometer. Boron estimation was done by the Azomethine-H method (Keren, 1996).

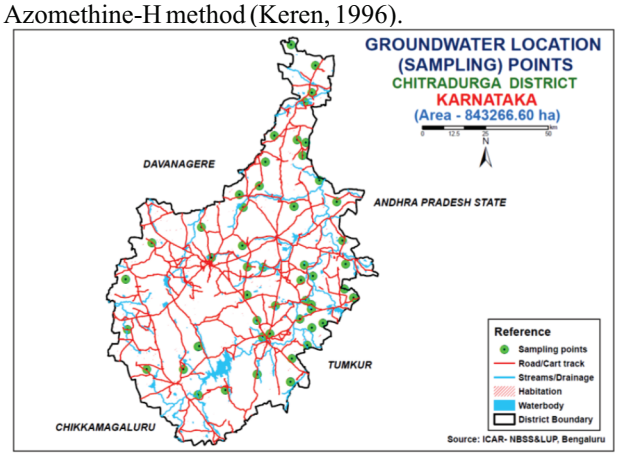


FIGURE 1 Groundwater location (sampling) points in Chitradurga district

2.3 | Preparations of different water quality diagrams, maps and figures

Piper diagrams (Piper, 1944), Wilcox (Wilcox, 1955), log Wilcox and riverside diagrams (USSL, 1954) were created for assessing groundwater qualities using Diagram 8.3 software. The Gibbs diagram (Gibbs, 1970) was prepared using MS Excel 2019. Pearson's correlation analysis of the water quality parameters was done by R Studio V 4.3.2 using the metal package, indicating ns, i.e. non-significant at p >= 0.05; significant at p <0.05 = r*; significant at p < 0.01= r**; and significant at p <0.001 = r ***. ArcGIS 10.7.1 software was used for making a geographical pattern of groundwater quality attributes in the investigation extent.

2.4 | Determinants of different water quality assessment parameters

2.4.1 | Water Quality Index (WQI)

WQI was computed in four levels (Ramakrishnaiah *et al.*, 2009). At the first level, all 9 water quality parameters have been assigned a weight (ai) based on their priority/ importance among all the quality parameters (Table 1) for drinking purposes. The highest weight of 4 has been given to pH, SO_4, and TDS, and the lowest weightage of 2 to Ca, Mg, and TH. In level two, relative weight (Ai) is computed from equation (1)

$$Ai = ai / \sum_{i=1}^{n} ai \quad \ldots\ldots\ldots\ldots (1)$$

Where Ai indicates relative weight, ai indicates the weight of the parameter, and n is the total number of parameters. Relative weight (Ai) values calculated for individual parameters are presented in Table 1. At the third level, a rating scale for quality (wi) for individual parameters is assigned by dividing the concentration (Ci) of each water sample by its corresponding standard (Si), as per the procedure outlined in BIS, and then multiplying by 100.

$$wi = (Ci / Si) \times 100 \quad \ldots\ldots\ldots\ldots (2)$$

Where wi indicates the quality rating, Ci represents the concentration of each individual water chemical parameter in mg l^{-1} for every water sample, while Si denotes the Indian drinking water typical for a parameter, also measured in mg l^{-1}

At the fourth level, the WQI was computed by calculating SIi, which is obtained by multiplying the already calculated Ai by wi, and then summing all the SIi to result in the WQI, as mentioned below in Equations 3 and 4.

$$SIi = Ai \times wi \quad \ldots\ldots\ldots\ldots (3)$$

$$WQI = \sum_{i=1}^{n} SIi \quad \ldots\ldots\ldots\ldots (4)$$

SIi indicates the subindex of the ith parameter; Ai indicates the relative weight and quality rating of the i^{th} parameter, and n indicates the total number of parameters.

Based on the computed WQI values, water quality was classified into five classes: excellent, good, poor, very poor, and unsuitable for drinking, corresponding to WQI values of <50, 50-100, 100-200, 200-300, and >300, respectively.

TABLE 1 Relative weight of water chemical parameters.

Water Chemical Parameters	Indian Standards	Weight (ai)	Relative weight (Ai)
pH	6.5-8.5	4	0.167
Ca mgl^{-1}	75-200	2	0.083
Mg mgl^{-1}	30-100	2	0.083
SO4 mgl^{-1}	200-400	4	0.167
HCO3 mgl^{-1}	244-732	3	0.125
Cl mgl^{-1}	250-1000	3	0.125
TH	300-600	2	0.083
TDS	500-2000	4	0.167

2.4.2 | Total Hardness

TH was estimated by the below-mentioned equation 5 (Todd 1980) and expressed as mg/l of $CaCO_3$.

$$TH = 2.497 \times Ca^{2+} + 4.115 \times Mg^{2+} \quad \ldots\ldots\ldots\ldots (5)$$

TH (mg l^{-1}) values up to 600 and up to 100 are permissible recommended limits for drinking purposes as per BIS (2012) and WHO (2004), respectively.

2.4.3 | Total Dissolved Salt (TDS)

TDS indicates the total dissolved solids present in the water, and it was empirically determined from electrical conductivity values (µS/cm) and expressed in mg l_{-1} as per Equation 6 below.

$$TDS\ (mg/l) = 0.67 \times Conductivity\ (\mu S/cm) \quad \ldots\ldots\ldots\ldots (6)$$

Groundwater samples as per TDS (Davis & De Wiest, 1966) values are classified as < 500, 500-1000, <3000, and >3000 as desirable, permissible, useful, and unfit for drinking and irrigation, respectively.

2.4.4 | Soluble Sodium Percentage (SSP)

SSP indicates the ratio of sodium to total cation multiplied by 100. A high sodium (Na+) percentage depletes the soil's permeability, thereby affecting plant growth. It can be calculated using Equation 7.

$$SSP = [(Na^+ + K^+) / (K^+ + Na^+ + Ca^{2+} + Mg^{2+})] \times 100 \quad \ldots\ldots\ldots\ldots (7)$$

SSP values <20, 20-40, 40-60, 60-80, and >80 are considered excellent, good, permissible, doubtful, and unsafe, respectively, for irrigation.

2.4.5 | Sodium Adsorption Ratio (SAR)

SAR indicates the proportion of concentration of sodium

(Na^{+}) ions to calcium (Ca^{+2}) and magnesium (Mg^{+2}) ions in a water sample, and it can be calculated as per equation 8 below.

$$SAR = Na^{+}/[(Ca^{+2}+ Mg^{+2})/2]^{0.5}(meq/l) \text{ ..... (8)}$$

Based on SAR values, water quality for irrigation suitability was done; if SAR values are <10, 10-18, 19-26, >26 are classified as excellent, good, doubtful, and unsuitable for irrigation, respectively.

2.4.6 | Residual Sodium Carbonate (RSC)

The surplus concentration of CO_3^{2-} and HCO_3^{-} anions in groundwater over the total of calcium (Ca^{+2}) and magnesium (Mg^{+2}) cations concentration is defined as residual sodium carbonate (RSC).

RSC is calculated by the following equation 9.

$$RSC = (HCO_3^{-} + CO_3^{2-}) - (Ca^{+2} + Mg^{+2}) \text{ ..... (9)}$$

If the RSC value is <1.25, up to 2.5, and >2.5 is suitable, marginally suitable, and unfit for irrigation, respectively (Lloyd & Heathcote, 1985).

2.4.7 | Kelley's Index (KI)

The estimated sodium concentration, alongside calcium and magnesium concentrations, is referred to as the KI value (Kelly, 1940), which can be calculated using Equation 10 below.

$$\text{Kelly index} = Na^{+}/(Ca^{+2}+ Mg^{+2}) \text{ ..... (10)}$$

If KI is >1 indicates high sodium content, then it is unsuitable for irrigation, whereas <1 is suitable for irrigation use. However, SAR is more generally applicable to identify sodium hazards than KI.

2.4.8 | Permeability Index (PI)

The soil permeability is influenced by the long-term irrigation and is affected by sodium (Na^{+}), calcium (Ca^{+2}), magnesium (Mg^{+2}), and bicarbonate (HCO_3^{-}) contents of the soil. PI is calculated by equation 11

$$PI\ (meq/l) = [(Na^{+} + \sqrt{HCO_3^{-}})/(Ca^{2+} + Mg^{2+} + Na^{+})] \times 100 \text{ ..... (11)}$$

According to PI, Doneen (1964a) categorized water into three categories: Class I, Class II, and Class III. Class I indicates 100% maximum permeability, making it suitable for irrigation; Class II indicates 75% maximum permeability, which is marginally suitable; and Class III indicates 25% maximum permeability, rendering it unsuitable for irrigation, respectively.

2.4.9 | Magnesium Hazard (MH)

A higher content of magnesium is formed due to the presence of exchangeable sodium in irrigated agricultural soils. Paliwal (1972) announced the MH and computed as per equation 12.

$$MH\ (meq/l) = [Mg^{2+}/(Ca^{2+} + Mg^{2+})] \times 100 \text{ ..... (12)}$$

An MH value greater than 50% is not suitable for irrigation, as it affects crop yield and soil structure.

2.4.10 | Potential Salinity (PS)

Potential salinity indicates the concentration of chloride ions (Cl^{-}) plus half of the sulphate (SO_4^{2-}) ions; it can be calculated as shown below (Doneen, 1964a) in equation 13.

$$PS\ (meq/l) = Cl^{-} + 1/2So_4^{2-} \text{ .....(13)}$$

Based on PS, water quality can be classified as excellent to good, good to injurious, and injurious to unsatisfactory if PS values are <5, 5-10, and >10, respectively.

3 | RESULTS AND DISCUSSION

3.1 | Chemical Formulation and Spatial distribution of Ground Waters, Chitradurga district

The results presented in Table 2 indicate the chemical properties of the groundwater, and Fig. 3 illustrates the spatial distribution of groundwater parameters. The pH ranged from 7.49 to 9.06, with a mean of 8.38. Approximately 51 % of the water is alkaline in reaction, with a pH above 8.5, and the permissible limit (BIS, 2012) for drinking purposes (Table 3). Gypsum present in the aquifer rock may be diluted, leading to higher salinity (Chaudhary & Satheeshkumar, 2018). The electrical conductivity ranged from 764 to 4400 µS/cm with a mean of 1599 µS/cm, indicating that the higher concentrations of cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (SO_4^{-2}, CO_3^{-2}, HCO_3^{-1}, Cl^{-1}) present in groundwater samples are contributing to medium to very high salinity. More than 66 % of water has very high salt concentrations. Higher EC might also due to weathering of aquifer minerals and human activities (Tanaya, 2024).

Among major cations, Na^{+} content recorded higher concentrations, which varied from 41.50 to 790.80 with a mean of 205.08 mg l^{-1} followed by Mg^{2+} concentrations (17.14-135.32 mg l^{-1}), Ca^{2+} (1.31-55.23 mg l^{-1}), and the lowest content is K^{+} (ranged from 0.34 to 79.25; a mean of 4.46 mg l^{-1}). Calcium content is <200 mg l^{-1}, which is within the permissible limit. Magnesium was also within the permissible limit (<100 mg l^{-1}) except for five water samples. The potassium content varied from low to high, and approximately 53 % of the samples were high (> 2 mg l_{-1} in K^{+}). Sodium concentration was high (>200 mg l^{-1}) in 38 % of the samples. Among anions, Cl^{-1} and HCO_3^{-1} recorded higher contents, which varied from 78.10-795.20 mg l^{-1} and 134.20-500.20 mg l^{-1}, respectively, followed by SO_4^{2-} (6.08-134.40 mg l^{-1}) and CO_3^{2-} (18-90 mg l^{-1}). Chlorine and Sulphate were recorded < 1000 mg l^{-1} and <400 mg l^{-1}.

Fig. 2 shows major cation and anion concentrations in groundwater, which indicates the relative proportion of ion concentrations in the order for cations: $Na^{+} > Mg^{2+} > Ca^{2+} > K^{+}$ and anions: $HCO_3^{-1} > Cl^{-1} > SO_4^{2-} > CO_3^{2-}$. Na^{+} and Mg^{2+} and HCO_3^{-1} and Cl^{-1} are the major causes of elevated levels of pH and EC in the district. The spatial distribution (*Fig. 2*) shows that sodium and potassium contents are higher in the northern part of Chitradurga, which is an arid region, due to high evaporation. This may also be attributed to tube wells with deeper depths and lower discharge rates. Groundwater investigations indicated that aquifers are present between the depths of 15 mbgl and 200 mbgl in the Chitradurga district, and bore wells drilled to a depth in the district ranged from 64 mbgl to 200 mbgl (CGWB, 2013).

However, boron concentrations were medium to high in the southern parts, a semi-arid region, which is due to sequential deposition of transported solutes in semiarid conditions. Among cations, Na^+ was the highest constituent, and K^+ was the lowest, which might be due to the low rate of weathering of potassic rocks, whereas in anions, Cl^- was the major constituent, and $SO4^{2-}$ was the lowest constituent, which might be due to the reduction of sulphate in the aquifer system. The correlation study (*Fig. 4*) shows that CO_3^{2-} is significantly strongly correlated with B ($r^{***} = 0.47$). pH is strongly negatively correlated with B ($r^{***} = -0.72$) and CO_3^{2-} ($r^{***} = -0.53$). EC was strongly positively associated with Mg^{2+} ($r^{***} = 0.66$), Na^+ ($r^{***} = 0.83$) and Cl^{-1} ($r^{***} = 0.87$), indicating that major salts in the groundwater are NaCl and $MgCl_2$. Cl^{-1} was strongly positively associated with Mg^{2+}($r^{***} = 0.70$) and Na^+ ($r^{***} = 0.74$), demonstrating those ions are derived from either halite (NaCl) or $MgCl_2$ sources. Na^+ significantly positively interrelated with Mg^{2+} ($r^{**} = 0.40$), HCO_3^{-1}($r^{**} = 0.41$) and SO_4^{2-}($r^{**} = 0.38$) indicating that which are derived from soil Na_2SO_4 and $NaHCO_3$ sources.

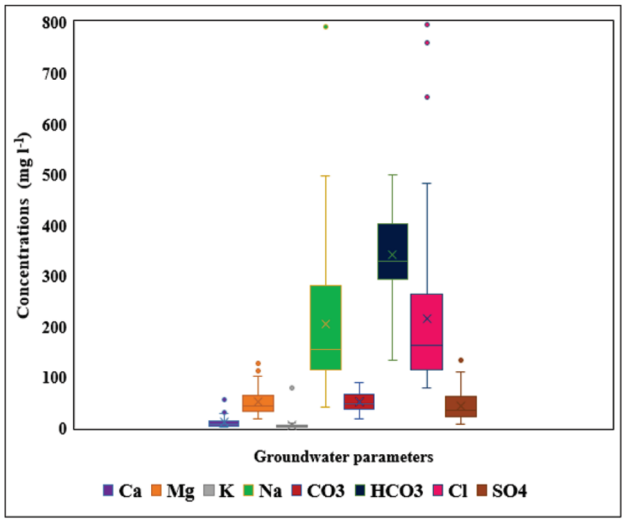
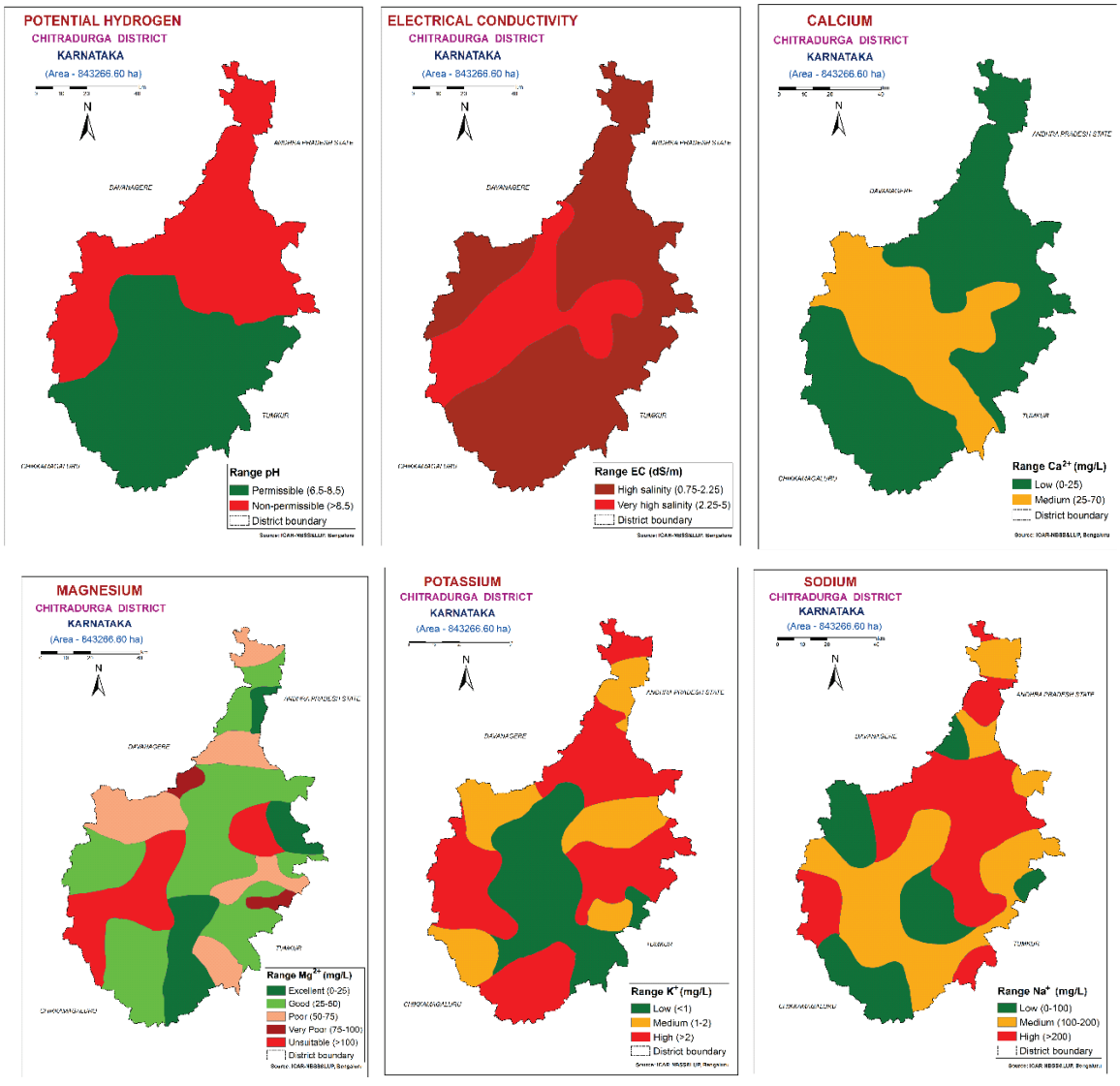


FIGURE 2 A box plot illustrating the concentrations of main cations and anions in groundwater within the Chitradurga district



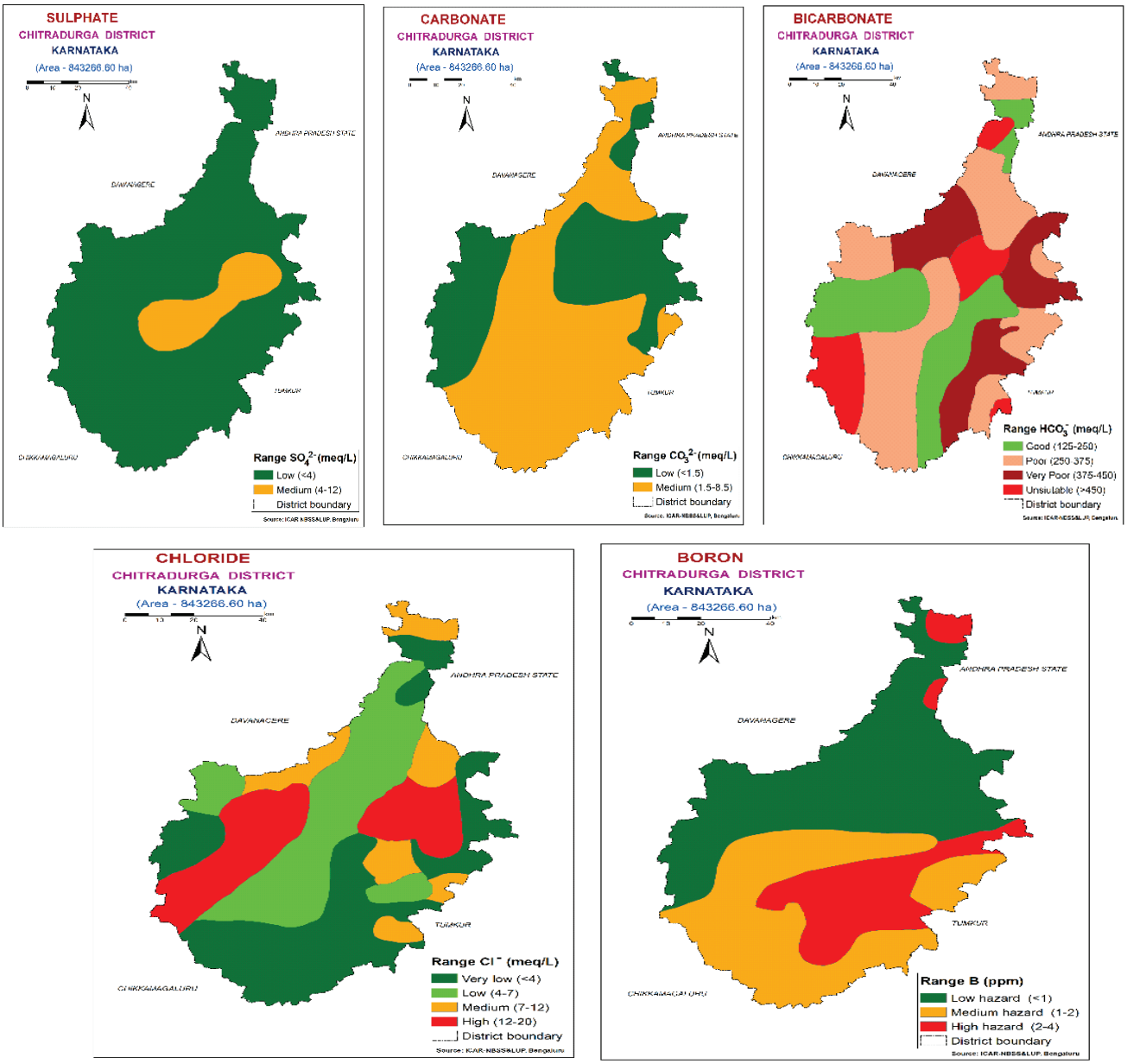


FIGURE 3 Geographical pattern of Chitradurga groundwater properties

TABLE 2 Descriptive statistics of groundwater parameters analysed

	pH	EC	Ca	Mg	K	Na	So_4	Co_3	HCO_3	Cl	B
		(µS/cm)	----------mg l^{-1}----------								(ppm)
Min	7.49	764	1.31	17.14	0.34	41.50	6.08	18.00	134.20	78.10	0.05
Max	9.06	4400	55.23	135.32	79.25	790.80	134.40	90.00	500.20	795.20	3.83
Average	8.38	1599	10.43	50.69	4.46	205.08	43.31	51.16	340.49	216.23	1.34
SD	0.45	669	10.44	26.73	10.47	131.82	29.22	19.11	78.28	156.77	1.06

TABLE 3 Permissible limits for groundwater parameters for drinking purposes

Parameter	BIS (2012)	WHO (2004)	
		Most desirable	Max. allowable
pH	6.5-8.5	6.5	8.5
EC (µS/cm)	3000	1400	-
TDS (mg l^{-1})	2000	500	1500
TH (mg l^{-1})	600	100	500
Ca^{+2} (mg l^{-1})	200	75	200
Mg^{+2} (mg l^{-1})	100	50	150
Na^{+} (mg l^{-1})	200	-	200
K^{+}(mg l^{-1})	10	-	12
Cl^{-}(mg l^{-1})	1000	200	600
$SO4^{-2}$ (mg l^{-1})	200	200	400

3.2 | Original and Classification of groundwater of Chitradurga district

Piper diagrams indicate the cation and anion combinations that form triangles on a common baseline, which is used to classify groundwater types diagrammatically. The Piper diagram (*Fig. 5*) indicates that the groundwater is dominated by the Na^{+}- K^{+}- Cl^{-}- HCO_3^{-} type, the (Na^{+}-Ca^{2+}-Mg^{2+}- Cl^{-}- HCO_3^{-}) type, and the mixed type, which regularly accumulates residual carbonate in irrigation water. The Piper diagrams also show alkalis (Na^{+}+K^{+}) were higher than alkaline earth metals (Ca^{2+}+ Mg^{2+}), and $Cl^{-}$and $HCO_3^{-}$are the major anions found in groundwater that might be an occurrence of halite (NaCl), $NaHCO_3$, KCl, and $KHCO_3$ dissolution.

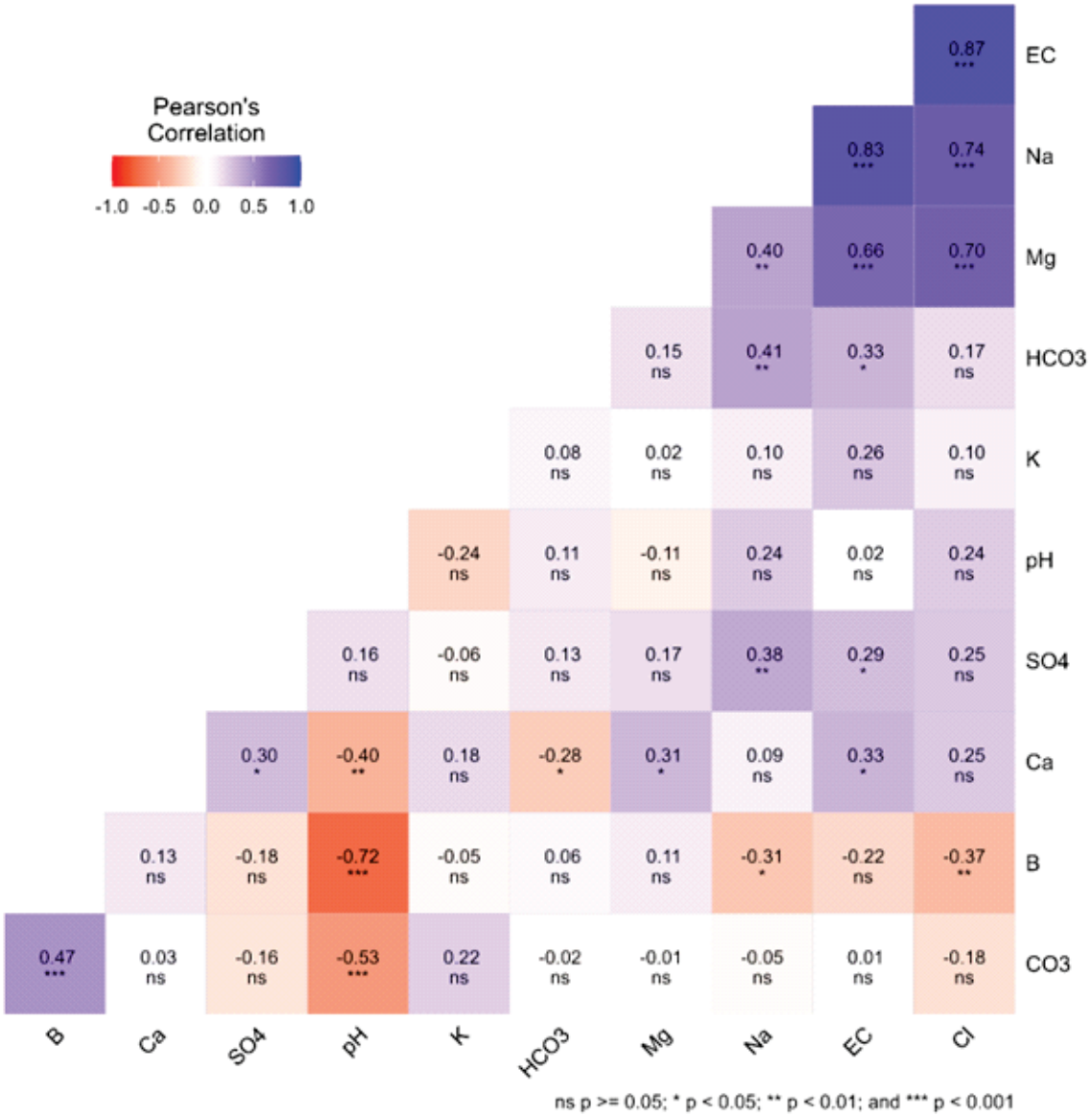


FIGURE 4 Association of groundwater parameters, Chitradurga district

A Gibbs diagram reveals the hydro-geochemical processes. The minerals influence water quality in the groundwater-aquifer system, which is helpful in understanding the genesis of groundwater. The Gibbs plot for cations (Na^+/ ($Na^+ + Ca^{2+}$) and anions (Cl^- / $Cl^- + HCO_3^-$) (Fig. 6) directs that most of the cations in groundwater are of 'evaporation and mineral dissolution origin' and evaporation-crystallization dominance' and anions are of rock origin. In arid and semiarid regions, the elevated evaporative demand, combined with chemical weathering of rocks and human activities, contributes to an increase in total dissolved solids (TDS) in groundwater. This shift indicates a transition from rock dominance to the evaporation zone, potentially influenced by a higher concentration of sodium ions (Na^+) relative to chloride ions (Cl^-) in water samples, which may result from cation exchange processes or pollution from anthropogenic sources. The sulfate-to-chloride ratio (SO_4^{2-}/Cl^-), which exceeds 0.05 in all analyzed water samples, suggests the influence of agricultural return flow, indicating that the application of gypsum fertilizers and the dilution of gypsiferous minerals affect the mineral composition of the groundwater. In the Chitradurga district, the primary water-bearing formations include gneisses, fractured granitic gneisses, and hornblende schists (CGWB, 2013).

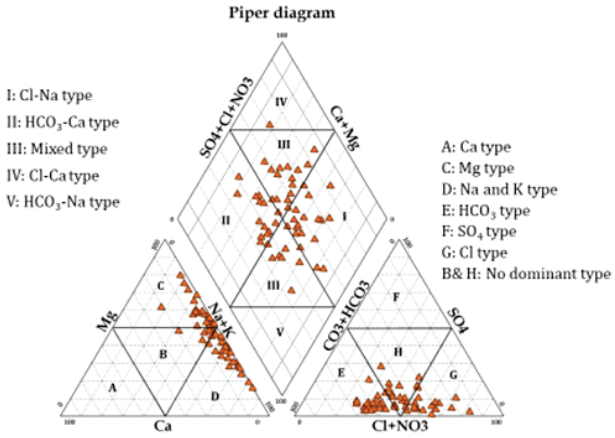


FIGURE 5 Piper diagram for the Groundwater's of Chitradurga district

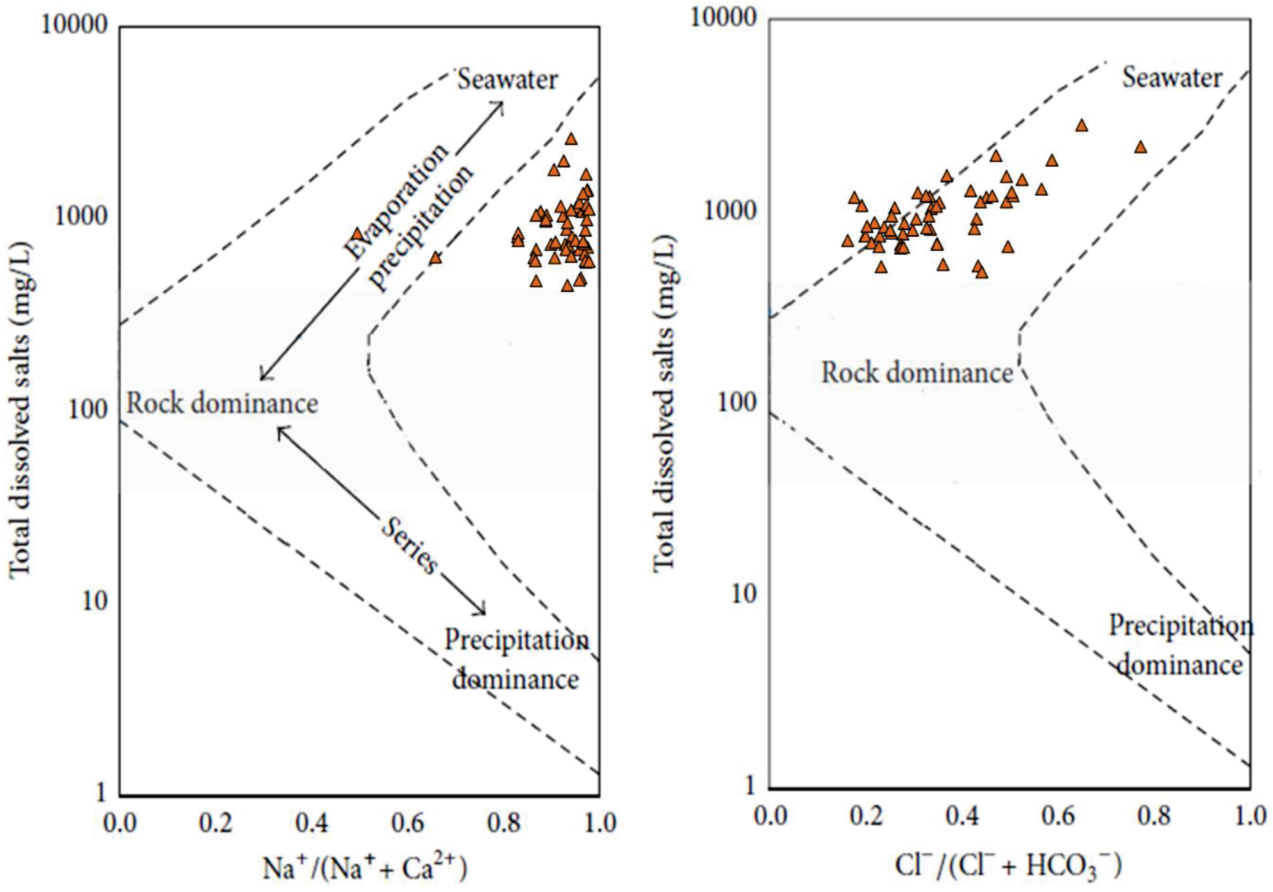


FIGURE 6 Gibbs diagram for the groundwaters of Chitradurga district

3.3 | Suitability of groundwater for drinking, Chitradurga district

The fitness of ground waters for drinking is evaluated using the water quality parameters *viz*., total hardness (TH), total dissolved solids (TDS), and water quality index (WQI), data presented in Table 4 and Fig. 7 show the spatial distribution of these parameters. The TH varied from 75.53 to 622.63 with a mean of 234.64, and the spatial distribution shows that more than 80% of the area has a high TH (>180 mg CaCO3 l_{-1}), indicating that the water is considered very hard. However, TH up to 600 mg $CaCO_3$ l^{-1} is suitable for consumption as per BIS maximum permissible limits (Sharma *et al.*, 2017). The water hardness may be due to the presence of carbonates and bicarbonates of alkaline earth metals, such as calcium and magnesium (Chaudhary & Satheesh kumar, 2018). The TDS varied from 488.96 to 2816.00, with a mean of 1023.49. The spatial distribution shows that it ranged from low to medium throughout the entire district. Higher TDS is directly related to the occurrence of elevated concentrations of soluble salts (Chaudhary & Satheeshkumar, 2018). TDS up to 1000 mg l^{-1} it fits for consumption, and up to 3000 mg l^{-1} is beneficial for irrigation (Sharma *et al.*, 2017). Thus, water can be used for drinking. However, the WQI ranged from 30 to 81, with a mean of 43, and the geographical pattern indicates that it is good to excellent in all the water samples in the district; thus, the Chitradurga groundwater is suitable for drinking. Since there were no major industries or municipalities, the groundwater has remained suitable for consumption and substantially unpolluted (Khatri *et al.,* 2020).

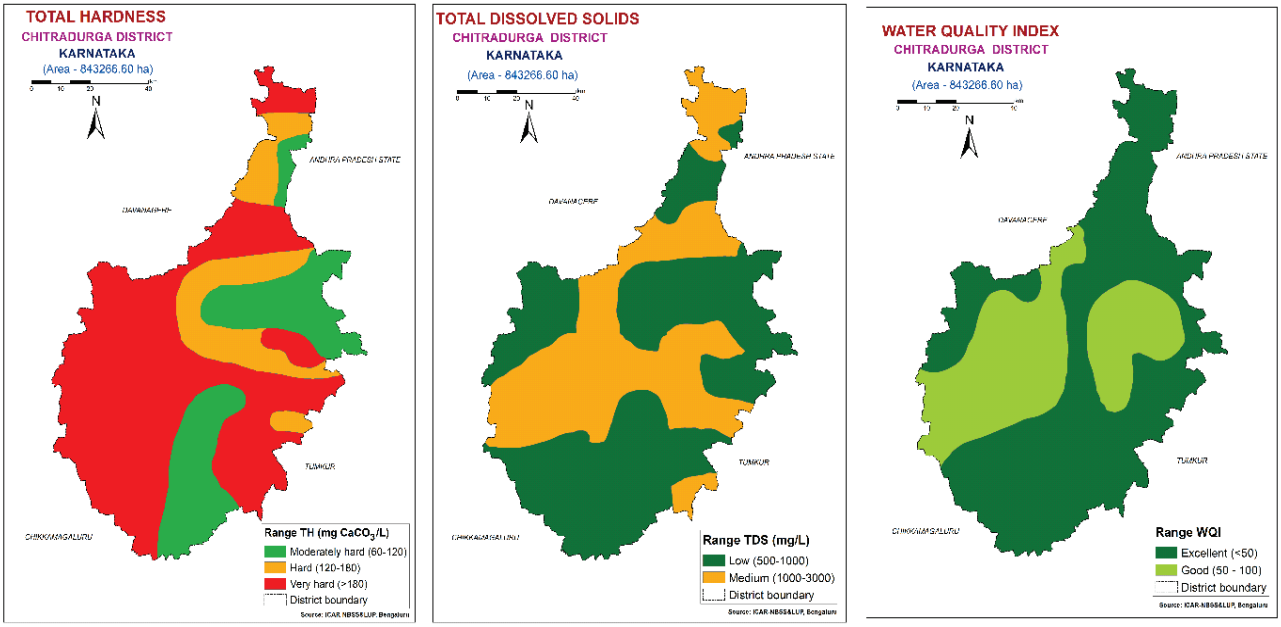


FIGURE 7 Geographical pattern of Chitradurga groundwater quality parameters for drinking suitability

3.4 | Irrigation suitability of groundwater for drinking, Chitradurga district

The major groundwater hydro-chemical quality parameters used to determine its suitability for irrigation (Table 4) are EC, soluble sodium % (SSP), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), Kelly's ratio/Kelly's index (KI), permeability index (PI) and magnesium ratio/magnesium hazard (MH). The spatial distribution of these quality parameters is presented in Fig. 8. To determine the suitability of groundwater for irrigation, sodium concentration is a primary parameter to consider in the assessment because sodium-rich water, when irrigated, reacts with the soil and reduces its permeability. When sodium interacts with carbonate and chloride, it leads to alkaline and saline soils, respectively. Higher levels of Na^+ in irrigation water can affect soil texture and permeability; however, Na^+ concentrations in groundwater of up to 60 are regarded as permissible for agricultural purposes (Sharma *et al.*, 2014). Thus, the groundwater chemical quality was studied by plotting analytical EC data v/s sodium per cent, i.e., Wilcox diagram (*Fig. 9*) shows that 50% of water samples belong to good to permissible, 40% falling under permissible-doubtful, six samples under doubtful-unsuitable, and three samples were unsuitable. Doubtful and unsuitable samples require proper treatment before irrigation, as these samples, when irrigated without treatment, may cause alkali and saline soils, thereby hindering crop production and productivity, as well as deteriorating soil health. The SAR ranged from 1.31 to 19.14 with a mean of 6.13. The U.S. Salinity Laboratory uses the Wilcox log diagram to plot electrical conductivity (EC) versus SAR, which classifies groundwater as CnSn, i.e., a pair of EC (C1-C4) and SAR (S1-S4) classes. Here, EC is referred to as a salinity threat, whereas SAR is considered an alkalinity threat. Wilcox's log diagram (*Fig. 9*) shows that 89% (49 samples) of the water samples belonging to C3S1 indicate high salinity and low Na, which requires drainage and is otherwise dangerous. However, 11

% (6 samples) of waters falling under C4S1 indicate very high salinity and low sodium, which cause salinity problems to soils upon irrigation. However, cotton or millets can tolerate slight salinity, while sensitive crops could be harmed by 'doubtful' water; hence, salt-tolerant crops can be grown in these areas. And also this water requires prior treatment, along with the provided drainage. Higher concentrations of salts (high EC) in irrigation water result in the creation of saline soil. Salinisation is a major threat to irrigated lands, causing a loss of production as it limits crop growth by adversely affecting germination and yields, and also affects the choice of crops. The US Salinity Laboratories Riverside diagram (*Fig. 10*) also shows that low sodium but high salts, except one sample, which recorded SAR >19, indicating potential salinity and sodicity issues, as hard-rock aquifers often yield saltier water with low sodium relative to calcium/magnesium, resulting in low SAR. Thus, water samples are too salty to irrigate if irrigated without proper drainage, which may cause soil salinisation, which needs proper drainage in soils and also requires cultivating salt-resistant crops. The salinity present in groundwater is a result of the weathering of rocks, along with the process of evapotranspiration, which releases soluble salts into the groundwater. These salts primarily consist of calcium, sodium, and magnesium chlorides, as well as bicarbonates, sulfates, and carbonates. The study found that the spatial distribution of SAR was good to excellent, and it is within the permissible limit (<26).

TABLE 4 Statistical analysis of parameters for assessing groundwater quality

	TDS (mg l^{-1})	SSP (%)	SAR	RSC	TH	KI	PI	MH	PS	WQI
Min	488.96	25.60	1.31	7.10	75.53	0.34	20.41	59.99	2.96	30
Max	2816.00	90.67	19.14	8.63	622.63	9.72	43.36	98.65	23.45	81
Average	1023.49	63.07	6.13	2.58	234.64	2.26	29.21	89.14	7.19	43
SD	428.17	14.37	3.67	2.72	120.76	1.71	4.51	8.67	4.52	10

Higher RSC in water causes the adsorption of higher sodium in the soil. The RSC ranged from -7.10 to 8.63 with a mean of 2.58. The geographical pattern of RSC was medium to bad in more than 66% of the area. Thus, 66% (36 samples) of groundwaters are not suitable for irrigation as these waters have more (CO_3^{2-} + HCO_3^{-1}) compared to alkaline earth metals (Ca^{2+}+Mg^{2+}), thus leading to complete precipitation of Ca^{2+} and Mg^{2+} and deposits residual carbonate in the soil upon irrigation, resulting in alkali build-up. The high amount of calcareous rocks may be the reason for the alkalinity of waters in the district (Nagaraju *et al.,* 2014). The PI is affected by Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-1}, and HCO_3^{-1} values in the soil, and it recorded 20.41 to 43.36 with a mean of 29.21. The geographical pattern of PI indicates that 78% (43 samples) of the samples have good permeability, and around 22% (12 samples) of the waters are unsuitable. A magnesium ratio of > 50 causes soil alkalinity/sodicity in soils due to a high concentration of $Mg^{2+,}$ as it behaves like Na^{+} and causes soil structure deterioration by dispersing clay content, particularly in irrigated lands/lowlands. The MH varied from 59.99 to 98.65 with a mean of 89.14 (SD: 8.67). The geographical pattern of MH shows that the entire Chitradurga district groundwater is found to be magnesium-hazardous, thus leading to alkalinity/sodicity upon irrigation. Consequently, 100% of the water samples are injurious and unsuitable for irrigation use. Higher magnesium levels in groundwater may be contributed by the dolomite source in the district (Nagaraju *et al.,* 2014).

Similarly, KI shows higher concentrations of sodium in water; when KI > 1, the water is unsuitable. The recorded concentrations ranged from 0.34 to 9.72, with a mean of 2.26. The spatial distribution of KI indicates that the Chitradurga ground waters were found to be non-permissible in around 86 % of water samples, as it recorded KI of >1. The SSP varied from 25.60 to 90.67% with a mean of 63.07%. The spatial distribution of SSP was found to be fair to poor in around 93 % (51 samples) of water samples, as higher sodium has the potential to react with the soil upon irrigation and leads to a reduction in soil permeability through the formation of sodium hazard in soil. The higher percent of soluble sodium might be due to the minerals sodium and potassium feldspar in this region, weathering and dissolution of these minerals and also addition of chemical fertilizers resulted higher levels of sodium and potassium contents in the groundwater (Chandrakala *et al.*, 2024) and also the phenomena of cation interaction and exchange between Ca^{2+} and Na^{+} also occurs naturally in the ground water (Chaudhary & Satheesh kumar, 2018).

Potential salinity indicates that groundwater containing salts with low solubility precipitate in the soil upon irrigation and accumulate in the soil itself. In contrast, the salts with higher solubility have the potential to cause soil salinity (Doneen, 1964b; Siamak & Srikantaswamy, 2009). Chitradurga groundwaters recorded PS of medium to high in more than 64 per cent (35 samples) of samples, thus may lead to soil salinity upon irrigation. The elevated concentration of salts negatively impact plant and crop growth by weakening plant stems and clogging soil pores (Singh *et al.,* 2024) Hwang *et al.* (2017) reported similar studies on assessing groundwater quality for irrigation suitability in Korea. Weathering processes affecting rocks, the return flow associated with agriculture, and the pronounced evaporation-precipitation of seawater

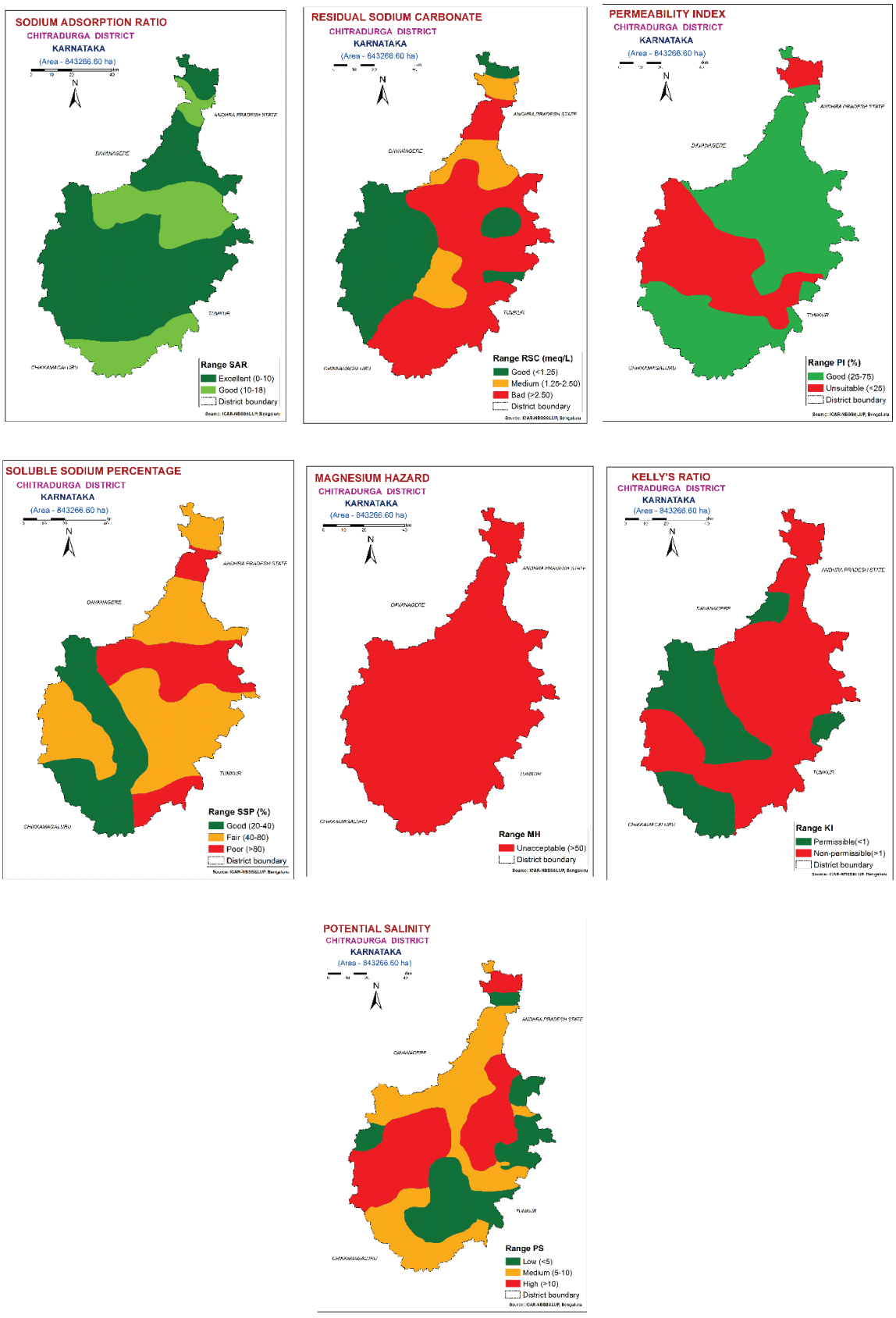


FIGURE 8 Spatial distribution of Chitradurga groundwater quality parameters for irrigation suitability

in arid zones are vital elements that contribute to higher levels of major anion and cation concentration, which makes the groundwater unsuitable for irrigation. Additionally, due to low rainfall, as the Chitradurga district is a drought-prone area, there was a low recharge of the aquifer, resulting in deterioration of groundwater quality.

Pesticide contamination and anthropogenic activities are also significant issues affecting groundwater quality in the district. Artificial recharge to groundwater through percolation tanks, check dams, and nalla bunds is the most effective solution to improve groundwater quality and reduce contamination, as it can dilute the groundwater with high-quality canal waters in the plain areas of the district (CGWB, 2013). And also strategies such as rainwater harvesting to dilute salts, crop rotation with salt-tolerant crops, or blending groundwater with canal water are recommended. Few methods for groundwater treatment include salinity reduction and removal of contaminants through adsorption and electrochemical techniques, as well as dilution of the contaminated water source with rainwater (Khatri *et al*., 2020; Gupta & Misra, 2016). Implementing best land use practices and optimum use of agricultural inputs can also help mitigate groundwater quality issues (Gupta., 2024)

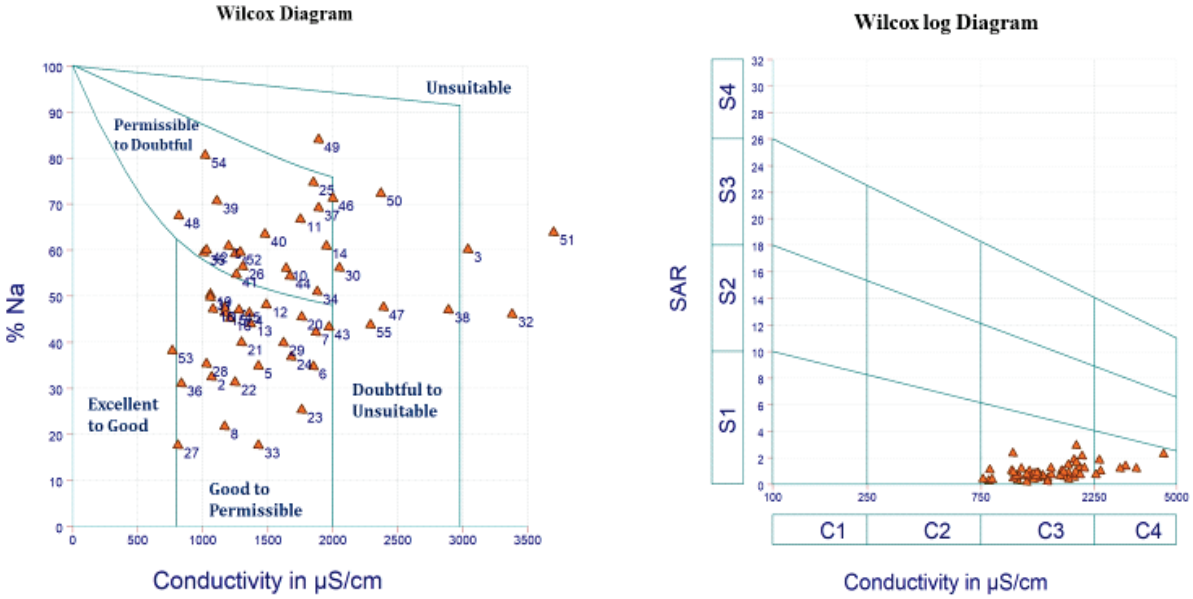


FIGURE 9 Wilcox and Wilcox log diagrams for the ground waters of Chitradurga district

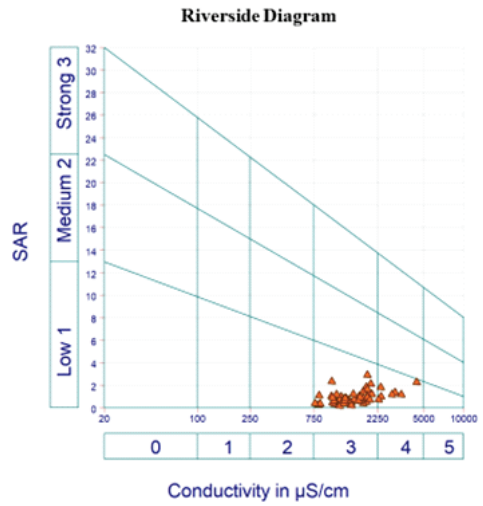


FIGURE 10 Riverside diagram for the ground waters of Chitradurga district

4 | CONCLUSIONS

This comprehensive assessment of 55 groundwater samples from Chitradurga district revealed Na^{+}-K^{+}-Cl^{-}-HCO_3^{-} dominated hydrochemistry, primarily originating from rock weathering processes and evaporation-precipitation mechanisms typical of semi-arid environments. The Piper diagram classification identified mixed cation-anion types with alkalis (Na^{+}+K^{+}) exceeding alkaline earth metals (Ca^{2+}+Mg^{2+}), indicating significant mineral dissolution and cation exchange processes. Water Quality Index (WQI) analysis demonstrated that 87% of groundwater samples (WQI: 30-50) meet excellent standards for potable use, while 13% fall within good quality range (WQI: 51-81). Total hardness values (75.53-622.63 mgl_{-1} $CaCO_3$) remained within BIS permissible limits, and total dissolved solids (488.96-2,816 $mg\,l_{-1}$) indicated generally acceptable quality for consumption, despite elevated salinity in localized areas.

Critical irrigation quality parameters revealed 70% of samples classified as C3S1 (high salinity, low sodium) and C4S1 (very high salinity, low sodium), requiring

drainage management, and 100% of samples demonstrated Magnesium Hazard (MH) values >50%, indicating universal risk of soil structure deterioration and alkalinity development. Geographic analysis revealed distinct contamination zones with higher sodium and potassium concentrations in northern arid regions, likely attributed to enhanced evaporation rates and deeper groundwater extraction. Boron concentrations were elevated in southern semi-arid areas due to sequential solute deposition processes. These findings provide essential baseline data for developing targeted groundwater management strategies in drought-prone semi-arid regions. The spatial distribution maps enable precision interventions for specific taluks, optimising resource allocation for water treatment infrastructure.

The irrigation suitability assessment offers critical guidance for crop selection and irrigation scheduling. Farmers can implement appropriate soil amendments (gypsum application, organic matter incorporation) and adopt salt-tolerant crop varieties in areas with high salinity groundwater. Results support evidence-based policy decisions for sustainable groundwater utilization, including mandatory water treatment protocols for irrigation in 70% of the study area and artificial recharge programs to dilute contaminated aquifers.

Nevertheless, the current analysis represents only pre-monsoon conditions (February-March 2023-2024). Comprehensive seasonal monitoring across monsoon and post-monsoon periods is essential to understand temporal hydrochemical fluctuations and establish dynamic management protocols. While natural processes dominate groundwater chemistry, anthropogenic contributions from agricultural fertilizers, industrial activities, and urban waste require detailed source apportionment studies using isotopic analysis and multivariate statistical techniques.

Further research is required to identify cost-effective treatments for chemical signatures such as high Na^+, Mg^{2+}, and HCO_3^-. Urgent pilot studies on ion exchange, reverse osmosis, and biological systems in local conditions are needed. Long-term monitoring incorporating climate data is vital to understanding how rainfall and temperature influence groundwater, especially in drought-prone areas. Although limited, field experiments assessing water quality impacts on soil and crops are essential for validation and improved management. The lack of comprehensive cost-benefit analyses restricts adoption by resource-limited farmers. Creating decision support systems that utilize real-time water, weather, and crop data represents a top research priority.

Based on these findings, immediate interventions should include: (1) implementation of artificial recharge programs using canal water to dilute contaminated aquifers, (2) mandatory water treatment for irrigation in high-risk zones, (3) promotion of salt-tolerant crop varieties and deficit irrigation techniques, and (4) establishment of continuous water quality monitoring networks to track remediation effectiveness and prevent further deterioration. These measures, combined with targeted research addressing identified gaps, will ensure sustainable groundwater utilization while maintaining agricultural productivity and soil health in Chitradurga district.

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CONFLICT OF INTEREST

There are no conflicts of interest

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DATA AVAILABILITY STATEMENT

Data is available with the corresponding author and will be provided if its required

AUTHOR'S CONTRIBUTION

CM is the principal investigator who conducted the investigation and wrote the manuscript, RC accompanied the PI during sample collection in the field and prepared the figures and graphs. GAT checked the manuscript for plagiarism using turnit in software and edited the plagiarized contents , SGC reviewed the draft manuscript, PS done the laboratory water analysis, HR and PMV prepared the maps in GIS and and RV co-ordinated the work.

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ORIGINAL ARTICLE

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Optimum Designing and Field Validation of a Multi-Objective Integrated Farming System in Indian North-Western Himalayas

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ABSTRACT

Multi-criteria decision making (MCDM) technique – compromise programming – was utilized to optimize an integrated farming system (IFS) operated by a representative small sized farm of Indian north-western mid-Himalayas (INWH). The optimization was undertaken to provide a better alternative for formulation of an IFS individually for such variable sized farms that are the majority, especially in INWH, as compared to non-mathematical fixed farm-size simulations that have been adopted in India, which follow a one-size-fits-all approach. The optimal IFS aimed to maximize farm income and food energy while minimizing soil loss – conflicting decision criteria chosen and prioritized by the farmer within constraints such as production input-output ratios, available resources, and preferences for local production to meet family needs. Optimization of selected farmers' IFS revealed potential to achieve better values of their farming attributes, more so revealed by its on-field implementation. Implementation of the formulated IFS plan, comprising crop cultivation and animal husbandry components, on the farm continuously for three years could achieve higher average farm income of >10% and food energy production of >1% compared to potential of 10.9% and 0.4% as per the optimal IFS plan, respectively. The success of the implemented IFS model based on the formulated index indicated that it has at least 67% probability of achieving its potential. Formulating farmer-specific IFS with MCDM, considering local needs and traits, helps small farms identify the best options across criteria, enabling them to move beyond subsistence and failure-prone farming.

1 | INTRODUCTION

Small and marginal farmers, comprising 86.1% of India's farming community but owning just 46.9% of operational land (Kumar and Pathak, 2024), form the backbone of the rural economy. Yet, they struggle to generate stable and adequate supplies of food, nutrition and cash. Their challenges are compounded by reliance on monsoons, persistent land degradation, dependent on labour-intensive practices, and the ongoing impacts of climate change. To sustainably improve their livelihoods, there is an urgent need to focus on farming systems that promote economic stability, soil sustainability, environmental quality, and ecological balance even in less favourable regions. With land per capita shrinking due to population growth, India has limited potential for expanding agriculture horizontally. Thus, vertical intensification, integrating diverse farming components, becomes essential to ensure consistent income for farm families. The Integrated Farming System (IFS) achieves this by linking various bio-systems, where outputs or by-products from one enterprise serve as inputs for another (Gill *et al.,* 2009). This synergy makes IFS a viable pathway for meeting rising demands for food and nutrition, while also providing income stability for small and marginal farmers who operate under resource constraints.

The scientific community widely endorses IFS as a suitable approach for these households (Dagar, 2014). Small landholders often focus on cereal crops that are highly vulnerable to climate variability. Failure of monsoon rains can quickly jeopardize family sustenance (Kumar *et al.,* 2013). Compared to mono-cropping IFS leverages synergies among multiple components, yielding more output with fewer inputs, conserving resources, and reducing production costs—thus improving both productivity and income (Akter *et al.*, 2024; Edwards *et al*., 1988). IFS also emphasizes by-product utilization,

enhancing the profitability and feasibility of resource-constrained farming (Behera and France, 2016). IFS encompasses a suite of practices designed to achieve sustained production, high profits, and minimal negative environmental impacts, while improving the living standards of small and marginal farmers (Gupta *et al.*, 2012; Lal and Miller, 1990; Kumar *et al.*, 2013). Mimicking natural diversity, IFS incorporates crops, animals, poultry, fish, and various plants to maximize year-round resource use (Kumar *et al*., 2015). When well-planned, integrating multiple enterprises with cropping offers greater returns than monoculture, which is especially crucial for resource-limited farmers (Gill *et al*., 2009). The benefits of IFS are multidimensional: it enhances food security, environmental sustainability, resource conservation, and social acceptability (Akter *et al.*, 2024; Chuanrum and Shrestha, 2024; Tipraqsa *et al*., 2007). Notably, IFS can address soil fertility depletion, thus supporting both productivity and sustainability (Gowing *et al*., 2020).

The IFS adoption is recommended for various Indian agro-ecologies (Balamatti and Shamaraj, 2017; Basavanneppa and Gaddi, 2017; Gill *et al*., 2009; Pankaj, 2018; Sahoo *et al*., 2015; Surve *et al*., 2014; Tanwar *et al*., 2018). Multiple regional case studies (Behera and Mahapatra, 1999; Bisht, 2011; Bohra *et al*., 2014; Gill et al., 2009; Goverdhan *et al*., 2020; Kumar *et al.*, 2012; Makdoh et al., 2014; Mohanty et al., 2016; Rautaray *et al.*, 2005; Sahoo and Behera, 2017; Sekar *et al*., 2001; Sharma *et al*., 2014; Sheokand *et al*., 2000; Singh *et al.,* 2012) inform policy and practice, and IFS has become a government focus for small and marginal farmers, aiming at livelihood security and a new Green Revolution. However, despite research efforts, many IFS findings have not translated into actionable recommendations for stakeholders (Dagar, 2014). A key limitation is the often rigid design of case studies—using fixed enterprise sizes and discrete landholding classes—while actual farm sizes and component mixes vary widely. Moreover, IFS is not prescriptive but must be tailored to local ecological and socioeconomic conditions (BAA, 1996; IACPA, 1996; Morris and Winter, 1999; FAO, 2001; Singh *et al.,* 1998; Yamin *et al*., 2010). Effective IFS planning requires a holistic, multidisciplinary, and context-specific approach, considering the entire farm unit and local resource and market realities. Given the complexity of farming systems—comprising soil, crops, animals, machinery, labour, capital, and family management—a decision-making tool capable of optimizing multiple, sometimes competing objectives is essential. Multi-Criteria Decision Making (MCDM) techniques enable simultaneous optimization of several goals ranked by farmers according to their needs and preferences. MCDM can determine optimal resource allocation (for example, ideal land area for each IFS component) tailored to specific farm constraints, objectives, and priorities-offering a precision lacking in previous simulation studies, which often ignored the realities of farm-level resource constraints and priorities.

HIGHLIGHTS

- Optimized Integrated Farming System (OIFS) using a multi-criteria decision-making technique boosted the farmer's annual net income by about 10%.
- Three years of field implementation of OIFS closely matched model predictions, with a success index indicating about a 67% chance of reaching projected gains.
- Scaling up, farmer-specific, multi-objective optimization approach can improve rural livelihoods and resilience in the Himalayan region.

Globally, few IFS case studies have employed optimization techniques (Groot et al., 2012; Liang et al.,2018;Rundengan, 2014), and such research is almost non-existent in India (Mandal et al., 2017). Notably, only Groot et al. (2012) implemented an optimized, multi-objective 96 ha mixed organic farm in the Netherlands. No study has yet developed and tested an optimal IFS in the Himalayan agro-ecosystem, tailored to a farmer's objectives, enterprise preferences, and real resource constraints. The objective of the present study is to optimally enhance an existing IFS for a small farmer in the Himalayan foothills, using an MCDM technique that accounts for the farmer's diverse and prioritized objectives, resource limitations, and enterprise preferences. The study also compares the actual outcomes of this implementation with the MCDM-generated recommendations.

2 | MATERIALS AND METHODS

2.1 | Study Area

The Indian North-Western Himalayan (INWH) region spreads to an approximate area of 33.13 million ha, which is about 10% of India's total geographical area. The region itself supports 2.4% (29.5 million) of the country's human population. The region accounts for only 3.7% (18.8 million) of the total livestock population of the country; however, animal husbandry is an integral part of hill agriculture as it is required for various purposes – milk, meat, wool, fur, hide, manure, and transportation. The major portion (76%) of the INWH region's population lives in rural areas. Agriculture and allied sectors provide direct employment to about 70% of the workforce. The net sown area of the region is only 12% (2019/20) of reported geographical area, ranging from 10% in Himachal Pradesh (HP) to 13% in Jammu & Kashmir (J&K) among the three, including Uttarakhand (UK), INWH states (GoI, 2022), which is low in comparison to that of the country (43%). Out of the net sown area of the INWH region, 34% is rain-dependent (ICAR-IASRI, 2024). However, agriculture is the backbone of the region as agriculture and livestock contribute 11.04% to 17.12% of the total Gross State Value Added (GSVA) of Agriculture and Allied Sector in total GSVA of the State at current prices (2021/22) across three states (GoI, 2022).

The average landholding per farmer in the region

ranges from 0.59 ha (Jammu & Kashmir) to 0.95 ha (Himachal Pradesh), which is below the national average of 1.08 ha (2015/16). Despite sparse population, pressure on agricultural land remains high due to only 12% of land being cultivated, leading to small land holdings. Over the years, the share of small and marginal farmers increased from 87-94% in 2005-06 to 89-95% by 2015/16. The share of total cultivated area owned by marginal and small farmers grew from 52%-70% in 2005/06 to 56%-73% in 2015-16 (ICAR-IASRI, 2024). The states within the INWH region have higher cropping intensity than India overall, reaching between 151% and 168% in 2019/20 (GoI, 2022), with a national average of 142%. Since agriculture is the primary livelihood for most residents, land use is highly intensive. Despite this, natural factors lead to land productivity remaining below the national average.

The main features of hill and mountain farming in INWH states include small, fragmented land holdings, sloping farmlands, rainfed agriculture, poor water management, and socio-economic challenges faced by farmers. The Himalayas are naturally susceptible to soil erosion due to fragile geology, steep slopes, and intense storms. Rainwater-induced soil erosion is a significant issue, with rates exceeding 10 Mg ha^{-1} yr^{-1}. Recent data show that the UK has the highest land area affected by water erosion (21%), followed by HP (18%) and J&K (9%). Erosion causes annual crop yield losses between 10% (J&K) and 20% (UK) in rainfed cereals, oilseeds, and pulses, mainly because of steep terrain and poor management practices (Sharda *et al*., 2010), resulting in reduced crop productivity (Sharda & Dogra, 2013). Overuse of natural resources has led to severe land degradation and paradoxical water scarcity despite the region's abundant water resources. The Himalayas, often called the "Water Towers of the Earth" (Messerli & Ives, 1997), supply nearly half (47%) of India's usable surface water through the Indus and Ganga-Brahmaputra-Meghna basins (Kumar *et al*., 2005). However, local communities face water shortages because ongoing mismanagement of catchment areas has decreased the perennial flow of natural springs and streams over time (Banskota & Chalise, 2000; Rawat, 1988; Sharda, 2005; Valdiya & Bartarya, 1991). About 78% of the region's total cropped area, where agriculture is the main source of local economic growth, relies on rainwater because of water scarcity, leading to less than optimal food production and increased poverty (Dogra *et al*., 2014).

2.2 | The IFS Farmer

Ashti watershed (473 ha), located between 770 47' 18" and 770 49' 48" E and 300 39' 10" and 300 40' 35" N (Fig. 1 & 2) in Dehradun district, in the north-western mid-Himalayas of the Indian state of Uttarakhand and representing major Agro-ecological Zone 14—namely Western Himalaya was selected by ICAR-Indian Institute of Soil and Water Conservation (formerly CSWCRTI), Dehradun, for development as a model watershed during the XI Plan under the National Watershed Development Project for Rainfed Areas (NWDPRA) funded by the Ministry of Agriculture, Govt. of India. The watershed features mountainous terrain with undulating topography and steep slopes (average slope 67%). It drains into the river Tons, a tributary of the Yamuna river in the Ganga-Brahmaputra-Meghna basins. The watershed has a well-developed drainage network. Soils in the watershed are light-textured, primarily gravelly sandy loam to silty clay loam, with high bulk density, infiltration, and permeability rates. Water-holding capacity is very low, with low available nitrogen and medium to high levels of phosphorus and potassium. Organic carbon content is very high in most soils due to frequent application of partially decomposed farmyard manure (FYM) and low temperatures. The annual rainfall is approximately 1600 mm, with most of it (75-80)% falling during the monsoon season (June-September). The area also experiences high-intensity storms and occasional cloud bursts. Snowfall occurs occasionally in the higher elevations. Winter season rainfall generally does not meet the water requirements of crops (CSWCRTI, 2009).

In 2014, a farmer from Tangri village in the Ashti watershed was selected for the study. Tangri had 16 small-scale farming families, each with plots no larger than 1.0 ha, from resource-poor backgrounds. The farmer's farm spans 0.67 ha, with 0.18 ha (26%) irrigated by seasonal streams and 0.49 ha (74%) relying on rainfall. Water supply depends on rainfall. His land is highly fragmented, with 30 small fields averaging 0.023 ha, mainly in Tangri and Jamuwa (see Fig. 3). He grows cereals, pulses, oilseeds, vegetables, and fodder. His livestock includes 8.1 SLU, comprising buffaloes, cows, bullocks, calves, and goats. His family has ten adults—five men, five women over 20—and seven children, with some working outside as teachers or students, while others are farm laborers. Farming is his main occupation, and he earns extra as a temporary laborer in road work during the off-season.

2.3 | Data Collection and Computations

All relevant data needed to create an optimal IFS plan (OIP), based on the existing/suboptimal IFS plan (ESIP) using an MCDM technique, was gathered from the farmer. Primary quantitative data for the selected farmer, required to outline the current IFS on his farm and its details, was collected through personal interviews and recorded on well-structured questionnaires. This data was collected during 2013-14 from the farmer, representing an average of the past three years. For data collection, his farm's production enterprises—such as cultivated cropping sequences in a year and owned livestock—were first listed. For crops, the sowing and harvesting dates were recorded to determine the land requirement period for each crop during the year. Data on cropping season-wise area allocation of rainfed and irrigated land for each crop, along with human and animal labor (month-wise), seed, farmyard manure (FYM), fertilizers, and pesticides, as well as the average yields of main and by-products, were documented. Livestock (sheep/goats) were considered collectively as a single enterprise. To evaluate the economics of these enterprises,

the prices of various inputs used and outputs produced were recorded. Input, output, and price data were collected as an average over the past five years.

To optimize the existing IFS according to the farmer's objectives—such as guiding improvement or optimization of farming attributes, decision criteria, as well as production enterprises' preferences and the farmer's actual resources and constraints—which greatly influence farming decisions—the following data collection and necessary calculations were undertaken.

- The farmer selected three decision criteria for optimization: net returns (farm income in Indian Rupees), nutrient energy (food production in Mcal), and soil loss (Mg). These criteria represented the farmer's objectives (Romero & Rehman, 2003), with each assigned a weight that sums to ten across all objectives. During the survey, the farmer recorded the importance of each objective: maximizing farm income (weight 5), maximizing food energy production (weight 4), and minimizing soil loss (weight 1) objectives.



FIGURE 1 Index map of District Dehradun in Uttarakhand State, India



FIGURE 2 Index map of Ashti watershed, District Dehradun in Uttarakhand State, India

- ·For each objective function, the respective coefficient of each production activity was calculated. A budgeting technique was used to determine the individual net returns of various crops (from main product only) and livestock (from cattle milk and goat meat) based on collected data. For crops, the estimates for this attribute or decision criterion were initially made based on the actual area cultivated for each, and then on a per-unit-area basis. For livestock, actual measurements of each animal (for goats and sheep, treated as one group) were used. The costs incurred for purchasing inputs for any production activity were not included in the net return estimation, as these costs were summed for all activities and separately accounted for in the net returns objective function of the MCDM model, following a linear programming approach by Sankhayan and Cheema (1991). Accordingly, the costs of fertilizers such as urea, DAP, and CAN were not used in calculating the net returns of crops for which they are applied. However, since pesticides were purchased in limited quantities only for the cultivation of tomato, their costs were included in the net return calculation for tomatoes. Similarly, this approach was applied for feed, which is purchased and fed only to lactating livestock. Food energy production from grains, seeds of cultivated cereals, pulses, and oilseeds; fruits, tubers, and corms of vegetables; livestock milk; and goat meat was calculated based on the standard nutritional values provided in Gopalan *et al.* (2012). Soil loss rates were not available for individual crops at the IFS location, particularly for rainfed crops like maize and finger millet grown during the rainy season. As a result, experimental data from similar nearby conditions were used as proxies. For irrigated crops, soil loss rates were considered negligible because they are cultivated under well-managed conditions (Sharda *et al*., 2010). The estimates for each production enterprise (net returns – INR ha^{-1}, food energy – 10^3 kcal ha^{-1}, and soil loss – Mg ha^{-1}) were used as coefficients per hectare in the formulation of the objective functions of the optimization model. For each livestock animal, these were represented as INR $animal^{-1}$ and 10^3 kcal $animal^{-1}$ for net returns and nutrient energy, respectively. It is also understandable that soil loss was assumed to be zero for each livestock animal.
- Quantitative data on utilized resources—including owned [rainfed/irrigated land, month-wise human (family) labor, drought animal power, farm-produced crop seeds, and farm equipment] and fodder (dry/green) harvested from various sources (crops, field bunds, community land, pastures, and forest) across different seasons—were collected. To identify the limited resources, the actual utilization of each resource across all

farm production enterprises was summed and compared to its respective total available resources owned by the farmer. This process helped identify resource constraints and formulate them for the MCDM model. Land constraints for crops were considered separately for rainfed and irrigated categories of cultivated land in each location and month, as the farmer practiced crop rotations that overlapped over time. These constraints were incorporated into the optimization model to ensure proper allocation of the limited cultivated land in each category. Each purchased input was regarded as a limited resource since the farmer did not own it, and purchased it using limited capital. The farmer used urea for all crops except wheat and peas. Fertilizers such as calcium ammonium nitrate (CAN) and di-ammonium phosphate (DAP) were used for tomato cultivation. Because these inputs were purchased and limited, they represented constraints for farming. The average input-output coefficients of these constraints were estimated using a budgeting technique based on the actual utilization of the limited resource for a crop production activity per hectare; for individual livestock, actual utilization served as the coefficients. In addition to the identified land resource and fertilizer constraints, such as summer+rainy season irrigated land at Jamuwa (month-wise), winter season irrigated land at Jamuwa (month-wise), summer+rainy season irrigated land at Tangri (month-wise), winter season irrigated land at Tangri (month-wise), and fertilizers [urea, DAP, and CAN], a simple land constraint was included for dairy activity in the optimization model (Sankhayan and Cheema, 1991). Other inputs were found to be non-limiting for achieving farming objectives due to their surplus availability. For example, human labor was not a constraint because of a large family size (1620 mandays/year). Similarly, fodder was not a constraint mainly due to good availability from nearby forests, and FYM was not a constraint because of the high livestock ownership (8.5 standard livestock units). These resources, which were not limited in production activities, were also valued and used to estimate the net returns of the activity, forming the coefficients for the net returns maximization goal function.

- An IFS can integrate bio-systems since the output of one can serve as the input for another, and vice versa. In the IFS of this study, the fodder produced by the crop component is the input for the livestock component, and the produced manure (FYM) is the input for the crops. These outputs are considered intermediate because they are consumed as inputs; therefore, they were not included in the net returns calculation. However, since costs were incurred in their production with the main outputs, they were included as costs whenever used as inputs for livestock and crops, respectively. For the same reason, the net returns of a fodder crop were considered negative, as it functions as an input for the livestock component of the IFS. Nutritional computation was not performed for any fodder because the goal was to maximize nutrient energy for the farm family.
- A set of capital constraints was used, including two based on the mentioned seasonal groups and one on the total capital limit. The optimization was conducted using the farmer's own capital, as he relied solely on his personal funds for farming activities. The coefficients for these constraints represented the cost per unit area for each production activity, excluding input purchase costs. (Sankhayan and Cheema, 1991).
- Two new production enterprises – paddy + fish inter-culture and drip irrigated tomato – were suggested to the farmer who agreed to include them in the OIP. Their costs and returns available from secondary sources were utilized for the analysis.
- Preferences regarding the farming enterprises (existing or any new), and their respective sizes (maximum/minimum/constant) in terms of area allocation/number recorded during survey were utilized as a set of constraints in the model. These preferences were for meeting the food and nutrition requirements of his large family from his own land, as well as the limitation of resources for allocation to high-input crops
- Technical restrictions formed the last set of constraints.

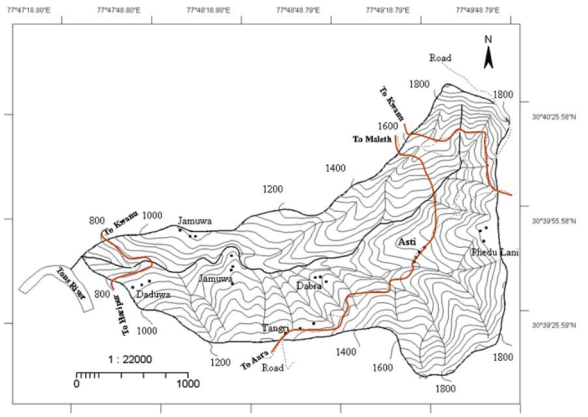


FIGURE 3 Map of Ashti Watershed

2.4| Optimization Model Formulation

Multi-Criteria Decision Making (MCDM) techniques have inherent properties which render them practically useful, e.g., multiple and conflicting criteria are explicitly accounted for, and rational, justifiable, and explainable decisions are provided (Belton & Stewart, 2002). MCDM has some desirable features that make it an appropriate tool for analysing complex natural resource management problems (Mendoza & Martins, 2006). Among MCDM techniques, compromise programming is a well-established mathematical programming technique, which has the inherent advantage of conceptual simplicity, especially for solving natural resources allocation problems (Romero &

& Rehman, 2003). Compromise programming (CP) allows handling of several objectives in those situations in which the existence of a high level of conflict between criteria does not permit simultaneous optimization of all the considered objectives (Raizada *et al*., 2008; Sankhayan, 1988). For optimization of IFS of the selected farmer, a multi-criteria optimization model was formulated following compromise programming, as given below, for simultaneously optimizing the farmer's three farming objectives as per his weight-based ranking of the objectives, his preferences for farming enterprises, and his resource constraints.

The model includes farming activities and constraints that characterize the farming enterprise of the selected farmer over a 12-month period. CP was utilized as the two objectives – maximization of farm income and food energy production - are inherently conflicting with the third objective of minimization of soil loss. In such cases, obtaining an ideal solution that simultaneously achieves the desired ideal values of the three objectives (indicated by individual optimization of each objective with no consideration of the other objectives in it) is difficult. The form of CP adopted for the study was as described in Dogra *et al*. (2014), as the best possible solution lies within the best compromise solutions defined by the two boundaries L_1 and L_∞. It is well established that L_1 and L_∞ matrices define the two boundaries of all the compromise solutions, and all other best compromise solutions fall between these two boundaries (Romero & Rehman, 2003). Therefore, two optimal solutions, termed as L_1 and L_∞, were generated by CP for the farmer's IFS.

Objective Functions

$$MaxFarmIncome = \sum_{c=1}^{C}\sum_{v=1}^{V} a_{cv}X_{cv} + \sum_{d=1}^{D} a_d X_d - \sum_{f=u,m,n} (1+i_r)p_f X_f - \sum_{r=y,w} i_r X_r \quad (1)$$

X_{cv} cultivated area allocated (ha) for crop c at location v
X_d livestock animal allocated d (unit)
X_f fertilizer f (u - urea, m - DAP, – CAN) quantity purchased for crops cultivation (kg)
X_f owned capital utilized (INR) except for purchasing in season r (y - summer+rainy, w- winter)
a_{cv} returns over variable cost other than of purchasing (INR ha^{-1}, from crop c at location v
a_d returns over variable cost other than of purchasing (INR) from livestock animal d
i_r rate of interest (%) charged on owned capital utilized during season r (y- summer+rainy, w- winter)
p_f price of a fertilizer f (u - urea, m - DAP, n - CAN) (INR kg^{-1})
c, d, v, f, r index of crops, livestock animals, location, fertilizers and cropping season, respectively
C, D, V number of crops cultivated/introduced, livestock animals owned, and locations, respectively

$$MaxFoodEnergy = \sum_{c=1}^{C} e_c X_{cv} + \sum_{d=1}^{D} e_d X_d \quad (2)$$

e_c nutrient energy (Mcal ha^{-1}) from crop c
e_d nutrient energy (Mcal) from livestock animal d

$$MinSoilLoss = \sum_{c=1}^{C} s_c X_{cv} \quad (3)$$

s_c soil loss (Mg $ha^{-1}yr^{-1}$) from cultivation of crop c

Constraints

The three objective functions were subjected to sets of six categories of constraints, *viz*. land, fertilizer, capital, individual crop's area, as well as animal's number as per farmers' preferences, and technical restrictions in the model, as they significantly affect production on the farm.

Land constraints set:

$$\sum_{c=1}^{C} X_{cv} \le L_{vmr} \quad (4)$$

L_{vmr} total irrigated/rainfed land r available (ha) for allocation at location V during month (m)

$$\sum_{d=1}^{D} l_d X_d \le L_d \quad (5)$$

I_d land required (ha) for animal shed of a livestock animal d
L_d total and available (ha) for animal sheds of d livestock animals

Fertilizer constraints set:

$$\sum_{c=1}^{C} z_{cfv} X_{cv} - X_f \le 0 \quad (6)$$

Z_{cfv} fertilizer f (u - urea, m - DAP, n - CAN) quantity required to cultivate crop c on a unit area at location v ($kgha^{-1}$)

Capital constraints set:

$$\sum_{c=1}^{C} k_{cr} X_{cv} + \sum_{d=1}^{D} k_{dr} X_d - X_r \le 0 \quad (7)$$

k_{cr} working capital required other than for purchasing during season r (y - summer+rainy, w - winter) to cultivate crop c on a unit area at location v ($INRha^{-1}$)
k_{dr} working capital required other than for purchasing during season r (y - summer+rainy, w - winter) for a livestock animal d (INR)

$$\sum_{f=u,m,n} p_f X_f + \sum_{r=y,w} X_r \le K \quad (8)$$

K total amount of own working capital actually utilized in a year for farming by the farmer for all crop and livestock production activities in the ESIP (INR)

Crop area restrictions set:

$$\sum_{c=1}^{C} X_{cv} \leq T_{cv} \quad (9)$$

$$\sum_{c=1}^{C} X_{cv} = T_{cv} \quad (10)$$

$$\sum_{c=1}^{C} X_{cv} \geq T_{cv} \quad (11)$$

T_{cv} area allocation (ha) restriction for crop *c* at location *v*

Animal number restrictions set:

$$\sum_{c=1}^{C} X_{d} = B_{d} \quad (12)$$

B_d number of a livestock animal *d*

After all the necessary data were generated, it was used in the optimization model. Optimal solutions, L_1 and L_∞, were obtained using software developed earlier (Cheema, 1992) and used for other studies, notably Raizada *et al*. (2008) and Dogra *et al*. (2014). The optimization exercise was done several times, as each generated OIP was discussed with the farmer, and his suggestions and preferences were incorporated in the input matrix for the optimization model to obtain the OIP that is as per the farmer's importance-ranked objectives, production enterprises' preferences, and his actual resource endowment and constraints. The final form of the matrix generated as per the above model had three objective functions, 31 production and non-production activities, and 94 constraints of various kinds. Before the implementation, the final optimal solutions, L_1 and L_∞, were discussed with the farmer for him to select one of these two OIP for implementation.

2.5 | Measurements of Success of Implemented IFS

Success of the implemented OIP was assessed based on cumulative comparison of values of its three objective functions to two different standards, namely (a) values of objective functions of farmer's ESIP, and (b) potential values of objective functions of OIP (*per se* before its implementation). For the measurement of success, two indicators were formulated. First indicator – Success Index – measured success of the implemented optimal IFS in the individual year of implementation:

$$Success\ Index = \sum_{i=1}^{n} w_i \left(\frac{v_i}{V_{is}}\right) \quad (13)$$

where,

V_i actual value of objective function *i* after implementation of the OIP on farmer's fields

V_{is} value of objective function *i* as per chosen standard *s* for measuring success

W_i weight assigned by the farmer to objective function *i*

n total number of objective functions optimized for the IFS

It measured how precisely the implemented OIP was able to generate higher farm income and nutrient energy (as "higher is better" is the universal norm for these two parameters) as well as lower soil loss (as "lesser is better" is the general norm for this parameter) as compared to the identified standards. Estimated value of the Success Index varied as per the standard based on which it was estimated.

The second indicator – Probability of Success – based on the estimated values of the first indicator (Success Index) over the years of implementation, estimated the probability of the implemented OIP being successful as per the two standards. As it was hypothesized that the implemented OIP would achieve higher values of farm income and nutrient energy, and lower values of soil loss as compared to the standard of ESIP values, therefore the implemented OIP was considered to be a success only if it happened accordingly, i.e., the Success Index has a value higher than 1.0. On the other hand, in case of second standard (expected values from OIP before its implementation), since it was hypothesized that the implemented OIP may or may not achieve the highest/potential values, therefore it was considered to be a success if values of the implemented OIP were higher than *or even equal to* those of the second standard i.e. the Success Index has a value higher than or equal to 1.0. Therefore, this indicator's value also varied as per the standard employed.

When the standard was ESIP values, number of years the value of Success Index was greater than 1.0 were counted for estimation of the probability of success:

$$Probability\ of\ Success = \frac{Number\ of\ years\ value\ of\ Success\ Index\ > 1.0}{Number\ of\ years\ of\ implementation} \quad (14)$$

When the standard was potential values of objective functions of OIP, the number of years the value of Success Index was equal to or greater than 1.0 were counted for estimation of the probability of success:

$$Probability\ of\ Success = \frac{Number\ of\ years\ value\ of\ Success\ Index\ \geq 1.0}{Number\ of\ years\ of\ implementation} \quad (15)$$

3 | RESULTS AND DISCUSSION

3.1 | Scope for Improvement in the Suboptimal IFS

Prior to the generation of two optimal solutions, L_1 and L_∞ using CP, the three decision criteria – net returns, nutrient energy from food, and soil loss - each expressed as an objective in the form of a mathematical function of decision variables - were individually optimized subject to same set of constraints using simple linear programming (LP). Thereby, three optimal plans were generated. From the values of the three decision criteria obtained from each LP optimal plan, a Payoff Matrix was generated for the farmer's farm (Table 1). The diagonal elements of the Payoff Matrix, called the Ideal Points, indicated the maximum scope (potential) of improvement of the value of an individual

decision criterion. The minimum value of a decision criterion in the Payoff Matrix, called its Anti-Ideal Point, indicates the extent to which it will have to be sacrificed when optimization is done for another decision criterion as the objective function. In light of the above, farm income individually can increase by a significant 11% (its Ideal Point) over the ESIP; but if other decision criteria are optimized, then the range of change in its value will be a reduction by 1% (its Anti-Ideal Point) to an increase by 10%. Similarly, nutrient energy individually can be increased by only 1% (its Ideal Point). When other decision criteria are optimized, it will decrease by 0.2% to 2% (its Anti-Ideal Point). Individually, soil loss can be reduced significantly by 43% (its Ideal Point), otherwise it will be reduced by 2% (its Anti-Ideal Point) to 3% only. This indicated that there was a conflict among the decision criteria. If the farm income LP optimization plan is implemented, the nutrient energy production on the farm will be 0.2% less than that from ESIP, though soil loss will decrease (2%), which is desirable but not the best one as it is not its Ideal Point. If the soil loss LP optimization plan is implemented, farm income (1%) and nutrient energy (2%) will be even less than that from ESIP, and the lowest, being their Anti-Ideal Points. Implementation of nutrient energy LP optimization plan will increase farm income (10%) and decrease soil loss (3%), but they are not their Ideal Points.

TABLE 1 Payoff matrix of IFS farmer's decision criteria

Planning Situation	Decision Criteria Value		
	Net Returns (INR)	Nutrient Energy (Mcal)	Soil loss (Mg)
Before optimization	269,776	68,156	5.32
Payoff matrix			
Farm income (maximized)	**299,308 (11)**	67,992 (-0.2)	5.24 (-2)
Nutrient Energy (maximized)	297,399 (10)	**68,519 (1)**	5.17 (-3)
Soil loss (minimized)	266,150 (-1)	66,495 (-2)	**3.04 (-43)**

Figures in parentheses are percentage change as compared to respective value before optimization.

The farmer selected the final form of the optimal solution L_1 for implementation as values of the decision criteria net returns and food energy of this solution were higher by INR 2373 (0.8%) and 233 Mcal (0.3%), respectively than of L_∞ solution. However, soil loss was 1 Mg (20%) higher from L_1 solution. The farmer, therefore, preferred to have more income and food energy from the IFS at the cost of higher soil loss (Table 2).

A comparison of decision criteria values of the ESIP against the same of the optimal solution L_1, i.e., the OIP (Table 3), indicated that the OIP could provide 10.9% (INR 29,302) significantly higher net returns of INR 299,078 (compared to INR 269,776) from the farm. Similarly, food energy can be improved, though marginally by 0.4% (68,443 Mcal compared to 68,156 Mcal). Further, these higher values can be achieved with 1.1% lower soil loss (5.26 Mg compared to 5.32 Mg) from the farm. The scope for improvement of last two decision criteria is lower than for net returns because of higher importance/weight given by the farmer to it, though many of the production enterprises are both a source of income as well as nutrition, which vary across the crops. Also, the scope for improvement is curtailed if the farmer's preferences and constraints are such that crops that are a better source of food energy are allocated a lesser area than higher income-generating crops in the OIP.

To examine the reasons for changes in decision criteria values due to optimization, the area allocations before and after optimization need to be reviewed (Table 4). In Jamuwa, among irrigated crops, ESIP allocated 10%, 40%, and 50% of the gross cropped irrigated area to clover, tomato, and pea crops, respectively. Conversely, in OIP, allocations of the gross cropped irrigated area of Jamuwa were 0% for clover, 47% for tomato, 47% for pea, and 7% for paddy+fish. For rainfed crops, ESIP allocated 10%, 7%, 33%, and 50% of the gross cropped rainfed area to ginger, chili, maize, and wheat, respectively. In contrast, the optimal OIP allocations were 8%, 8%, 32%, and 52% of the gross cropped rainfed area to these crops, respectively.

TABLE 2 Comparison of the compromise programming generated optimal solutions

Optimal Solution	Net Returns (INR)	Food Energy (Mcal)	Soil loss (Mg)
L_1	299,078	68,443	5.3
L_∞	296,704	68,210	4.4
Difference	2,373	233	0.9
	(0.8)	(0.3)	(20)

Figures in parentheses are percent difference of L_1 from L_∞

For Tangri, the ESIP allocations from gross cropped irrigated area were 39%, 10%, 13%, 25%, and 13% for tomato, maize, potato+coriander, rapeseed, and pea crops, respectively. However, the OIP allocations differed—22%, 0%, 13%, 17%, 26%, and 22%—for tomato, maize, potato+coriander, rapeseed, pea, and tomato-drip, respectively, of the gross cropped irrigated area. For rainfed crops at the location, the ESIP allocations were 6%, 9%, 6%, 38%, 2%, 10%, and 30% for colocasia, chilli, ginger, maize, pigeonpea, fingermillet, and wheat, respectively, of the gross cropped rainfed area. In the case of OIP, the allocations were 4%, 8%, 7%, 42%, 2%, 8%, and 29% for colocasia, chilli, ginger, maize, pigeonpea, fingermillet, and wheat, respectively, of the gross cropped rainfed area of Tangri.

From these allocations, it is clear that for the OIP, area allocations increased for irrigated crops such as tomato and paddy+fish, at the expense of declining areas under clover and pea at Jamuwa. Similarly, there was an increase in area for tomato-drip and pea compared to tomato, as well as for maize and rapeseed at Tangri. For rainfed crops, the area allocated in the OIP increased for chili and wheat, with decreases in ginger and maize at Jamuwa, and similarly for ginger and maize compared to colocasia, chili, fingermillet, and wheat at Tangri. Overall, no area was allocated to clover at Jamuwa or to irrigated maize at Tangri (see Table 4). Higher areas were allocated to cash crops such as tomato and chili at Jamuwa, and pea and ginger at Tangri, compared to ESIP, although the areas for other cash crops like pea and ginger at Jamuwa, and tomato and chili at Tangri, decreased. The new production enterprises—paddy + fish intercultural cultivation and drip-irrigated tomato—were allocated 0.01 ha and 0.05 ha, respectively, by the OIP. The area under potato and coriander remained unchanged. For cereal crops, the area allocated to maize decreased while that for wheat increased at Jamuwa. At Tangri, the area for the remaining crops decreased, except for rainfed maize. Since net returns received the highest weight in the OIP, the area for less profitable crops decreased in favor of more profitable ones. A similar trend was observed for the next most important decision criterion, food energy, based on its assigned weight. Regarding the livestock component of the IFS, the farmer preferred to maintain the current number of livestock units (8.1 SLU), as they were deemed optimal for the farm's maintenance and meeting the family's needs.

TABLE 3 Comparison of decision criteria values before and after optimization

Decision Criteria	Optimization	Existing/ Suboptimal IFS	Optimal IFS	Expected change
New Returns (INR)	Maximized	269,776	299,078	29,302 (10.9)
Energy (Mcal)	Maximized	68,156	68,443	287 (0.4)
Soil Loss (Mg)	Minimized	5.32	5.26	0.1 (-1.1)

Figures in parentheses are percent difference of optimal IFS from existing IFS

3.2 | Resource Use Change

With optimization, there was a change in the use of purchased inputs, namely urea, DAP, and CAN fertilizers, included as constraints in the optimization model. The annual quantity of urea used increased slightly by 4% (3.27 kg), from 81.37 kg in the ESIP to 84.64 kg in the OIP. For DAP, although the increase was significant at 20%, from 24.86 kg to 29.83 kg in the respective plans, the actual increase in use was only 4.97 kg, similar to urea. In the case of CAN, utilization decreased by 16%, from 1.09 kg to 0.92 kg in the respective plans. The overall quantitative decrease was a small 0.17 kg. Therefore, the changes in fertilizer use proposed by the OIP were marginal. Even with these small changes in fertilizer utilization due to shifts in cultivated area allocations, there was a potential for an 11% increase in net returns, along with marginal but positive improvements in the other two decision criteria.

3.3 | Optimal IFS Implementation

The selected OIP was implemented by the farmer on his farm over three years (2014-15 to 2016/17) under the technical guidance of ICAR-IISWC. During the implementation period, yield data of the crops grown according to the OIP, as well as the owned livestock, were recorded (Table 5). The new production activity of paddy-fish interculture was not adopted or implemented by the farmer, although he initially agreed to adopt it, and it was considered for optimization. The location, Jamuwa, where this activity could be adopted, is situated a significant walking distance via footpath across the watershed landscape (Fig. 3) from Tangri, where the farmer resides. He expressed an inability to prevent fish from escaping the field to wild animals. Additionally, since paddy cultivation is a new intervention on a small area of 0.01 ha (the smallest among all optimal allocations), he did not implement this activity at any point during the three-year study. This indicates that small or marginal hilly farmers face difficulties in adopting new farming activities due to inherent constraints.

Over the recorded period, yields of chili and maize were higher than their average yields, while the yields of other crops ranged from higher to lower. During 2014/15, yields of most cultivated crops were either less than (for 10 crops) or equal to (for 5 crops) their respective averages.

Potato, coriander, rapeseed, fingermillet, colocasia, and wheat-Tangri had yields equal to their averages, while all other crops, except chili and maize at both locations, had lower yields (Table 5). The differences in yields for these crops ranged from (-)8% (wheat-Jamuwa) to (-)65% (tomato-drip). The low yields during this year were mainly attributed by farmers to poor rainfall. During 2014/15, there was an 18% rainfall deficit (ICAR-IISWC, 2014), primarily due to low rainfall (883 mm) during monsoon months (July to September 2014), compared to 1257 mm and 1123 mm in 2015/16 and 2016/17. Even irrigated crops experienced low yields due to limited water availability for irrigation. However, chili yielded significantly more than average, ranging from 52% to 116%, along with maize at 6% to 7%. Both crops performed well at both locations despite the low rainfall during the year. There was no change in yield for livestock products (milk and meat) during this period.

TABLE 4 Existing and optimal IFS plan cultivated area allocations

S.No	Production activity and location	Cultivation period months	Rainfed/Irrigated	Existing/Subo ptimal IFS plan (ha)	Optimal IFS plan (ha)	Difference in plans (%)
			Jamuwa			
1	Clover	January-June	Irrigated	0.015	0.000	-100
2	Tomato	March-June	Irrigated	0.062	0.070	14
3	Ginger	April-October	Rainfed	0.025	0.020	-19
4	Chilli	April-October	Rainfed	0.018	0.020	8
5	Maize	May/June-October	Rainfed	0.082	0.080	-3
6	Paddy+Fish	May/June-July	Irrigated	-	0.010	NA
7	Pea	October-December	Irrigated	0.077	0.070	-9
8	Wheat	November-April	Rainfed	0.126	0.130	4
			Tangri			
9	Tomato	March-June	Irrigated	0.082	0.050	-39
10	Tomato-Drip	March-June	Irrigated	-	0.050	NA
11	Colocasia	March/April-Oct.	Rainfed	0.031	0.020	-35
12	Chilli	April-October	Rainfed	0.044	0.040	-9
13	Ginger	April-October	Rainfed	0.031	0.035	13
14	Maize	May/June-October	Irrigated	0.022	0.000	-100
15	Maize	May/June-October	Rainfed	0.196	0.215	10
16	Pigeonpea	June/July-Oct/Nov.	Rainfed	0.011	0.010	-8
17	Fingermillet	June-November	Rainfed	0.050	0.040	-19
18	Potato+Coriandor	July-September	Irrigated	0.027	0.030	12
19	Rapeseed	October-December	Irrigated	0.054	0.040	-27
20	Pea	October-December	Irrigated	0.027	0.060	123
21	Wheat	November-May	Rainfed	0.152	0.150	-1
			Total	1.130	1.140	

During 2015/16 and 2016/17, most crops had yields that were higher than or equal to the average yields (Table 5). In 2015/16, except for rapeseed (-14%), pigeonpea (-14%), and fingermillet (-13%) at Tangri, crop yields were higher at both locations. The increase ranged from 1% (ginger-Jamuwa and colocasia) to 60% (maize-Tangri). There was no change in the yields of potato+coriander intercropping and wheat-Tangri. Equivalent yields were also produced in intercrops in 2016/17. Additionally, there was no change in the yields of rapeseed, fingermillet, and colocasia. All other crops, except wheat-Tangri (-15%), had higher yields than their average yields. Higher yields ranged from 7% (pigeonpea, tomato-drip) to 80% (maize-Tangri). The higher-than-average yields over the two years were attributed to near-normal rainfall. Regarding livestock, buffalo yields were 4% and 21% higher than average during the two years, respectively. However, cow yields increased by 2% in 2015/16 but declined in 2016/17 due to the end of its lactation period. There was no change in meat yield from goats.

3.4 | Decision Criteria Values after Implementation

To estimate the year-wise net returns for each production activity of the implemented optimal IFS, the recorded yield data over the years were used. It was assumed that input utilization remained constant. Constant prices, used for

optimal planning, were applied for net return estimations across the years. For nutrient energy, the energy per unit crop area or livestock unit, used in planning, was employed to estimate nutrient energy production from the yields. As a result, varying yields of the production activities led to different values of the two decision criteria over the years. Regarding soil loss, the values based on proxy experimental data used for optimal planning were assumed as soil loss estimates.

Farm income from the implemented OIP could not reach the potential 11% higher value during 2014/15 due to lower yields (-11% to -65%, Table 5) of cash crops like tomato, pea, and ginger, which occupied 31% of the gross cropped area, compared to the respective average yields at both locations (Table 6). The below-average yields were mainly caused by below-average rainfall (18% deficit), especially during the rainy season (30% less than 2015/16 and 21% less than 2016/17). Other external factors may also have contributed to the lower yields. Among cash crops and all crops, ginger yields the highest average net returns from both locations (INR 1,072,141 ha^{-1}), followed by tomato (INR 695,258 ha^{-1}) and pea (INR 232,741 ha^{-1}), each with their respective average yields. Although chili, a cash crop, had higher (52% to 116%) yields than the average during 2014/15 at both sites, it only partly offset income losses because it provides the lowest net returns (average INR 64,816 ha^{-1} across both locations) among cash crops, with area allocation at only 5% of the gross cropped area. Food crops grown on the farm, mainly for family consumption, also have monetary value. Among these, colocasia stands out with the highest net returns (INR 261,700 ha^{-1}), and it can supplement farm income, especially when cash crop returns are low, as its 2014/15 yield matched the average. Tuber colocasia, in addition to being a high-income cash crop, is a nutrient-rich food crop that can be stored for future use. Similarly, crops like potato+coriander (INR 220,776 ha^{-1}), rapeseed (INR 19,530 ha^{-1}), fingermillet (INR 13,635 ha^{-1}), wheat-Tangri (INR 7,924 ha^{-1}), as well as livestock like buffalo (INR 42,345), cows (INR 8,819), and goats (INR 17,986), can increase farm income. Although maize has a lower income value (average INR 25,188 ha^{-1}) than cash crops, it contributed to income maximization by yielding 6%-7% more than its average yield. Other food crops experienced yield decreases ranging from -8% (wheat-Jamuwa, INR 10,324 ha^{-1}) to -64% (pigeonpea, INR 136,669 ha^{-1}), which negatively affected farm income. Overall, the farm income was 25% below the ESIP target (Table 3). The low yields of cash crops also reduced total food energy produced on the farm during 2014/15, especially since ginger (average 18,427 $Mcalha^{-1}$) and tomato (average 7,957 $Mcalha^{-1}$) have higher energy values than most other food crops. Pea (average 4,632 $Mcalha^{-1}$) also saw a reduction in on-farm energy due to low yields at both locations. Although chili's yield increase of 116% could not fully compensate for the energy shortfall from other cash crops, it has a relatively low energy value (average 861 $Mcalha^{-1}$). Among food crops, pigeonpea, with a 64% yield decline (4,641 $Mcalha^{-1}$), reduced energy production. Similarly, wheat-Jamuwa (4,360 $Mcalha^{-1}$) showed a decline, whereas wheat-Tangri nearly maintained its potential energy output, with no change in yield. Other crops like colocasia (18,842 $Mcalha^{-1}$), potato+coriander (14,516 $Mcalha^{-1}$), maize (average 7,695 $Mcalha^{-1}$), fingermillet (4,264 $Mcalha^{-1}$), and rapeseed (3,246 $Mcalha^{-1}$), contributed to total energy production due to yields at or above average. Overall, food energy was only 1% below the ESIP target (Table 6). Since soil loss could not be measured at the IFS location, it was assumed that there was no change in this criterion's value, despite the low rainfall in 2014/15 and normal or above-normal rainfall in the other study years.

In 2015/16 and 2016/17, higher than average yields across all cash crops and most food crops resulted in more than 11% higher net returns during these years. Cash crops, especially those with high income values, contributed to increased farm income in 2015/16, with yield increases ranging from 1% to 26% on 36% of the cultivated land. Although the highest income cash crops like ginger and tomato showed slightly lower yields at Jamuwa (1% to 2%) compared to Tangri due to distance management issues, the yields of other cash crops still boosted net returns. Among food crops, colocasia (INR 261,700 ha^{-1}), potato + coriander (INR 220,776 ha^{-1}), maize (INR 25, 188 ha^{-1}), and wheat (INR 9, 124 ha^{-1}) saw yield increases of 1% to 60%, contributing to income growth. Milk yields from buffalo and cow increased by 2% to 4%, further supporting income gains, along with goats. Conversely, crops like rapeseed, pigeonpea, and fingermillet experienced decreased productivity (-13% to -14%), negatively affecting farm income. Overall, net returns rose by 23.5% in 2015/16. The following year, 2016/17, saw even higher crop yields (except for wheat at Tangri (-15%) and the cow (-100%), boosting farm income by 32.3% (see Table 6). High-value cash crops such as ginger (31% to 33%), tomato (7% to 29%), and chilli (31% to 59%) were significant contributors. In food crops, maize (53% to 80%), pigeonpea (7%), and wheat at Jamuwa (8%) stood out as main contributors. Intercropped potato and coriander, fingermillet, colocasia, and rapeseed also contributed additional yields. In energy terms, crops increased energy production by more than expected by 0.4% in both 2015/16 and 2016/17 thanks to higher yields for most crops. Although pea and chilli, ranked lower for energy production, showed yield increases of 3% to 59%, ginger and tomato at Tangri contributed more energy than in 2014/15 with increases of 15% to 33%. Maize, with high energy content, experienced yield increases of 24% to 80%. Colocasia and potato + coriander, ranked high for energy, also contributed positively, with yields matching average yields. The total decision criterion value increased by 2.7% in 2015/16, and in 2016/17, the increase was slightly higher at 2.8%, driven by yield increases across most crops. Over the three years of OIP implementation, farm income increased on average by 10.2%, and food energy production grew by 1.4%.

TABLE 5 Yields during Implementation of optimal IFS plan

Location-wise production activity	Average yield before 2014/15 ($Mgha^{-1}$)	Yield ($Mgha^{-1}$) under optimal IFS implemented during			Difference (%)		
		2014/15	2015/16	2016/17	2014/15	2015/16	2016/17
			Jamuwa				
Tomato	32.6	14.0	33.3	39.7	-57	2	22
Pea	9.8	8.4	11.5	10.6	-14	17	8
Ginger	29.1	19.8	29.3	38.0	-32	1	31
Chilli	3.2	6.9	3.3	4.2	116	3	31
Maize	1.7	1.8	2.1	2.6	6	24	53
Wheat	1.2	1.1	1.4	1.3	-8	17	8
			Tangri				
Tomato	35.3	14.9	40.7	45.5	-58	15	29
Potato+Coriander	14.0[#]	13.9	14.0	14.1	-1	0	1
	4.5[##]	4.5	4.5	4.5	0	0	0
Rapeseed	0.7	0.7	0.6	0.7	0	-14	0
Pea	10.0	8.9	12.3	11.9	-11	23	19
Chilli	2.7	4.1	3.4	4.3	52	26	59
Maize	1.5	1.6	2.4	2.7	7	60	80
Fingermillet	1.5	1.5	1.3	1.5	0	-13	0
Ginger	25.9	18.2	30.0	34.5	-30	16	33
Colocasia	19.4	19.4	19.5	19.4	0	1	0
Pigeonpea	1.4	0.5	1.2	1.5	-64	-14	7
Wheat	1.3	1.3	1.3	1.1	0	0	-15
Tomato-Drip	42.3	14.9	49.5	45.5	-65	17	7
Livestock							
Buffalo*	1,703	1,703	1,779	2,068	0	4	21
Cow*	548	548	557	0	0	2	-100
Goats*	30	30	30	30	0	0	0

*[#]Potato data row, [##]Coriander data row; *Litre; **kg*

TABLE 6 Decision criteria values of implemented optimal IFS plan

Particulars	Decision Criterion		
	Farm Income (maximization) ($INRyr^{-1}$)	Food Energy (maximization) ($Mcalyr^{-1}$)	Min Soil Loss (minimization) ($Mgyr^{-1}$)
Farmer assigned weight	5	4	1
Value from existing/suboptimal IFS plan	269,776	68,156	5.32
Potential value from optimal IFS plan	299,078	68,443	5.27
	(10.9)	(0.4)	(-1.1)
Value from implemented optimal IFS plan			
2014/15	201,433	67,334	5.27
	(-25.3)	(-1.2)	(-1.1)
2015/16	333,219	70,003	5.27
	(23.5)	(2.7)	(-1.1)
2016/17	356,906	70,069	5.27
	(32.3)	(2.8)	(-1.1)

Figure in parentheses is percent difference from respective suboptimal IFS value

3.5 | Success of Implemented IFS

To evaluate the overall benefit to the farmer across three decision criteria during different implementation years of the formulated OIP, and to estimate the probability of the OIP's future success on the farmer's field based on success in individual years, the Success Index was calculated using two standards for each year. Results showed that in the first year, the index ranged from 0.8 to 0.9 below 1.0 across both standards (Table 7), mainly due to significantly low yields in nine production activities, which affected farm income and food energy production. In the subsequent two years, the index increased to between 1.1 and 1.2, as poor yields occurred in one to three activities, while most remaining activities yielded well. Consequently, the success probability of the OIP was estimated at 67% under both standards, primarily due to poor rainfall—a factor beyond human control. Despite this 67% success chance, the potential of the OIP to enhance farm income and food energy output while reducing soil loss suggests that the farmer would benefit more from adopting the OIP over the ESIP in the future.

TABLE 7 Success index and probability of success of the optimal IFS plan

Year	Standard for measurement							
	Values of objective functions of existing/ suboptimal IFS plan				Expected Values of objective functions of IFS optimal plan			
	Farm Income	Food Energy	Soil Loss	Success Index	Farm Income	Food Energy	Soil Loss	Success Index
2014/15	0.75	0.99	1.01	0.9	0.67	0.98	1.00	0.8
2015/16	1.24	1.03	1.01	1.1	1.11	1.02	1.00	1.1
2016/17	1.32	1.03	1.01	1.2	1.19	1.02	1.00	1.1
Probability of Success (%)				67				67

4 | CONCLUSIONS

This study aimed to use a multi-criteria decision-making (MCDM) tool for a structured, systematic, and mathematical approach to optimize an integrated farming system (IFS). The optimization considered location- and farmer-specific conditions rather than fixed-size farm simulations often used in studies, especially in India, leading to a better (or new) IFS plan compared to the suboptimal existing one. The compromise programming method was employed to develop an optimal IFS plan (OIP) for a typical small farmer in the Indian north-west Himalayas, involving crop cultivation and animal husbandry. The OIP was designed to balance three conflicting but essential goals: increasing farm income, boosting food energy production, and reducing land degradation by minimizing soil loss for sustainability. The OIP was formulated based on crop and livestock input-output ratios, available resources, constraints, and farmer preferences to meet local family needs. After three years of implementing the OIP, using constraints specific to each location, farm income increased by 10.2% and food energy production by 0.4%. The overall results showed an average income increase of 10.2% and food energy increase of 1.4%. The OIP demonstrated the potential to improve the farmer's decision criteria compared to the existing system, especially as evidenced by field results. A formulated index from two different standards indicated that the OIP has a 67% chance of achieving or exceeding its potential to enhance the farmer's farming attributes.

Formulating such optimal IFS using multi-criteria decision-making tools can be a promising approach to support the Indian Government's focus on integrated farming systems. This can help marginal and small farmers, who are central to the Indian rural economy, move away from subsistence and high-risk farming due to limited resources and climate variability. Stakeholders need to advocate for policies supporting this. An individual farmer approach should be adopted in developing integrated farming systems, supported by policy proposals. Developing decision support systems (DSS) to provide customized IFS models tailored to specific farming conditions—especially under fluctuating input/output prices, technology, and policy changes—can enhance farmers' food production, net income, employment, risk management, and other benefits of IFS. Including environmental protection features, like soil erosion reduction and water conservation in IFS planning through optimization should be mandatory via appropriate policies, ensuring sustainability amid climate change. Generating optimal IFS models using suitable multi-criteria decision-making (MCDM) tools, combined with advanced mathematical methods such as multi-period programming—leveraging real-time data on input and output prices—and artificial intelligence (AI), can further amplify the benefits of IFS.

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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 paper.

DATA AVAILABILITY STATEMENT

Data is available with the corresponding author and will be provided as and when required.

AUTHOR'S CONTRIBUTION

Conceptualization: PD; Data curation: PD, ACR, SP, MM, NKS; Methodology: PD; Resources: ACR; Software application: PD; Validation: PD, ACR, SP; Visualization: PD; Writing – original draft: PD; Writing – review and editing: PD, ACR, SP, MM, NKS.

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ORIGINAL ARTICLE

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Sustainable Intensification of Rice-Fallow Areas through Strategic Crop Selection and Fertilizer Management in Lower Indo-Gangetic Plains

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ABSTRACT

In rainfed lowland rice ecosystem of eastern part of India, farmers generally sow various winter crops like lentil, lathyrus, chickpea field pea and linseed in the standing rice crop field just before the harvest of crop in order to utilize the post harvest soil moisture and nutrients. In this experiment the performance of *utera* crops was studied with fertilizers applied both in soil and foliar under rainfed rice ecosystem. The experiment was conducted with 3-main plot treatments consisting 3 *utera* crops viz. linseed, lentil and lathyrus; and 3 sub-plot treatments of fertilizer management viz. Suphala (NPK15:15:15) @ 150 kg ha^{-1} (22.5 kgNha^{-1}), Di-ammonium phosphate (DAP: NP18:46) @ 125 kg ha^{-1} (22.5 kg N) applied on saturated rice soil as basal 4 days before seed sowing of *utera* crops and DAP spraying@ 2 g/lit of water at 20,40 and 60 days after sowing respectively.The results of experiment in the lowland rainfed rice ecosystem revealed that legumes crops like lathyrus and lentil recorded the higher yields than linseed *utera* crops. In the experiment, soil application of suphala (NPK15:15:15) @ 150 kg ha^{-1} gave the highest grain yield followed by DAP soil application; DAP foliar spray recorded least.The variation in crop growth and yield attributes of *utera* crops were also similar to the trends as noted in crop yields. The variation in built up soil fertility was noted by the *utera* crops specially legumes. The actual ET of utera crops were veried being the lowest ETa, whereas, linseed had maximum ETa value. Crop water use efficiency value was more in lathyrus and with suphala but least value was noted in linseed crop and with DAP foliar spray.The maximum benefit-cost ratio was obtained in lentil and DAP soil application. Based on the results of experiment, lathyrus, lentil and linseed may be grown as *utera* crops with the soil application of complex fertilizer suphala (NPK15:15:15) @ 150 kg ha^{-1} in low land rice ecosystem of lower Indo-Gangetic Plains.

1 | INTRODUCTION

The 'Rice-fallow' term is used for rainfed *kharif* rice areas, which remain fallow or uncropped during the *rabi* season due to various abiotic and biotic constraints (Kumar *et al*., 2020). Rainfed rice agro-ecosystems play a crucial role in food production, and there is a significant opportunity to utilize residual moisture in rice-fallow areas to cultivate short-duration, low-input, and demanding pulse and oilseed crops. However, the success of crops grown on rice fallows largely depends on the method and cultivars of rice adopted (Kumar *et al.,* 2025). Rice-fallows extend over a large area (~22.3 million ha) in South Asia, with around 88.3% (~19.6 million ha) in India alone. In India, rice is cultivated on ~43.3 million hectares (Kumar *et al.,* 2018; Kumar *et al.*, 2021). On average, ~11.7 million hectares of *kharif* rice area remain fallow during consecutive *rabi* seasons due to various constraints in the country (Kumar *et al*., 2022; Srivastava *et al.,* 2023). Rice fields are scattered in the central regions, eastern plains, coastal peninsula, and northeast hills. The rice-fallow area under eastern India covers ~82% of the area alone, in states of Uttar Pradesh (0.35m ha), Jharkhand and Bihar (2.20 m ha), West Bengal (1.72 m ha), Odisha (1.22 m ha), Madhya Pradesh and Chhattisgarh (4.3 m ha), and Assam (0.54 m ha). Rice-fallow is the *kharif* (wet season) rice land that remains fallow during *rabi* (dry season). Rice is the principal crop during the *kharif* season in eastern India, occupying 26.8

million hectares, which accounts for 63.3 percent of the country's total rice-growing areas (Mahapatra *et al.,* 2022). Thus, India should focus on producing more food to meet its growing needs by increasing rice yields during the wet monsoon season, from June to October, and bringing more area (rice-fallow) under pulse or oilseed cultivation during the dry post-monsoon season, from November to April (Peramaiyan *et al.,* 2023). The moisture status of *aman* rice leaves an excellent scope for taking up another crop in *rabi* in low-land situations. Sometimes, farmers in the area grow *utera* crops during the post-rainy season, utilizing the in-situ soil moisture. In rainfed agriculture, water availability is the primary factor controlling crop productivity in rice-fallow systems. However, the growing of relay crops in rice-fallow systems during the post-rainy season has scope for utilizing carry-over soil water and residual soil fertility (Bandyopadhyay *et al*., 2016). There is a good scope for growing lentil, grass pea, oat, linseed, gram, and mustard as *paira* crops after the harvest of transplanted rice (Behera *et al*., 2020). The intensification of existing agricultural systems is a pressing need to meet the rising demand for food and ensure nutritional security in the country (Chowdhury *et al.,* 2020). In this respect, developing a sound land resource inventory (LRI) and its proper land use planning are on priority for rice-fallow areas in eastern India (Bandyopadhyay *et al*., 2019; Choudhary and Behera, 2019).

In West Bengal, farmers generally sow various winter crops, such as lentils, lathyrus, chickpeas, field peas, and linseed, in the standing rice crop field just before harvest, which helps ensure germination using the residual moisture. Among the abiotic factors, low soil moisture content and rapid soil moisture depletion frequently led to drought situations at flowering and harvesting. Even if the crop is managed well with residual soil moisture, short of winter rains at the grain-filling stage often lead to complete crop failures (Kumar *et al.,* 2018). Poor soil moisture and nutrient status are the primary limiting factors for the production of pulses and oilseeds in rice-fallow systems. Site-specific nutrient deficiencies (P, Zn, S, B, Mo), soil acidity, and low soil organic carbon (SOC) directly affect pulse and oilseed production in rice–fallow systems (Behera *et al*., 2020). Therefore, nutritional management for maximizing yield in pulses and oilseeds is a pressing need to address the malnutrition of people in developing countries. Since *paira* crops in relay cropping with rice suffer from nutritional stresses during the reproductive phase, late application of N is effective in reducing flower and pod drop in legume and in increasing seed yield (Singh and Satapathy, 2019). As soil moisture stress limits nodule formation by inhibiting the transport of carbohydrates from leaves to nodules, it is the perfect time to supply nitrogen and phosphorus to the legume plants at 40-50 days. The foliar application of 2% DAP significantly increased the seed yield in black gram, green gram, cowpea, and horse gram (Mahewari *et al.,* 2017). Foliar application of DAP is more effective than basal nitrogen and phosphorus fertilization because it supplies nutrients continuously over a more extended period, which may help photosynthates move steadily and increase crop yields (Sarkar *et al*., 2019). Therefore, there is a scope for Di-ammonium phosphate (DAP) and Suphala (NPK) complex fertilization in *utera* crops as top dressing in the mud soil in standing rice before harvest of the crop, or DAP foliar spray in the early growth period (20-50 days). The present experiment was conducted to investigate the response of *utera* crops to nutrient management in the lowland rice ecosystem of the lower Indo-Gangetic Plains in West Bengal.

HIGHLIGHTS

- Lathyrus (grass pea) and lentil legume crops showed potential for sustainable rice-fallow intensification.
- Soil application of Suphala (NPK 15:15:15) at 150 kg ha^{-1} produced the highest seed yield (650 kg ha^{-1}), outperforming DAP soil application (634 kg ha^{-1}) and DAP foliar spray (566 kg ha^{-1}).
- Lathyrus demonstrated superior water use efficiency (5.42 kg ha-mm^{-1}), while lentil with DAP soil application achieved the maximum benefit-cost ratio of 3.03, indicating both resources efficiency and economic profitability

2 | MATERIALS AND METHODS

A field experiment was conducted at the Agricultural Instructional Farm, Jaguli, Bidhan Chandra Krishi Viswavidyalaya, Nadia, West Bengal (22º56'N latitude, 88°32' E longitude, 9.75m above mean sea level) to study the performance of *utera* (no-till) crops as influenced by nutrient management in rice eco-system during *rabi* (winter) seasons of 2018-19 and 2019-20. The experimental site is located in a sub-tropical, sub-humid climate. The average rainfall is 1,450 mm, with 75% of it received between June and September. During the crop growth period, maximum temperature ranged between 23.34 °C and 33.99 °C, and minimum temperature varied between 9.97 °C and 18.04 °C (Table 1). The maximum relative humidity varied from 94.1% to 97.2%, and the minimum relative humidity varied from 44.9% to 59.6%. Total rainfall was distributed throughout the experimental period, but the highest rainfall was received in the month of November (44.3 mm), followed by December (26.8 mm).

The texture of the experimental topsoil was sandy clay loam (38-46:29-35:24-26%) and it belongs to the order Inceptisol with medium fertility and almost neutral soil pH (Table 2). The experiment was conducted on well-drained Gangetic alluvial soil. It was laid out in a split-plot design with three replications, featuring different utera crops in the main plots: C1-Linseed cv Neela, C2-Lentil cv Maitri, C3-Lathyrus cv Ratan, while different nutrient management treatments were applied in subplots, i.e., N1-Suphala (NPK 15:15:15) at 150 kg ha^{-1}, N2-DAP (NP 18:46) at 125 kg ha-1, N3-DAP spray (2% dilution) three times. The main plot size measured 12 m x 3 m, and the subplots 4.0 m x 3.0 m. Utera crops were sown in the first week (4th and 5th) of November in both 2018-19 and 2019-20. Seeds were sown with a higher seed rate (20% more), specifically 40 kg ha^{-1} for linseed, 80 kg ha^{-1} for lathyrus, and 40 kg ha^{-1} for lentil. Before sowing, seed priming was done with clean water for 6 hours, and seeds were broadcast in standing rice fields 10 days before rice harvesting when soils were sufficiently

oversaturated. Soil application of complex Suphala and DAP (Di-ammonium Phosphate) fertilizers was made to the crop fields 4 days prior to seed broadcasting, when the rice field had a thin film of ponding water (1-2 mm). For the spray treatment of DAP @ 2% dilution (500 liters ha^{-1}), battery-powered sprayers were used three times at 20, 40, and 60 days after sowing. *Utera* crops received winter rains totaling 44.3 mm and 26.8 mm during early stages, but no rainfall occurred during flowering and maturity periods.

The crop was harvested when the plants turned yellowish to brown and had near-optimal seed moisture. After harvest, the crops were left in the field for 2-3 days to sun-dry. Then, the harvested bundles from each plot were taken to a clean threshing floor, where threshing was performed separately for each plot. Growth parameters such as plant height, dry matter accumulation (DMA), crop growth rate (CGR), primary and secondary branches per plant at flowering, and nodules per plant were recorded periodically at 30, 45, and 60 DAS, as well as at harvest. Yield components including plant population at harvest, number of pods per plant, seeds per pod, 10-pod weight, and test weight (1000-seed weight) were recorded at harvest. After threshing, seeds were sun-dried, cleaned, weighed, and converted to kg ha^{-1}. Stover yield was also estimated in kg $ha^{-1.}$ The residual effects of utera crops were assessed by analyzing the soil nutrient status after harvest, following standard methods.

The gravimetric method was used to determine the moisture content in the soil samples at depths of 15 and 30 cm. Soil samples for profile soil moisture status were taken at 15-days intervals from sowing to the harvest period. Soil moisture (SM) content was calculated using the equation below.

$$SM\ (\%) = \frac{\text{Weight of wet soil - Weight of dry soil}}{\text{Weight of dry soil}} X\ 100$$

The total water expenditure in this study was calculated in terms of actual evapotrnaspiration (ETa), which was calculated as profile contribution (PC) plus ER (effective rainfall) as ETa (mm) = PC+ ER and

$$PC\ (mm) = \frac{SMh\text{-}SMi}{100}\ X\ BD\ x\ D$$

Where, SMh- harvest soil moisture (%), SMi- initial soil moisture (%); BD-soil bulk density (g cc^{-1}), D-depth of soil profile (cm).

The water productivity of crops was calculated in terms of water use efficiency (WUE) as dividing the seed yield (Y) by actual evapotranspiration (ETa). Water use efficiency (WUE) was estimated as

$$WUE\ (kg\ ha\text{-}mm^{-1}) = \frac{Y\ (kg\ ha^{-1})}{ETa\ (mm)}$$

Where, Y-seed yield, ETa-Actual evapo transpiration.

The data collected on growth parameters, yield components, and yields were analyzed following the method of analysis for split-plot design as described by Gomez and Gomez (1984). The significance of different sources of variation was tested at a probability level of 0.05. The standard error of mean (SEM) and the value of CD were indicated in the tables to compare the difference between the mean values.

TABLE 1 Meteorological data during the experimental period 2018-19 and 2019-20 (mean)

Month	Temperature (^{0}C)		Relative humidity (%)		Total rainfall (mm)	Pan evaporation (mm day^{-1})	Bright Sunshine (hr)
	Max.	Min.	Max.	Min.			
November	29.48	14.76	96.96	59.56	44.3	2.03	7.77
December	32.48	10.41	96.61	57.06	26.8	1.40	5.78
January	23.34	9.97	97.19	51.80	0.0	1.55	8.85
February	29.45	12.99	97.21	46.10	0.0	2.22	12.05
March	33.99	18.04	94.06	44.93	0.0	3.93	6.59

Source: Department of Agricultural Meteorology and Physics, B.C.K.V., Mohanpur, Nadia

TABLE 2 Soil texture, bulk density, and saturated hydraulic conductivity in the soil profile of lowland rice-ecosystem

Soil layers (mm)	Textural group (%)			B.D (Mg m^{-3})	Saturated hydraulic conductivity (mm h^{-1})
	Sand	Silt	Clay		
0-150	46.14	24.25	29.61	1.41	4.6
151-300	38.23	26.32	35.54	1.46	1.8
301-450	32.13	29.19	38.68	1.51	1.5
451-600	45.32	23.42	31.26	1.48	2.8
601-1200	56.12	16.23	27.65	1.46	7.2

3 | RESULTS AND DISCUSSION

3.1 | Growth Attributes

Plant growth, measured by the plant height of *utera* crops, was significantly influenced by nutritional management practices. Among *utera* crops—linseed, lentil, and lathyrus—plant height increased consistently as the crops developed (Table 3). At harvest, plant heights of linseed, lentil, and lathyrus ranged from 45.0 to 61.9 cm, with linseed reaching the tallest height at 61.9 cm. In the experiment, utera crops fertilized with Suphala (NPK 15:15:15) achieved the highest plant height of 67.6 cm, followed by 56.4 cm, while DAP spray treatment resulted in the shortest height of 49.5 cm. Higher plant heights, with proper nutrition, indicated better internode elongation and improved vegetative growth throughout the crop cycle.

Total dry matter production increased gradually with the advancement of crop age and reached its peak at the time of crop harvest. Among the utera crops, linseed, lentil, and lathyrus, dry-matter accumulation increased progressively with the advancement of crop growth, and their variations were due to differences in crop nutrition.

At harvest, dry-matter production among utera crops, such as linseed, lentil, and lathyrus, varied from 209.9 to 288.8 g m^{-2}, with a 37.58% variation. The highest dry matter production (288.8 g m^{-2}) in lathyrus was recorded. In the experiment, *utera* crops fertilized with DAP foliar spray recorded highest dry matter production of 257.1g m^{-2} followed by DAP Soil (NP 18:46) 254.2 g $m^{-2,}$ and least value of dry matter production 243.8 g m^{-2} was recorded under Suphala (NPK 15:15:15). Application of foliar nutrition at later stage was helpful for plants to grow and produce higher amount dry-matters.

Dry-matter partitioning of crop growth over time in terms of crop growth rate (CGR) of utera crops was significantly affected by different nutrient management practices (Table 3). Although CGR was slow during the early initial stage (just after sowing), it then increased progressively with crop age up to the active vegetative and reproductive stages (Table 3). From 60 DAS to harvest, the CGR value of utera crops ranged from 2.03 to 3.18 g m-2 day-1, with a 56.65% variation, and the highest crop growth rate was observed in lathyrus (3.18 g m-2 day-1). In the experiment, utera crops fertilized with DAP (NP 18:46) recorded the highest CGR value at 3.32 g m-2 day-1, followed by Suphala (NPK 15:15:15) at 3.19 g m-2 day-1.

The production of branches in *utero* crops, such as linseed, lentil, and lathyrus, at flowering time varied significantly with variations in different nutritional management practices (Table 3). At flowering time, the number of primary branches of the crop varied from 6.3 to 8.4, with a 33.33% variation, and a larger number of branches (8.4) in the lentil crop and a smaller number of secondary branches (6.3) in the linseed were seen (Table 3). In the experiment, utera crops fertilized with Suphala recorded the largest number of secondary branches (7.5), followed by DAP-spray 7.3 and the smallest number of secondary branches (6.5) was recorded under DAP (NP 18:46).

The number of active nodules at the flowering stage of crop growth was significantly affected by different nutritional management practices (Table 3). Variations due to crop nutrition were observed from the initial flower stage to 50% flowering, but after flowering was complete, the nodule number continued to decline. Among the paira crops like lentil and lathyrus, the nodule numbers per plant at the flowering stage ranged from 24.8 to 26.0, with the higher number recorded in lathyrus (26.0). In the experiment, utera crops fertilized with DAP (NP18:46) had the highest number of nodules per plant (18.7), followed by Suphala (NPK 15:15:15) with 17.8, while the lowest was under DAP spray treatment with 14.3 nodules per plant. Similar effects of crop nutrition on the growth attributes of utera crops have been reported by Kumar *et al.*, 2023.

TABLE 3 Effect of fertilizer management on growth parameters of *utera* crops in rice-fallow (pooled data of two years)

Treatments	Plant height at harvest (cm)	TDM at harvest (gm^{-2})	CGR at 60-harvest (gm^{-2} day^{-1})	Branching at flowering	Nodule $plant^{-1}$ at flowering
***Utera* crop**					
Linseed	61.9	209.9	2.03	6.3	0.00
Lentil	45.0	256.4	2.32	8.4	24.8
Lathyrus	51.1	288.8	3.18	6.6	26.0
S.Em(±)	0.65	1.15	0.09	0.05	0.05
C.D (p=0.05)	2.42	4.63	0.37	0.21	0.19
Crop Nutrition					
Suphala	54.8	243.8	3.19	7.5	17.8
DAP Soil	53.8	254.2	3.32	6.5	18.7
DAP Spray	49.5	257.1	2.80	7.3	14.3
S.Em (±)	0.34	1.25	0.14	0.12	0.08
C.D (p=0.05)	1.07	3.59	0.44	0.39	0.23

TDM- Total dry matter; CGR- Crop growth rate

3.2 | Yield Attributes and Yield

Plant population at harvest, an important parameter in *utera* crops, was significantly influenced by nutrient management in lowland rice ecosystem (Table 4). The maximum plant population was 49.7 plants per m², and the minimum was 42.8 plants per m². Crop nutrition with DAP soil fertilizer in the *utera* crops had a distinctive impact on the population. The maximum plant population was observed with Suphala fertilizer management in the lathyrus crop. Pods plant^{-1}of *utera* crops like linseed, lentil and lathyrus in rice ecosystem was significantly influenced by nutrient management practices (Table 4). Among *utera* crops lentil recorded the highest number of pods plant^{-1} (27.1) followed by lathyrus (25.4) but linseed crop gave the lowest number of pods plant^{-1} (8.7). The *utera* crops fertilized with Suphala recorded the highest number of pods plant^{-1}(21.6), followed by DAP-soil (20.5), and a relatively smaller number of pods plant^{-1} (19.0) were recorded in DAP-spray. Kumar *et al. (*2023) reported similar impacts of fertilization on *utera* crops.

The number of seeds per pod of utera crops was also significantly affected by nutrient management practices (Table 4). Among these crops, linseed recorded the highest number of seeds per pod at 6.9, followed by lathyrus at 4.1, while lentil produced a significantly lower number of seeds per pod at 2.1. In the experiment, utera crops fertilized with Suphala recorded the highest number of seeds per pod (5.1), followed by DAP soil application treatment (4.2), with the lowest number recorded in DAP spray (3.9). Seeds per pod were also influenced by nutrient management. Linseed, a small-seeded oilseed crop, produced more seeds per pod than lathyrus and lentil. The 10-pod weight of utera crops such as linseed, lentil, and lathyrus in the rice ecosystem was significantly affected by nutrient management practices (Table 4). Among these, lentil recorded the highest 10-pod weight at 2.37 g, followed by lathyrus at 2.03 g, while linseed yielded significantly less at 0.55 g. In the experiment, utera crops fertilized with Suphala (NPK 15:15:15) recorded the highest 10-pod weight at 1.86 g, followed by DAP (NP 18:46) soil application, while the lowest was in DAP foliar spray treatment at 1.38 g. The plumpness or boldness of seeds, measured as test weight (1000 seed weight), was significantly affected by diversified nutrient management. Among these crops, lathyrus had the highest test weight at 59.1, followed by lentil at 20.9, while linseed had a very low test weight at 5.3. In the experiment, utera crops fertilized with Suphala (NPK 15:15:15) recorded the highest test weight at 30.2, followed by DAP (NP 18:46) treatment at 28.6, with DAP spray showing the lowest at 26.5. Many researchers have reported a positive response of nutrient management on the growth and yield attributes of utera crops (Maheswari *et al.*, 2017; Kumari et al., 2024; Saha *et al.*, 2025).

The land productivity, in terms of seed yield, of utera crops like linseed, lentil, and lathyrus grown in a rice ecosystem was significantly influenced by nutrient management practices (Table 4). Among the *utera* crops, lathyrus recorded the highest yield of 725 kg ha^{-1} followed by lentil (721 kg ha^{-1}), but linseed crop gave significantly less yield of 404 kg ha^{-1}. In harmony with our findings, Bandyopadhyay *et al*. (2018) also reported that a higher yield of lentil was obtained in the no tillage condition than in the conservation and minimum tillage conditions. The yield variation among the *utera* crops was 79.45%. In the experiment, *utera* crops fertilized with Suphala (NPK 15:15:15) @ 150 kg ha^{-1} recorded the highest grain yield (650 kg ha^{-1}), followed by DAP (NP 18:46) @ 125 kg ha^{-1}, and the lowest seed yield (565.83 kg ha^{-1}) was recorded in DAP foliar spray treatment. The yield variation due to differential nutrition was 14.85% which was much less under the zero-till situation. The availability of nutrients may have contributed to the increased translocation of photosynthates to the sink, resulting in improvements in yield attributes and crop yields of legume crops (Singh *et al*., 2018; Kumar *et al*., 2023).

The biomass productivity in terms of stover plus seed yield of *utera* crops like linseed, lentil and lathyrus in rice ecosystem was significantly influenced by the nutrient management practices (Table 4). Among the *utera* crops, lathyrus recorded the highest biomass yield of 2481 kg ha^{-1}

TABLE 4 Effect of fertilizer management on yield attributes and yield of *utera* crops in rice-fallow (pooled data of two years)

Treatments	Plant population at harvest	No of pods plant^{-1}	Seeds pod^{-1}	10 pod weight (g)	Text weight (g)	Seed yield (kg ha^{-1})	Biomass yield (kg ha^{-1})	Harvest Index
***Utera* crop**								
Linseed	42.8	8.7	6.9	0.55	5.3	404	1508	0.27
Lentil	49.0	27.1	2.1	2.37	20.9	721	1970	0.37
Lathyrus	49.7	25.4	4.0	2.03	59.1	725	2481	0.29
S.Em(±)	0.23	0.41	0.39	0.15	0.82	12.6	12.7	0.06
C.D (p=0.05)	0.63	1.15	1.10	0.44	2.69	37.17	37.73	0.19
Crop Nutrition								
Suphala	49.6	21.6	5.0	1.86	30.2	650	1910	0.29
DAP Soil	49.8	20.5	4.2	1.71	28.6	634	1965	0.25
DAP Spray	42.1	19.0	3.9	1.38	26.5	566	2084	0.26
S.Em(±)	0.21	0.61	0.14	0.10	0.35	15.56	8.47	0.08
C.D (p=0.05)	0.64	1.83	0.42	0.31	1.04	45.91	24.74	NS

followed by lentil (1970 kg ha^{-1}) but linseed crop gave very less biomass yield of 1508 kg ha^{-1}. In the experiment, *utera* crops fertilized with DAP foliar spray recorded the highest biomass yield (2084 kg ha^{-1}) followed by DAP (NP 18:46) the treatment (1965 kg ha^{-1}) and the lowest biomass yield (1909 kg ha^{-1}) was recorded in Suphala treatment. Source to sink ratio in terms of harvest index of *utera* crops like linseed, lentil and lathyrus in rice ecosystem was significantly influenced by nutrient management practices (Table 4). Among *utera* crops, lentil recorded the highest harvest index of 0.37 followed by lathyrus (0.29) but linseed crop gave very less harvest index of 0.27. *Utera* crops fertilized with Suphala (NPK 15:15:15) recorded the highest harvest index (0.29), followed by DAP spray treatment (0.26), and the lowest harvest index (0.25) was recorded in DAP (NP 18:46) treatment. Similar positive response of DAP has been reported by Suhathiya and Ravichandran (2018).

TABLE 5 Effect of fertilizer management on nutrient status in post-harvest soil of *utera* crops in rainfed rice-fallow (pooled data of two years)

Treatments	Nutrient status in post-harvest soil			
	Nitrogen (kg ha^{-1})	Phosphorus (kg ha^{-1})	Potassium (kg ha^{-1})	SOC (%)
Utera crop				
Linseed	190.2	28.8	194.0	0.56
Lentil	227.9	42.2	207.4	0.65
Lathyrus	225.5	38.7	200.2	0.63
S.Em(±)	1.91	1.14	5.80	0.10
C.D (p=0.05)	7.56	4.58	23.40	0.50
Crop Nutrition				
Suphala	216.8	35.2	228.5	0.62
DAP Soil	234.7	42.1	189.6	0.66
DAP Spray	192.2	32.5	183.6	0.61
S.Em(±)	2.93	1.42	4.34	0.12
C.D (p=0.05)	8.71	4.38	13.35	0.38
Initial Value*	156.8	25.0	146.8	0.60

*pH 7.61; Interactions - significant

3.3 | Nutrient Dynamics

The status of available N, P, K, and soil organic carbon (SOC) in soil was significantly affected by different nutrient management practices (Table 5). Among utera crops, linseed, lentil, and lathyrus, the results revealed that N, P, K, and organic carbon content differ significantly.

The data on the available nutrients in the soil after crop harvest are presented in Table 5. The status of available N, P, K, and SOC in soil was significantly influenced by different *utera* crops and nutrient regimes. The results were encouraging, as the N, P, and K contents increased significantly, regardless of the various crops and fertilizer regimes, compared to the initial value. The legume crops, such as lentil and lathyrus, also enhanced the organic carbon content. Maximum content of available nitrogen, phosphorus, potassium and organic carbon content was noted under lentil crop grown field i.e. (227.9 kg ha^{-1}, 42.3 kg ha^{-1}, 207.4 kg ha^{-1} and 0.65%) followed by lathyrus grown field i.e. (225.5 kg ha^{-1}, 38.8 kg ha^{-1}, 200.2 kg ha^{-1} and 0.63) but linseed grown field gave less available nutrient status i.e.(190.2 kg ha^{-1}, 28.8 kg ha^{-1}, 194.0 kg ha^{-1} and 0.56%). This might be attributed to the combined effects of legume N-fixation and applied fertilizer, which was utilized less in rainfed situations. Among the different nutrient management practices available, nitrogen, phosphorus, and % of organic carbon were found to be maximum in the plot fertilized with DAP (NP 18:46) soil application i.e., (234.7 kg ha^{-1}, 42.1 kg ha^{-1} and 0.66%) and potassium status was maximum in the plot fertilized with suphala (NPK 15:15:15) i.e. (228.5 kg ha^{-1}). The lowest nutrient status was observed under the DAP foliar spray treatment only. The larger increase in NPK status happened in lentil and lathyrus than in linseed. This was also true in carbon sequestration in lentil and lathyrus but organic carbon decreases in lentil *utera* crops. Similar findings on SOC and built-up soil fertility in utera crops in rice-fallow systems have been reported by Kumar *et al*. (2022).

3.4 | Soil Moisture Dynamics

Soil moisture extraction pattern of *utera* crops like linseed, lentil and lathyrus was very much influenced by crop nutrition sources (*Fig.1*). *Utera* crops were sown on saturated paddy soils in standing rice 10-days before harvest of crop. Fertilizers like Suphala and DAP were applied 4-days before seed sowing of crops. Soil moisture varied from 38.8 to 42.0% at the seed sowing stage, and at harvest, soil moisture varied from 17.6 to 18.3% at 0-15 cm soil depth, and at a lower depth of soil (15-30 cm), soil moisture was from 22.4 to 25.4% depending on the type of crops. The results of soil moisture variations corroborate the findings of Kumari *et al*. (2024).

Variation in actual evapotranspiration (ETa) of utera crops was greatly influenced in the no-till rice ecosystem (Table 6). The Lathyrus crop, with its extensive ground coverage, has the lowest ETa value (133.8 mm). In contrast, the linseed crop, characterized by deep roots and less ground cover, recorded the highest water uptake, showing an Eta value of 182.00mm. The variation in Eta

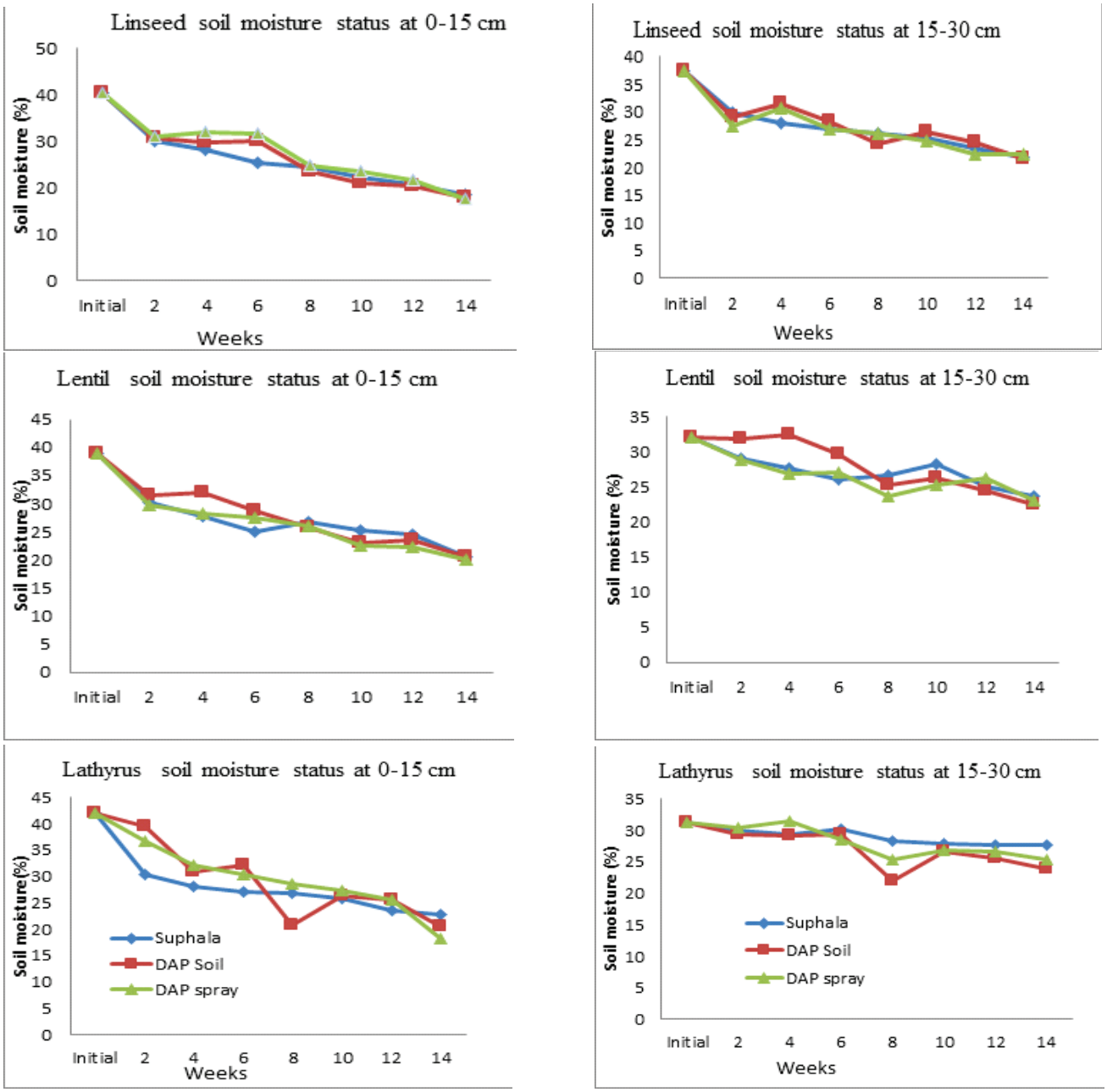


FIGURE 1 Soil depletion pattern at 0-15 and 15-30 cm soil depth as influenced by type of *utera* crops grown and fertilizer used

was 36.0%, which may be attributed to differences in canopy cover and water extraction. Fertilizer application of DAP soil registered the highest ETa value of 187.7 mm, followed by Suphala (156.5 mm), while the least ETa was observed in DAP spray. Here, the variation in ETa was up to 19.9%, likely caused by their nutrient mining capacity in *utera* cropping systems. In rainfed rice-fallows, ETa is influenced by profile moisture and rainfall, which affect crop water productivity in utera crops (Bandopadhyay *et al.,* 2016).

Water use efficiency (WUE) of utera crops like linseed, lentil, and lathyrus in rice ecosystems was much influenced by nutrient management practices (Table 6). The WUE of linseed, variety Neela, recorded 2.42 kg ha-mm^{-1}, while the highest WUE was achieved by Lathyrus at 5.42 kg ha-mm^{-1}, with a variation of more than double (124.2%) in no-till rice ecosystems. This wide variation may be due to the smothering habit of lathyrus, which helped conserve soil moisture by reducing evaporation. Differences in nutrient feeding among utera crops resulted in a narrower variation (16.9%) in WUE values. Among fertilizer sources, Suphala proved to be the most effective, followed by DAP foliar spray based on WUE. The DAP foliar spray consistently resulted in the lowest yield among these three *utera* crops. Crop WUE was higher in lathyrus, while the lowest was

observed in linseed. In rainfed lowland rice ecosystems, soil profile contribution, winter rainfall, and nutrient management of utera crops significantly influenced seed yield, ultimately affecting WUE values (Das and Goswami, 2017).

The lentil crop depleted more soil moisture than the lentil and lathyrus. Regarding fertilizer sources, soil moisture depletion was greater by Suphala (NPK 15:15:15) than DAP (NP 18:46). DAP spray had little impact on soil moisture extraction. Soil moisture extraction differentiation was more pronounced at flowering to pod development (6-12 weeks) of *utera* crops. At harvest, the linseed crop recorded a soil moisture content of 17.5% in the top layer (0-15 cm).

3.5 | Production Economics

The economics of *utera* crops- linseed, lentil, and lathyrus-production in terms of gross returns, net returns, and benefit-cost ratio were calculated for different modes of nutrient treatments (Table 7). The lentil crop had the highest net return of ₹ 23024 per hectare with the highest benefit-cost ratio of 2.73, followed by lathyrus. The direct effect of fertilizer management on production economics was more pronounced in Suphala and DAP soil application than in DAP spray. The combined effects of utera crop and fertilizer application were studied; for example, in the case of lentil with DAP (NP 18:46) treatment combination (C_2N_2), the highest gross return of ₹ 40836 was recorded, whereas the lowest gross return of ₹ 14793 was observed under linseed with DAP (NP 18:46) foliar spray treatment combination (C_1N_3). Among the paira crops, the net returns for lentil with DAP (NP 18:46) treatment (C_2N_2) were the highest at ₹ 27,380. Conversely, linseed with DAP (NP 18:46) treatment (C_1N_2) recorded the lowest net return of ₹ 4316. The same treatment combination also recorded the highest benefit-cost ratio of 3.0 in lentil with DAP soil application (C_2N_2). In the case of linseed with DAP (NP 18:46), the benefit-cost ratio was the lowest at 1.36. Availability of nutrients likely enhanced translocation of photosynthates to sinks, leading to improved crop yields and increased income for lentil, along with a higher B:C ratio (Kumar *et al.*, 2023; Saha *et al*., 2025).

TABLE 6 Effect of fertilizer management on actual evapo transpiration (Eta) and water use efficiency (WUE) of utera crops in rainfed rice-fallows (mean value of two years)

Treatments	Eta (mm)	Yield (kg ha^{-1})	WUE (kg ha-mm^{-1})
Utera crop			
Linseed	182.0	440	2.42
Lentil	157.4	721	4.58
Lathyrus	133.8	725	5.42
S.Em(±)	-	12.61	-
C.D (p=0.05)	-	37.17	-
Crop Nutrition			
Suphala	156.5	650	4.15
DAP Soil	178.7	634	3.55
DAP Spray	138.1	566	4.10
S.Em(±)	-	15.56	-
C.D (p=0.05)		45.91	-

TABLE 7 Effect of fertilizer management on production economics of *utera* crops in rainfed rice fallows (mean values of 2 years)

Treatments	Cost (₹ ha^{-1})	Gross returns (₹ ha^{-1})	Net returns (₹ ha^{-1})	B:C ratio
***Utera* Crops (C)**				
Linseed (C_1)	11320	17151	5831	1.51
Lentil (C_2)	13374	36398	23024	2.73
Lathyrus (C_3)	12571	30223	17652	2.40
Crop Nutrition (N)				
Suphale (N_1)	12807	29536	16728	2.29
DAP Soil (N_2)	12586	28663	16077	2.25
DAP Spray (N_3)	11872	25573	13701	2.10
Interaction effect				
C_1N_1	11756	20249	8493	1.72
C_1N_2	12096	16412	4316	1.36
C_1N_3	10110	14793	4683	1.46
C_2N_1	13706	29841	16135	2.18
C_2N_2	13456	40836	27380	3.03
C_2N_3	12960	38517	25557	2.97
C_3N_1	12206	28742	16536	2.35
C_3N_2	12546	23410	10864	1.87
C_3N_3	10560	20525	9965	1.94

4 | CONCLUSIONS

This study successfully evaluated the performance of three utera crops (lathyrus, lentil, and linseed) under different fertilizer management strategies in the rainfed lowland rice-ecosystem of the Lower Indo-Gangetic Plains. The findings provide valuable insights for sustainable intensification of rice-fallow areas through optimized cropping and nutrient management practices. Among the tested *utera* crops, lathyrus (grass pea) emerged as the most promising option, achieving the highest seed yield of 725 kg ha^{-1}, followed closely by lentil at 721 kg ha^{-1}. Both leguminous crops demonstrated superior adaptation to the rainfed conditions compared to linseed, which yielded only 404 kg ha^{-1}. The excellent performance of lathyrus and lentil can be attributed to their drought tolerance, efficient nitrogen fixation capabilities, and better utilization of residual soil moisture from the preceding rice crop.

The study shows soil application of Suphala (NPK 15:15:15) at 150 kg ha^{-1} yields the highest grain (650 kg ha^{-1}), outperforming DAP soil (634 kg ha^{-1}) and foliar spray (566 kg ha^{-1}). This highlights the importance of balanced nutrients, including potassium, for crop performance under moisture stress. Lathyrus has the best water productivity (5.42 kg ha-mm^{-1}) with the lowest evapotranspiration (133.3 mm), making it ideal for water-scarce areas. Linseed shows poor water efficiency (2.42 kg ha-mm^{-1}) with higher water use (182.0 mm). Economically, lentil with DAP achieves the highest benefit-cost ratio (3.03), offering better profitability despite lathyrus' slightly higher yields.

The study recommends cultivating lathyrus with Suphala (NPK 15:15:15) at 150 kg ha^{-1} to maximize yield and water efficiency, and lentil with DAP (NP 18:46) at 125 kg ha^{-1} for better economic returns. Avoid linseed in rainfed utera systems due to poor performance. This research supports the sustainable intensification of rice-fallow areas in the Lower Indo-Gangetic Plains, helping farmers improve land productivity, food security, and income, aligning with the national goal to expand cultivation and promote water- and cost-efficient cropping systems.

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CONFLICT OF INTEREST

The authors have no conflict of interest.

DATA AVAILABILITY STATEMENT

The corresponding author is liable to make the data available on request.

AUTHOR'S CONTRIBUTION

CB: Conducted the experiment as part of an M.Sc. (Ag) research project; SG: Prepared the manuscript write-up; RM: Assisted with soil moisture calculation and graph preparation; SKM: Helped with data recording; SBG: Supervised the work and edited the write-up.

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ORIGINAL ARTICLE

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Biomass and Nutrient Accumulation of Green Manure Species in Humid Tropical Subsistence Cropping Systems of Papua New Guinea

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Weed suppression

ABSTRACT

This study aimed to identify leguminous green manure species with strong adaptability, high nutrient accumulation, and effective weed suppression for subsistence farming in Papua New Guinea. It also examined the optimal termination age of 45 and 65 days after planting (DAP) for lablab, velvet bean, calapo, centro, and puero. The agronomic performance was compared to natural vegetation in a field experiment laid out in a Randomized Complete Block Design. Velvet bean produced the highest aerial dry matter (11.2 t ha^{-1}), leading to significantly greater accumulation of the primary nutrients nitrogen (374 kg ha^{-1}), phosphorus (61 kg ha^{-1}), and potassium (119 kg ha^{-1}) within 65 days. The green manure crops evaluated derived 21.8%–87.7% of their N from atmospheric fixation. Within 28 DAP, velvet bean and lablab suppressed weed growth by 87% and 53%, respectively. Termination age significantly affected the nutrient accumulation in velvet bean, suggesting 65 DAP could be ideal for soil incorporation, whereas lablab can be terminated at 45 DAP. Our findings suggest that integrating velvet bean and lablab in improved fallow systems could enhance soil fertility and weed management in humid tropical regions.

1 | INTRODUCTION

In Papua New Guinea (PNG), food production primarily relies on subsistence farming, which includes practices such as food garden fallows, slashing, and burning of fallow vegetation (Hartemink, 2003). However, these methods are becoming increasingly environmentally unsustainable and threaten long-term soil fertility and crop yields (Walter *et al.,* 2010). Continuous cropping and crop intensification without sufficient fallow periods further damage soil health and reduce agricultural productivity. About 75% of soils under food crop cultivation in PNG have low to moderate nitrogen levels and are at risk of erosion (Hartemink, 2003), which worsens soil degradation. This decline in natural resources endangers food and nutritional security (Meena *et al.,* 2018). However, limited availability of organic manure, high costs, and inaccessibility of inorganic fertilizers, and the insufficient contribution of primary nutrients from fallow vegetation under humid tropical conditions pose major challenges to maintaining soil fertility (Hartemink, 2003; Kaupa & Rajashekhar Rao, 2014); Ramakrushna *et al.,* 2022

Maintaining tropical soil fertility involves increasing soil organic carbon (Mosier *et al*., 2021). Organic matter boosts soil processes, nutrient dynamics, water relations, and soil health, impacting productivity (Kaupa & Rajashekhar Rao, 2014; Mosier *et al.*, 2021). Continuous application of organic matter via crop residues, manure, legumes in rotations or as intercrops, green manure, and fallow species, combined with fertilizers, is vital (Kumar *et al*., 2020; Sunil Kumar *et al.*, 2024). In subsistence farming, integrating legume green manures into crop rotations or fallows can improve yields (Anand, 2018). Legumes or cover crops enhance soil fertility by accumulating nutrients for subsequent crops. Although they mainly fix N_2 via legumes, integrating green manures is climate-friendly, boosts organic carbon, biological fertility, and nutrient availability, and reduces erosion (Kumar *et al.*, 2020). Limited information exists on the best green manure species for subsistence agroecosystems. These vary in growth habits, flowering, biomass, chemistry, climate adaptation, optimal incorporation age, and nitrogen fixation, especially in legumes (Hauser & Nolte, 2002; Hirpa *et al.*, 2009; Singh *et al*., 2013). In PNG's humid tropics, ideal legume green manures should produce high biomass, fix nitrogen, and suppress weeds quickly. This study aimed to identify legume green manure species suitable for subsistence farming in humid tropical regions, specifically in PNG. It evaluated green manures based on biomass, nutrient uptake, nitrogen fixation, and weed suppression across five species—lablab, velvet bean, Calopo, Centro, and Puero—grown in various PNG zones. Lablab and velvet bean are popular in the highlands for their edible seeds and pods (Bourke and Harwood, 2009). Centro is used as a cover

crop to reduce weeds in rubber and coconut plantations. Velvet bean, Puero, and Calopo improve soil fertility and control weeds in oil palm farms (Pipai, 2014).

2 | MATERIALS AND METHODS

2.1 | Experimental Site

The study was initiated in August 2022 at the experimental farm of the PNG University of Technology (6°41′S, 146°98′E, altitude 65 m a.s.l.) located in Morobe Province, Papua New Guinea. The location of the study site is presented in Fig. 1. The site's climate is classified as "tropical and rainy" under the Köppen system (classification code Af), with a unimodal distribution and over 60 mm of rain in the driest month based on 10-year average conditions. In the 2022 meteorological year, total precipitation was 2,158 mm, with each month receiving at least 100 mm of rainfall. Monthly rainfall totals were 201 mm, 116 mm, 168 mm, and 215 mm for August, September, October, and November, respectively. Minimum and maximum temperatures ranged from 19.3-21.7°C and 28.5-30.6°C, respectively.

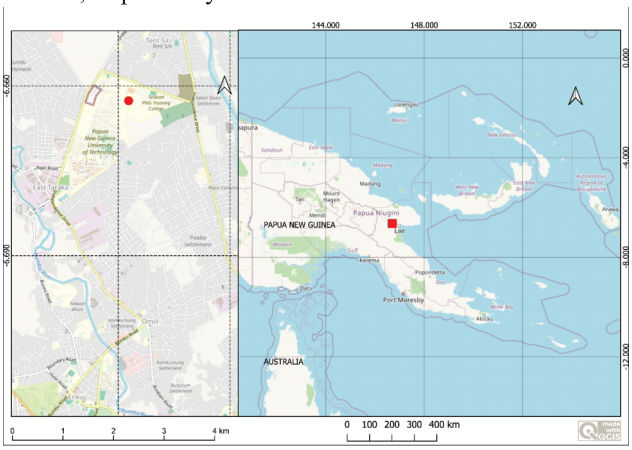


FIGURE 1 The study location is shown on the map with a red marker.

A composite soil sample (0–15 cm) was collected from 10–12 random points across the experimental site before starting the study. The sample was air-dried in the shade for five days, gently crushed, and sieved through a 2 mm mesh. Soil samples in triplicate were analyzed for soil pH using the potentiometric method (1:2.5 soil: water v/w), organic carbon by the Walkley-Black method, available phosphorus by $NaHCO_3$ extraction (Olsen's method), and measured with a UV-Vis spectrophotometer (Shimadzu UV-1800, Shimadzu Corporation, Brisbane, Australia at 882 nm. Soil texture was determined by the Bouyoucos hydrometer method. Total nitrogen was estimated using the semi-micro Kjeldahl steam distillation method (Rayment & Lyons, 2011). The topsoil (0–15 cm) was slightly acidic (pH 6.36), with a total nitrogen content of 1.94 g kg^{-1} and an organic carbon content of 1.67%. Extractable Ca, Mg, and K concentrations of the soil were 13.4, 4.81, and 0.13 c mol kg^{-1}, respectively. The soil was classified as a mixed, isohyperthermic, Typic Tropofluvents (USDA Soil Taxonomy), well-drained, slightly gravelly, with a sandy loam texture (83.2% sand, 6.40% silt, and 10.4% clay).

HIGHLIGHTS

- Velvet bean and lablab were the top green manure species, yielding high biomass, nutrients, and weed suppression in humid tropical farming.
- Early harvest at 45 days lowered yields, showing growth duration's importance.
- Using selected green manures sustainably boosts soil health, nutrient cycling, and weed control in humid tropics.

2.2 | Green Manures

Five legume green manure crops were chosen for the experiment based on the local availability of seeds. The species selected for the screening trial were lablab [*Lablab purpureus* (L.) Sweet], late-maturing white-seeded velvet bean [*Mucuna pruriens* var. utilis (L.) D.C.], Calopo [*Calopogonium mucunoides* (Desv.)], Centro [*Centrosema pubescens* (Benth.)], and Puero [*Pueraria phaseoloides* (Roxb.) Benth.]. Fig. 2 presents pictures of the seeds and the green manure plants evaluated. Lablab seeds were sourced from the Lae Main Market in Morobe Province, while seeds of Calopo, Puero, and Centro were obtained from farmers in peri-urban settlements and along the Bumbu River in Lae, as well as the Markham area of Morobe Province. Velvet bean seeds were obtained from NARI-Kerevat in Rabaul, East New Britain Province, PNG. Seed germination rates exceeded 90%. To break dormancy, Centro, Calopo, and Puero seeds were soaked in hot water for three minutes before sowing.

2.3 | Experimental design and green manure crop cultivation

Before planting the green manure seeds, the natural vegetation was cut back, and the land was plowed twice using a tractor-mounted cultivator. Raised plots measuring 2m x 4m were manually built with shovels. Treatments included five green manure crops arranged in a randomized complete block design (RCBD) with three replications. Plots without green manure crops served as controls. Seeds were manually drilled in rows spaced 0.4 m apart, and four weeks after planting, plants were thinned to two per hill at 0.4 m spacing within the rows, so the plant population per plot was 160. No mineral fertilizer or irrigation was applied during the study. Planting occurred in August, and harvest took place in November. A preventive insecticide spray (Orthene®, Acephate 75SP) was applied once to control leaf defoliators and aphids. To prevent green manure plants from encroaching on neighboring plots, weekly monitoring was conducted, and any vines crossing plot borders were manually redirected.

2.4 | Sampling of green manures, weeds, and chemical analysis

Green manure samples were collected and weighed from 0.5 m × 0.5 m independent quadrats in each plot at 14, 35, 45, 55, and 65 days after planting (DAP) to estimate biomass at each time point. Approximately 500 g of fresh green manure biomass was carefully rinsed with tap water, followed by distilled water, air-dried to remove excess moisture, and then oven-dried at 70°C in a forced- air oven until it reached a constant weight. Oven-dried plant samples

collected at 45 days and 65 DAP, ground to 0.5 mm with a stainless-steel grinder, were analyzed in triplicate for total N concentration using the Micro Kjeldahl method (BÜCHI Speed Digester K-436 and BÜCHI Distillation Unit K-350, Avantor, Australia). A powdered sub-sample was digested with an HNO_3-$HClO_4$ mixture and analyzed for P and K concentrations using ICP-OES at the Analytical Services Laboratory of the PNG University of Technology. Nitrogen, P, and K accumulation were calculated by multiplying their respective concentrations by the dry biomass weight per plot.

The potential of green manure crops to suppress weeds was evaluated by measuring the fresh and dry weights of weed biomass at 14, 28, and 42 DAP. Weeding was carried out in each plot using 0.5 m × 0.5 m independent quadrats that remained undisturbed from previous sampling. Weed plants were manually uprooted, soil particles were gently shaken off the roots, and the fresh weight was recorded with an electronic balance. The weed samples were then washed with tap water, oven-dried at 70°C in a forced-air oven until their weight was constant, and then recorded.

The amount of biologically fixed N2 was estimated using the N difference method, which compares N accumulation in legume green manure crops with that in non-N_2-fixing natural weeds from the control plots. The natural weed flora was dominated by *Cyperus esculentus*, *Cynodon dactylon,* and *Panicum maximum*. The difference in total shoot nitrogen accumulation per plot between the legume crops and natural weeds was attributed to symbiotic N2 fixation by the legumes. This method assumes that both legumes and non-legumes absorb the same amount of soil nitrogen.

Diazotrophic N_2 fixation was calculated using Equation (1) from Unkovich *et al.* (2008):

Diazotrophically fixed N_2 (kg ha^{-1}) =

Total N yield $_{(fixingsystem)}$ – Total N yield $_{(non\text{-}fixingsystem)}$ -------- (1)

2.5 | Statistical Analysis

The fresh and dry matter yields of green manure samples and weeds, along with major nutrient concentrations in green manures, nutrient accumulation, and biological N2 fixation estimates at different DAP, were analyzed using factorial analysis of variance (ANOVA) in Statistix 8.0 software for MS Windows®. Green manure crop species and termination age were treated as two factors. Termination age refers to the time interval (days) between planting and the point when a green manure crop is terminated—usually by slashing or weedicide application—and subsequently incorporated into the soil. To identify significant differences among treatments, the Least Significant Difference (LSD) test was conducted at $p \leq 0.05$.

3 | RESULTS AND DISCUSSION

3.1 | Adaptability of green manures, biomass production, and weed suppression potential

The green manures tested varied significantly ($p < 0.001$) regarding biomass yield (*Fig. 3*). Biomass yield increased



FIGURE 2 Green manure plant seeds with corresponding plants (45 DAP)

significantly ($p < 0.05$) as time progressed from 14 to 55t ha^{-1} and 10–48 t ha^{-1}, respectively (*Fig. 3a*), over the 65 days, compared to the natural vegetation or control (7–10 t ha^{-1}). The dry matter followed a similar pattern, with velvet bean and lablab producing dry biomass ranging from 2–11 t ha^{-1} and 1–9 t ha^{-1},respectively, over the 65 days, compared to the natural vegetation (1–1.9 t ha^{-1}) (*Fig. 3b*). Velvet bean and lablab produced nearly 6× and 5× more dry matter than natural vegetation, respectively. Apart from velvet bean and lablab, all other green manure crops produced dry biomass of less than 3.0 t ha^{-1}.

Biomass accumulation potential is a key criterion

in the selection and success of green manure crops in cropping sequences. Velvet bean plants established quickly and grow vigorously, producing substantial amounts of above-ground fresh biomass (up to 22 t ha^{-1}) within the first month, and nearly 50 t ha^{-1} of fresh biomass after 60 days, which was within the range (11.4-60 t ha^{-1}) reported by Philipp and Gamboa (2003) from Nicaragua. The fresh (48 t ha^{-1}) and dry biomass (9 t ha^{-1}) accumulation in lablab, at 65 days after planting in this study, were comparable to the 47 t/ha fresh biomass and 9 t/ha dry matter observed by Bhardwaj and Hamama (2019) at around 90 days after planting. The biomass weights of velvet bean obtained in this study closely align with the values reported by Kaizzi *et al.* (2006) and Hauser and Nolte (2002), who found dry matter yields ranging from 2.6–7.9 t ha^{-1} during 22 weeks of growth in the tropics.

The differences in biomass yield of green manures observed in this study compared to other research likely result from various factors. These include the timing of green manure termination, management practices influencing weed competition, genetic differences among species and accessions, N uptake and fixation capabilities, and favorable environmental conditions such as soil quality and rainfall at the site (Hauser & Nolte, 2002; Bhardwaj & Hamama, 2019). Additionally, other green manure crops like Calopo, Centro, and Pueraria took longer to establish and were similar in growth to natural vegetation.

Significant differences were observed in weed growth, as shown by the weed biomass recorded among different green manures (*Fig. 3c*). The fresh weed biomass under velvet bean and lablab decreased by 80% and 17%, respectively, from 14 to 28 days after planting due to the vigorous growth of these green manures. In contrast, weed biomass under calopo, centro, and puero plots increased by 40-60%. Mucuna and lablab plots had the lowest mean dry weed biomass, at 26 kg ha^{-1} and 36 kg ha^{-1}, respectively, compared to calopo (87 kg ha^{-1}), centro (93 kg ha^{-1}), and puero (94.6 kg ha^{-1}) (*Fig. 1d*). A highly significant ($p<0.01$) interactive effect was observed between the growth of green manures and weed biomass.

3.2 | Nutrient accumulation and N_2 derived from atmosphere

Green manure plants and natural vegetation significantly differed in their accumulation potential of primary nutrients (N, P, and K) (*Fig. 4*). N accumulation in the above-ground biomass of velvet bean at 45 and 65 days after planting was significantly higher at 218.5 kg ha^{-1} and 374.2 kg ha^{-1}, respectively, followed closely by lablab with 193.2 kg ha^{-1} and 226.9 kg ha^{-1}. Velvet bean and lablab also showed significantly higher P and K accumulation potentials (*Fig. 4b and 4c*). The accumulation of P and K by lablab declined slightly with increasing plant age, which is indicative of the need to incorporate this green manure into the soil early (45 days). The C:N ratio in the above-ground tissue of the legume green manure crops ranged from 11.2 to 15.8. The mean C:P and C:K ratios of the above-ground tissue of the green manure crops ranged from 59-101 and 29-51, respectively, over 65 days.

The termination age of green manure influences its chemical makeup, including nutrients and biochemical constituents such as cellulose, carbohydrates, proteins, polyphenols, and lignin (Sunil Kumar *et al*., 2024). Previous studies have shown N accumulation in velvet bean ranging from 147-222 kg ha^{-1} at 40 DAP (Hauser & Nolte, 2002), 80-200 kg ha^{-1} at 154 DAP (Kaizzi et al., 2006), and 80-100 kg ha^{-1} over 45-60 days (Meena *et al*., 2018). Therefore, velvet bean varieties differed in their growing periods, total biomass production, and N uptake. Green manures such as Calopo, Centro, and Pueraria did not acquire significant amounts of P and K compared to natural soil vegetation. Wendling *et al*. (2015) suggested that the ability of certain green manure species to accumulate nutrients may depend on root architecture, such as root length and large surface area, to extract nutrients from deeper soil layers.

Green manures and their termination age significantly influenced N_2 fixed by manure species (Table 1). On the 45th day after planting, all species except for velvet bean and lablab showed negative values for biologically fixed N_2. This was due to lower N accumulation in legumes than in non-N-fixing weeds, likely because the legumes relied primarily on soil N during their early growth stages. Poor growth as reflected by biomass and delayed onset of N_2 fixation may have further contributed to this pattern (Unkovich *et al.,* 2008). The contribution of N derived from the atmosphere after 65 days was highest in velvet bean (87.7%), followed by lablab (79.7%), Pueraria (45.8%), Centro (36.7%), and the lowest in Calopo (21.9%). Velvet bean and lablab were superior in terms of early biological N fixation. By 65 days after planting, velvet bean had significantly higher N_2 fixed (328.1 kg ha^{-1}) compared to all other legume green manures. The N difference method assumes that the difference in total shoot nitrogen accumulation between legume crops and natural weeds is attributed to symbiotic N_2 fixation by the legumes, based on the assumption that both absorb equal amounts of soil nitrogen. The negative values indicate that N uptake by legumes was lower than that of the natural weeds, possibly due to the legumes relying solely on soil N, delayed N_2 fixation, and exhibiting poor growth. The N_2 fixation appeared to be directly related to the ability of the crop to produce biomass. This trend aligns with the expectation that increased legume cover generally results in more N_2 fixation, as suggested by Silva *et al.* (2011). Their study reported that around 70% of the N in the shoots of *Mucuna pruriens* var. utilis is derived from atmospheric N (Silva *et al*., 2011).

3.3 | Implications for managing subsistence food systems

The study results showed a strong potential for producing nitrogen-rich biomass using green manures such as velvet bean and lablab. Incorporating these effective green manure species into subsistence farming systems as alternatives to natural fallow practices might also pose environmental risks. In tropical areas with high rainfall, residue

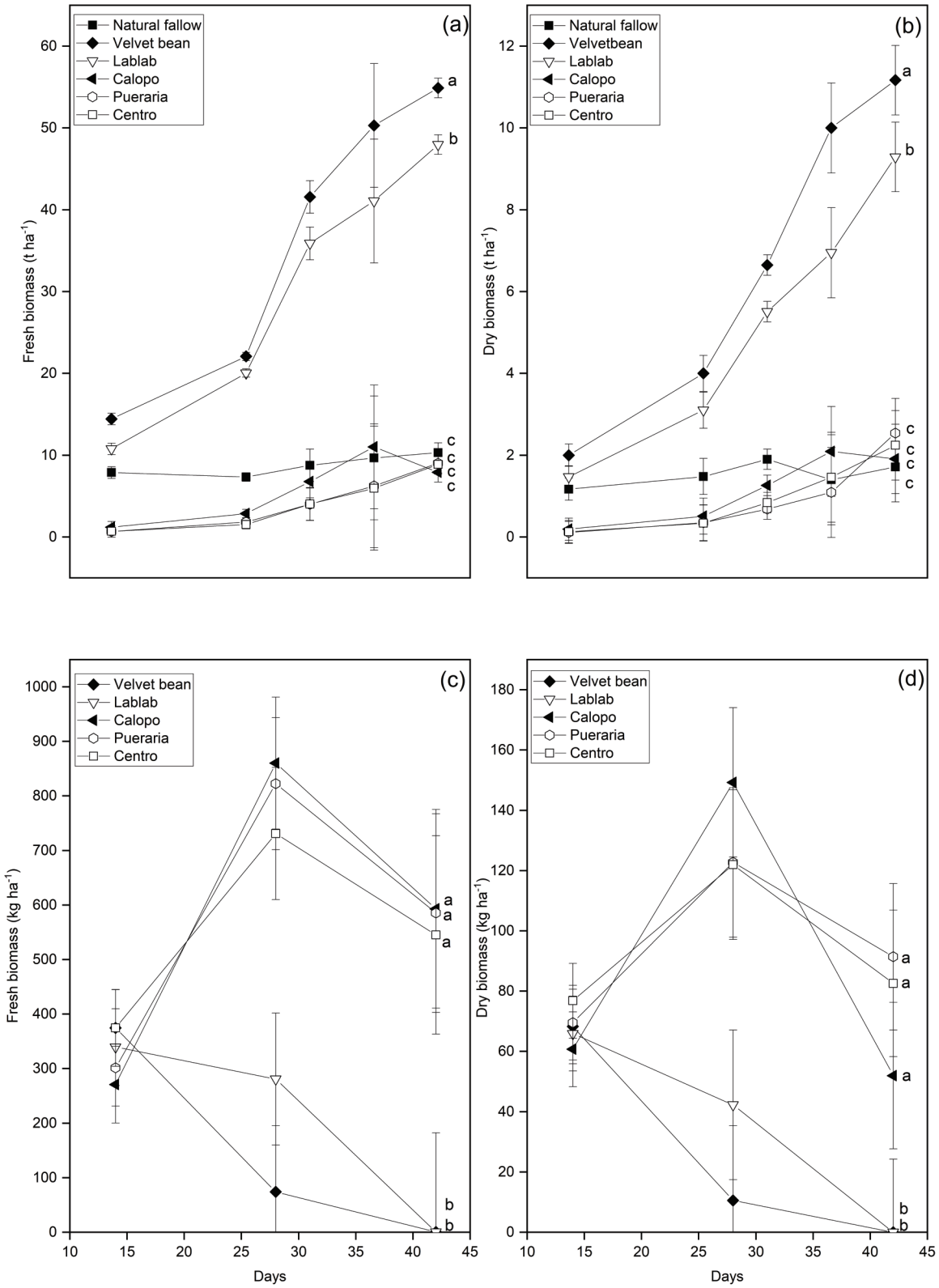


FIGURE 3 Green manure (a & b) and weed growth (c & d) over time. Error bars indicate LSD $_{(p\ 0.05)}$

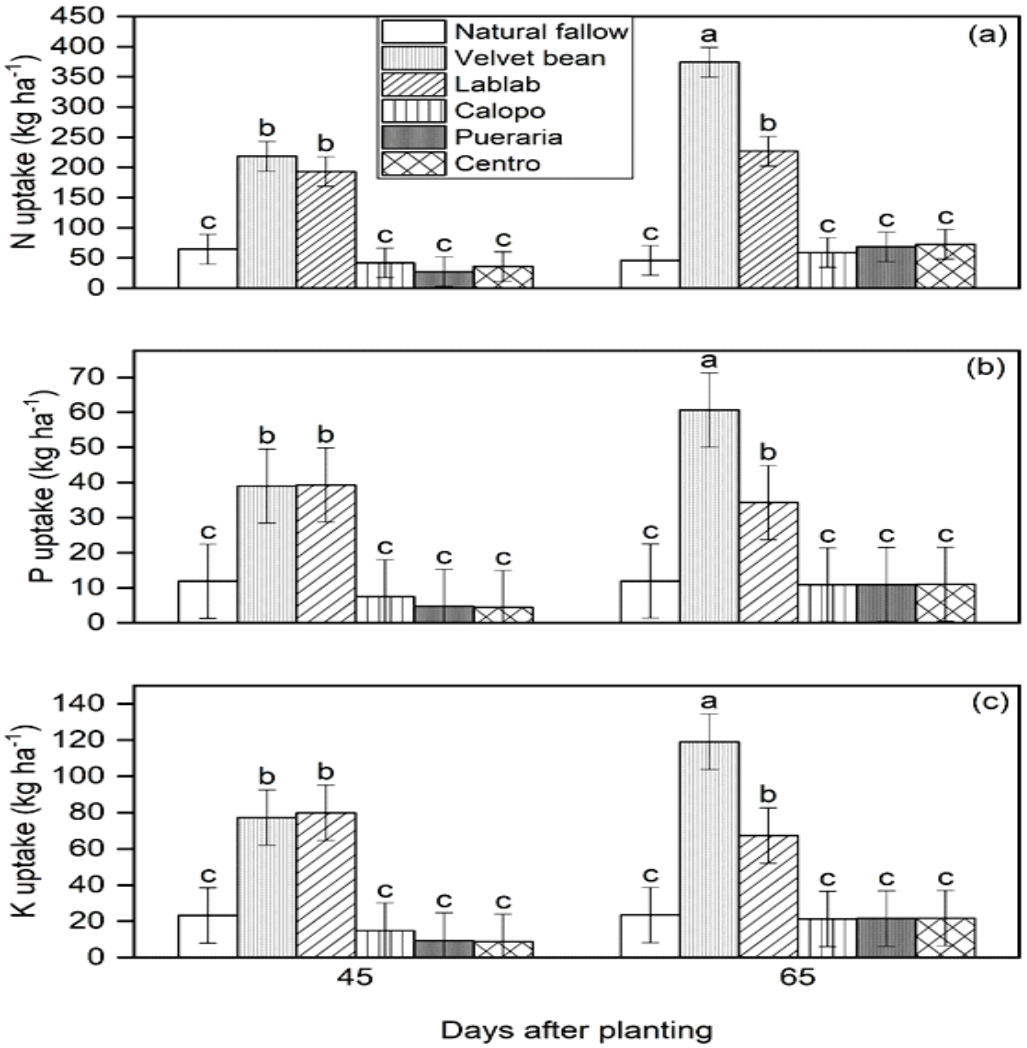


FIGURE 4 Nutrient accumulation in green manures over time. Error bars show $LSD_{(0.001)}$.

TABLE 1 The N uptake, N fixed by N-difference technique and % of N_2 derived from atmosphere (%Ndfa)

Green manures	Absolute N uptake (kg ha^{-1})		N_2fixed (kg ha^{-1})		%Ndfa	
			Termination age			
	45 days	65 days	45 days	65 days	45 days	65 days
Natural vegetation	64.60c	46.20c	-	-	-	-
Velvet bean	218.49b	374.20a	153.89b	328.15a	70.43	87.67
Lablab	193.16b	226.88b	128.56b	180.68b	66.56	79.66
Calopo	41.97c	59.08c	-22.63cde	12.88cde	0.00	21.88
Pueraria	27.45c	77.56c	-37.15e	31.36c	0.00	45.77
Centro	36.02c	72.94c	-28.58de	26.74c	0.00	36.68
F test significance						
Green manures		***	***			
Termination age		***	***			
Green manures x Termination age		**	*			

Values with different superscripts in columns are significantly different; ***, $p < 0.001$ and *, $p < 0.05$.

decomposition speeds up due to warm, moist conditions that boost microbial activity and nutrient mineralization. The heavy rain can also cause excessive leaching of mineralized nutrients, especially nitrogen in nitrate form, which reduces nutrient availability for crops and raises the risk of groundwater contamination (Kaupa & Rajashekhar Rao, 2014). Proper management is essential to align nutrient release with crop needs and minimize environmental losses. Green manures harvested 45 days after planting tend to have a lower C:N ratio, indicating they decompose more quickly because of higher nitrogen content and lower lignin levels (Toleikiene *et al.*, 2024). This leads to rapid nutrient release when incorporated, benefiting subsequent crops if timing is correct, but potentially causing nutrient loss in areas with very high rainfall, such as humid tropics. On the other hand, green manures harvested at 65 days usually have a higher C:N ratio and more lignified biomass, resulting in slower decomposition and longer nutrient release, which helps build soil organic matter over time—though it may delay nutrient availability for crops. The age at which green manure is terminated influences the residue quality and helps determine the best timing for incorporation to optimize nutrient availability and reduce environmental risks.

Within Papua New Guinea's subsistence farming systems, the use of green manure crops faces many adoption challenges. Most smallholder farmers have limited land, and dedicating space to non-food crops like velvet bean or lablab is often seen as impractical because it could threaten food production. Labor availability and small-scale machinery for soil incorporation are also important constraints, as growing and applying green manure requires extra time and effort that busy families may lack due to existing farm workloads (Meena *et al*., 2018; Kaupa & Rajashekhar Rao, 2023). Additionally, a lack of knowledge and training on the benefits and management of green manure discourages farmers from adopting it. The unavailability of green manure seeds, especially in remote rural areas, is another barrier. For farmers focusing on short-term income and food security as subsistence farmers, perceived risks and limited immediate benefits further decrease the likelihood of adopting green manure as an improved fallow system (Kaupa & Rajashekhar Rao, 2023)

3.4 | Limitations of the study

Caution is advised when interpreting the results of N_2 fixation measurements. The N difference method tends to underestimate N_2 fixation at 45 and 65 days after planting because legumes generally use less soil nitrogen than non-legume weed fallow. Furthermore, since roots and nodules were not examined for nitrogen content and accumulation in this study, they may also contain some fixed N_2 (Unkovich *et al*., 2008).

4 | CONCLUSIONS

The results of the study clearly highlight the substantial potential of green manures, particularly velvet bean and lablab, in generating above-ground biomass, effectively suppressing and smothering weeds, and accumulating significant quantities of primary nutrients. These findings suggest that velvet bean and lablab are superior to natural vegetation, making them highly beneficial for integrating into improved fallow systems. Both velvet bean and lablab demonstrated an early onset of nitrogen fixation within the first 45 days of growth, marking them as suitable green manure crops for humid tropical conditions. The high biomass yield, along with the accumulation of primary nutrients alongside their weed suppression capabilities, makes these legumes highly effective for possible soil improvement. Delaying the termination of legume green manure beyond 45 days may not offer additional benefits in terms of N, P, and K availability from the phytomass, except for velvet bean. This research supports the incorporation of velvet bean and lablab as early maturing, highly effective green manure crops for improved fallows in humid tropical regions. However, future research should focus on multi-season and multi-location trials to capture variability across soil types, rainfall regimes, and management practices. Such studies are essential to confirm the long-term benefits of green manure legumes for soil fertility restoration, crop productivity, and resilience of subsistence farming systems in the humid tropics.

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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 paper.

DATA AVAILABILITY STATEMENT

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

AUTHOR'S CONTRIBUTION

PK: Conceptualization, methodology, investigation, writing – original draft; RR: Data curation, formal analysis, writing – review & editing, supervision.

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ORIGINAL ARTICLE

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Optimizing Soilless Growing Media for Red Amaranthus (*Amaranthus tricolor*) Production

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ABSTRACT

A pot culture experiment was conducted to evaluate seven media formulations using coirpith (CP), vermicompost (VC), and sand (S) in varying ratios to identify optimal combinations for growth, yield, and nutrient use efficiency of Red Amaranthus (*Amaranthus tricolor*), a widely consumed leafy vegetable in India. Media analysis revealed that sand inclusion reduced salinity, while vermicompost enriched nutrient availability. The treatment coirpith and vermicompost taken in equal proportion recorded the highest mean plant height (25.8 cm), maximum leaf area (63.79 cm^2), and stem girth (2.8 cm). It also outperformed other treatments, producing the highest biomass (61.52 g fresh weight pot^{-1}; 17.42 g dry weight pot^{-1}) along with superior uptake of N (0.190 g pot^{-1}), P (0.085 g pot^{-1}), and K (0.160 g pot^{-1}) followed by the treatment CP:VC (2:1). The fresh weight recorded by CP:VC (1:1) was 203 percent higher than the coirpith alone. The highest apparent nutrient recovery percentage (5.411 for N, 10.587 for P and 30.700 for K) and response ratio (3.046 for N, 13.374 for P and 20.507 for K) was also registered by CP:VC (1:1). In contrast, coirpith alone restricted root growth (9.6 cm), lowest apparent nutrient recovery (3.074 for N, 6.565 for P and 20.067 for K) and response ratio (1.006 for N, 4.417 for P and 6.773 for K). The results validate CP:VC (1:1) as an effective substrate for enhancing growth and nutrient dynamics in urban cultivation of Red Amaranthus.

1 | INTRODUCTION

Vegetables are an essential element of the daily diet, especially in India. Out of common leafy vegetables, amaranthus is the most popular vegetable consumed by people all over India (Akbugro *et al*., 2007; Swamy, 2023). Red amaranth is a purple-red color leafy vegetable and is well known as an excellent food crop owing to its ability to grow under a wide range of climatic conditions, such as drought, heat, pests, and diseases. It grows in short duration, quick response to manures and fertilizers, high yielding, easy to cultivate, and has wide adaptability to diverse agroclimatic situations, making it a favourite crop to farmers (Srivastava, 2017). The leaves of red amaranth are a reasonable source of proteins, dietary fibers, fat, carbohydrates, minerals such as iron, calcium, phosphorus, magnesium, potassium, and zinc (Kachiguma *et al*., 2015; Sarker & Oba, 2019). Other nutrients like vitamins C, beta carotene, betalains, betaxanthins, and betacyanins are also present in the leaves of red amaranth (Sarker & Oba, 2019), making it a vital component of daily diets.

In urban contexts, Red Amaranthus has emerged as a preferred crop for terrace and container gardening due to its compact growth habit and responsiveness to organic inputs (Jacob *et al*., 2012). With increasing interest in urban farming and vertical gardening systems, there is a growing need to develop efficient, space-saving cultivation protocols that ensure consistent yield and nutrient quality. Soilless cultivation with organic substrates presents a promising approach for urban vegetable farming, especially in areas where land and soil quality are limiting factors. Vertical farming, which involves multitier cropping systems, can maximize the yield per square meter of land, addressing the increasing popularity for fresh food without overburdening agricultural land (Beecham *et al*., 2019).

Identifying an optimal combination of organic materials to formulate effective growing media is critical for ensuring adequate root anchorage and a sustained supply of water and nutrients, especially under urban cultivation systems. Soilless substrates such as coco coir, vermiculite, and organic manures like farmyard manure (FYM) and poultry manure have been widely adopted for microgreen production (Pradeepa *et al*., 2023). Among these, coirpith has shown promising results both as a standalone medium and in blends with other organic or inorganic components

(Poulter, 2014; Hongpakdee & Ruamrungsri, 2015; Xiong *et al*., 2017; Stewart-Wade, 2020; Mariotti *et al*., 2020). Vermicompost, when applied in moderate quantities, enhances substrate quality by improving its physical structure and chemical fertility, thereby promoting plant growth (Bachman & Metzger, 2007; Grigatti *et al*., 2007).

Despite the increasing use of organic substrates in urban horticulture, there remains a critical lack of standardized recommendations for optimal growing media composition and nutrient management explicitly tailored to Red Amaranthus cultivation under urban conditions. This pot culture experiment was therefore undertaken to identify the most effective media combination for enhancing growth, biomass yield, and nutrient use efficiency in Red Amaranthus. By integrating media analysis, plant performance metrics, and nutrient recovery indices, the study aims to establish a practical and replicable substrate recommendation for urban and semi-urban vegetable growers, contributing to sustainable intensification of leafy vegetable production in constrained spaces.

HIGHLIGHTS

- A growing medium consisting of a 1:1 ratio of coirpith (CP) and vermicompost (VP) is the most effective substrate for Red Amaranthus in soilless culture.
- The CP:VC (1:1) combination produced a 203 % higher fresh weight compared to using coirpith alone.
- Inclusion of sand helps to reduce salinity, while the use of a coirpith-only medium results in a high root-to-shoot ratio, indicating that the plant is under stress.

2 | MATERIALS AND METHODS

2.1 | Study Area Description

The location of the experimental site is the Central Farm Machinery Centre, Vanavarayar Institute of Agriculture, Pollachi, Tamil Nadu, India (10.6560° N, 77.0221° E, 293 m from the mean sea level), which falls under Western agroclimatic zone of Tamil Nadu, India, having a tropical climate with annual average rainfall of 715 mm. The monthly weather data corresponding to the entire course of the study period, viz., maximum temperature, minimum temperature, relative humidity at 08.30 IST, and monthly rainfall, were collected (*Fig.* 1).

2.2 | Crop Management

2.2.1 | Seeds and Sowing

The seeds of the Red Amaranthus variety CO-6 obtained from the Department of Vegetable Science, Horticulture College and Research Institute, Tamil Nadu Agricultural University (TNAU), Tamil Nadu were used in this study. The study was conducted using plastic pots of 4 kg capacity having a dimension of 25 cm diameter × 20 cm height. Fifteen seeds were broadcast in each pot. After two weeks of germination, five seeds were maintained after establishment, and moist conditions were maintained in the growing media supporting the crop throughout the crop period.

2.2.2 | Treatment structure and Experimental design

The treatment structure comprised different media combinations, which were replicated three times in a completely randomized block design. According to the randomization of treatments, two kg of growing media were filled into each container. The treatment details are as follows T_1 - CP+VC (1:1); T_2 - CP+VC+S (1:1:1); T_3 - CP+VC (2:1); T_4 - CP+VC+S (2:1:1); T_5 - CP+VC (1:2); T_6 - CP+VC+S (1:2:1) and T_7 - CP alone in which CP refers to Coirpith, VC refers to Vermicompost and S refers to sand (< 2mm). All the substrates were mixed on an equal weight basis.

2.2.3 | Substrate sampling schedule

Sampling was performed destructively at defined crop growth stages to monitor changes in media properties and plant performance. Specifically, pH and electrical conductivity (EC) of the growing media were recorded at four intervals: 0 DAS (before sowing), 10 DAS, 20 DAS, and 30 DAS. These stages were selected to capture the dynamic shifts in substrate chemistry during early establishment and vegetative growth of Red Amaranthus.

2.2.4 | Fertilization for Red Amaranthus in a soilless system

The composition of the fertilizer mixture was worked out according to the recommended fertilizer dose for the fertigation of the Amaranthus crop. The recommended fertigation dose for Amaranthus is 60:30:20 kg N, P_2O_5, and K_2O ha^{-1} (Indurthi et al., 2024). For soilless media, there is no P and K fixation expected due to soil particle adsorption and surface reaction (Elakiya, 2021). Hence, only 50% of P and K doses were adopted, resulting in a modified dose of 60:15:10 kg ha^{-1}. The per-pot requirement was derived by dividing the total requirement by the plant population of 5,00,000 (20 cm × 10 cm spacing), which gives 0.8 g of N, 0.2 g of P_2O_5, and 0.1 g of K_2O. This was adopted in soilless crop experiments, for 42 pots by converting g to kg N, P_2O_5, and K_2O.

The fertilizer requirement for different crop stages was scheduled (Table 1). Accordingly, the calculated quantity of water-soluble fertilizers, viz., Urea, Di Ammonium Phosphate (DAP), and Muriate of Potash (MOP), was worked out, and split doses were given in two split doses, one as basal and the other during 20 DAS. Surface application of a specific fertilizer dose at a specific crop stage was done by mixing the mixture in 4.2 litres of water, and 100 ml was supplied per container. A micronutrient mixture spray was given @ 0.5% percent on 20 DAS.

2.2.5 | Cultural operations and observation

All plant protection measures were carried out periodically to control pests and diseases during crop growth as per recommendations. To prevent microbial contamination, Metarhizium anisopliae was incorporated at 3 g per pot to

suppress soil-borne pests and to prevent the coconut grub attack. Neem-based products were initially sprayed in the vegetative stages to control the sucking pests. 0.3 ml Chroanthril (Chlorantraniliprole 18.5% SC) per liter of water was sprayed to control Helicoverpa armigera and ensure to cover the entire foliage.

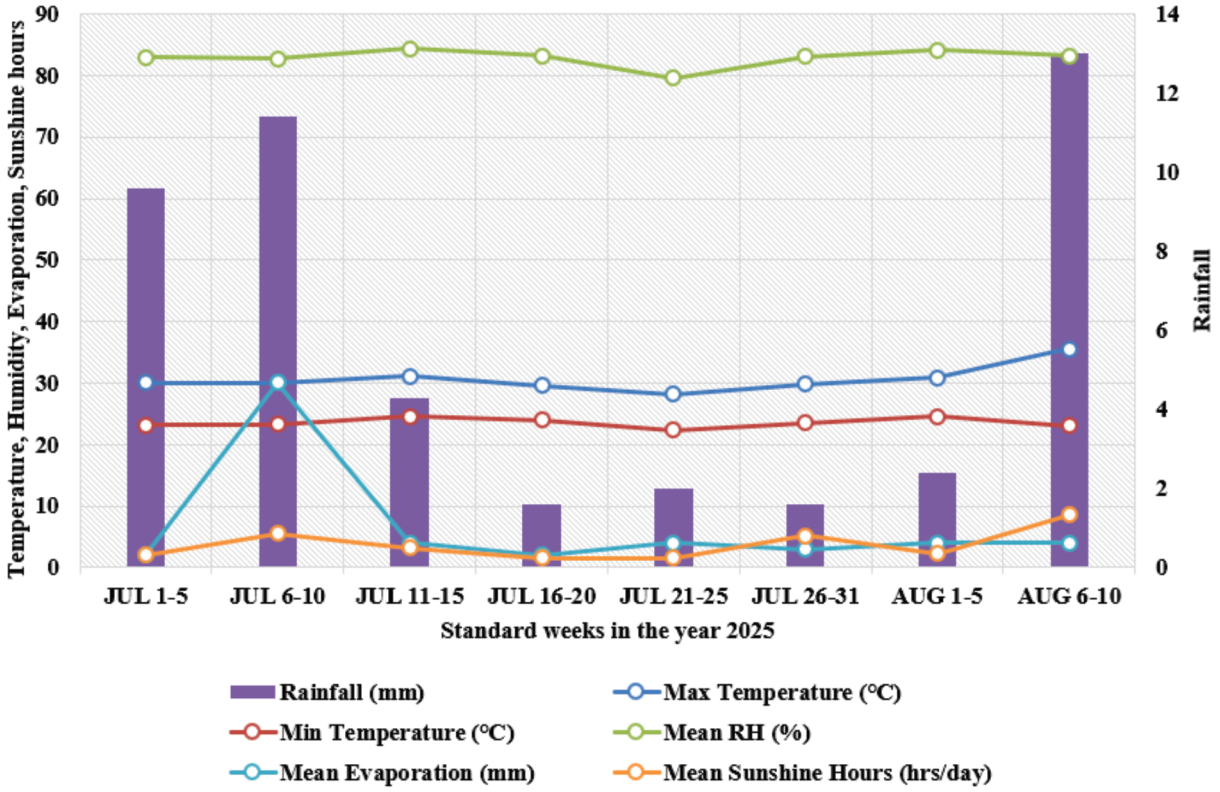


FIGURE 1 Weather prevailed during the cropping period (July – August 2025) (VIA, Pollachi)

Source: The weather data were collected from the meteorological observatory of Vanavarayar Institute of Agriculture, Pollachi

TABLE 1 Fertilizer dose applied for Red Amaranthus in soilless experiment

1. Recommended dose of fertilizers			
Nutrients →	N	P_2O_5	K_2O
Recommended Fertilizer for Fertigation - for 5,00,000 plants/ hectare	60 kg	30 kg	20 kg
Recommended Fertilizer for each pot (5 plants/pot)	0.60 g	0.30 g	0.20 g
Recommended Fertilizer for 42 pots	25.2	12.6	8.4

2. Fertilizer sources and day of applications			
Fertilizer application day (Days after sowing -DAS	Fertilizer used g for 42 pots		
	Urea	DAP	MOP
Basal dose	27.5	14	7
20 DAS	27.5	0	0
Total	55	14	7

DAP - Diammonium phosphate (18-46-0), MOP - Muriate of potash (0-0-60), No. of pots used in pot experiment – 42, *Method of application of fertilizers:* Surface application on growing media in each pot (calculated quantity of fertilisers were mixed in 4.2 litres of water and applied at the rate of 100 ml per pot)

2.3 | Calculation of Nutrient Uptake & Nutrient Use Efficiencies

Total nitrogen (N), phosphorus (P), and potassium (K) contents in oven-dried plant samples were determined using standard procedures (Piper, 1966; Jackson, 1973). These values were used to compute nutrient uptake and fertilizer use efficiencies.

Nutrient uptake: Nutrient uptake was calculated by multiplying the nutrient concentration (%) by the dry matter yield and expressed as grams per pot.

$$\text{Nutrient uptake} = \frac{\text{Nutrient content (\%)} \times \text{Total dry matter yield (g pot}^{-1}\text{)}}{100} \quad (1)$$

Response ratio: It is the increase in yield per unit quantity of nutrient applied, which is calculated by using the formula

$$\text{Response ratio} = \frac{\text{(Yield in fertilized pot – Yield in unfertilized pot)}}{\text{Quantity of applied nutrient}} \quad (2)$$

Physiological efficiency: It is the increase in yield per unit quantity of nutrient utilized by plant (total uptake), which is calculated by using the formula.

$$\text{Physiological efficiency} = \frac{\text{(Yield in fertilized pot – Yield in unfertilized pot)}}{\text{Quantity of absorbed nutrient}} \quad (3)$$

Apparent nutrient recovery: Recovery of added fertilizer nutrient is calculated separately for N, P, and K. Apparent nutrient recovery (ANR) is an obvious measure of fertilizer use efficiency and expressed in percentage (Mengel *et al*., 2006; Jalpa *et al*., 2020).

$$\text{ANR (\%)} = \frac{\text{(Nutrient uptake in fertilized pot – Nutrient uptake in unfertilized pot)}}{\text{Quantity of applied nutrient}} \times 100 \quad (4)$$

2.4 | Statistical Analysis

The data on growth and yield parameters of Red Amaranthus, along with nutrient uptake and efficiency, were analyzed statistically using analysis of variance (ANOVA) and continued with Duncan's Multiple Range Test (DMRT) if the results showed significant differences.

3 | RESULTS AND DISCUSSION

3.1 | Initial characteristics of particulate organic substrates/inorganic materials

Raw coirpith exhibited (Table 2) the lowest bulk density (0.118 Mg m^{-3}) while vermicompost (0.592 Mg m^{-3}) recorded the highest bulk density. The pH of the coirpith (6.49) was slightly acidic, while that of vermicompost was near neutral (7.46). The EC of raw coirpith recorded the highest 4.53 dS m^{-1}, and for vermicompost, the EC recorded was 1.86 dS m^{-1}, respectively. Similar to EC, TDS was highest for raw coirpith (2296 mg L^{-1}) and low with 886 mg L^{-1} for vermicompost. While comparing the substrates, the highest carbon (33.84 %) and widest C/N ratio (52.9) was found in coirpith. A moderate organic C of 16.62 per cent and a moderate C/N ratio (25.1) were recorded for vermicompost.

With respect to total nutrient content, the highest N was noticed for vermicompost (11.265 g kg^{-1}), whereas coirpith recorded a total N of 2.821 g kg^{-1}. In case of total P, high content was found in vermicompost (5.065 g kg^{-1}) and lowest was found in coirpith (0.193 g kg^{-1}). High total K was recorded in coirpith (2.324 g kg^{-1}) followed by vermicompost (1.162 g kg^{-1}).

3.2 | Physico-chemical properties of growing media in crop stages

Electrical conductivity decreased with crop growth stages from 2.41 to 1.07 dS m^{-1} (*Fig.* 2). The observed reduction in electrical conductivity (EC) in treatments containing sand might be due to dilution in the quantity of organic materials, which are the sources of salts. This dilution effect lowered the overall salt concentration in the growing medium, thereby mitigating salinity stress and improving plant performance. These results are in line with the findings of Elakiya (2021). When comparing the treatment mean values, the treatment containing coirpith alone registered slightly acidic pH throughout the crop growth stages (*Fig.* 3). The mean pH was found to rise from slightly acidic (6.42) to a near neutral state (7.34) with advancement in crop growth stages. Treatments incorporating sand demonstrated a reduction in salinity, underscoring its functional role in substrate optimization.

3.3 | Effect of media combination on Growth Parameters of Red Amaranthus

Significant differences were observed in the growth attributes of Red Amaranthus due to the effect of combinations of growing media. The plant height, number of leaves per plant, leaf length, leaf breadth, and leaf area were recorded (Table 3) for growth parameters.

3.3.1 | Effect of media combination on plant height and leaf count

Plants grown in the media consisting of coirpith: vermicompost (1:1) attained the highest mean plant height (25.8 cm) followed closely by coirpith: vermicompost (2:1) (22.5 cm). These treatments consistently outperformed others, highlighting the synergistic effect of vermicompost with lightweight porous media. The lowest plant height was observed in coirpith (11.5 cm). Media enriched with vermicompost consistently outperformed coirpith alone, reaffirming the role of vermicompost as a nutrient-dense amendment rich in microbial activity. Similar results were obtained while optimizing soilless media for Red Amaranthus where cocopeat-vermicompost showed significantly higher growth and yield than cocopeat alone. Vermicompost enhanced nutrient availability and root development (Shetty *et al*., 2024).

Apart from providing mineral nutrients, vermicompost contributes to the biological fertility of growing media by adding beneficial microbes. Vermicompost contains residues of mucus excreted through the digestive canal of earthworms that would stimulate antagonism and competition between diverse microbial populations, resulting in the production of favourable antibiotics and hormones boosting plant growth. Mucus accelerating and enhancing decomposition of organic matter composing stabilized humic substances, which release plant available nutrients at high levels (Atiyeh *et al*., 2000) and embody water-soluble phytohormonal elements

(Edwards *et al*., 2004) have been reported.

Coirpith is highly resistant to biological degradation, hence it could render physical support stablyto the plant roots for several months. On average, coirpith is composed of 75–80 % coir dust and 20–25 % short fibre (Stewart-Wade, 2020). Coirpith dust is highly hydrophilic, having increased wettability, structural stability, total porosity and air content, total water-holding capacity, and reduced bulk density (Shara *et al*., 2017).

As an inert physical particle, sand may have aided in increasing the porosity of the media. The particle sizes of sand expressed significantly different results in porosity. However, sand addition in growing media decreased the proportion of other organic constituents in growing media (Elakiya, 2021). This would have reduced the contribution of nutrients to the plant growth, and hence the yield would have declined in the treatments where the sand was a part of the growing media.

TABLE 2 Physical properties, chemical composition and nutrient content of substrates used for media preparation

Physical properties and chemical composition				
S.No	Parameter	Unit	Coirpith	Vermi compost
1	Bulk density	Mg m^{-3}	0.118	0.592
2	Carbon	%	33.84	16.62
3	TDS (1:5 dilution)	mg L^{-1}	2296	886
4	pH (1:5 dilution)	pH	6.49	7.46
5	EC (1:5 dilution)	dS m^{-1}	4.53	1.86
6	C/N Ratio		52.9	25.1
Nutrient Composition				
S.No	Nutrients	Unit	Coirpith	Vermi compost
7	Total N	g kg^{-1}	2.821	11.265
8	Total P	g kg^{-1}	0.193	5.065
9	Total K	g kg^{-1}	2.324	1.162

TABLE 3 Effect of media composition on vegetative parameters of Red Amaranthus at harvest stage

Treatment	Plant height (cm)	Number of leaves $plant^{-1}$	Leaf length (cm)	Leaf breadth(cm)	Leaf area (cm^2)	Stem grith (cm)
CP+VC (1:1)	25.8 a	10 a	10.5 a	8.1 a	63.79 a	2.8 a
CP+VC+S (1:1:1)	21.7 b	7 c	6.7 c	6.2 c	31.16 d	1.2 e
CP+VC (2:1)	22.5 b	8 b	7.8 b	7.4 b	43.29 b	2.2 b
CP+VC+S (2:1:1)	22.1 b	8 b	7.1 c	7.4 b	39.41 c	1.9 c
CP+VC (1:2)	21.3 b	7 c	6.8 c	6.5 c	33.15 d	1.4 d
CP+VC+S (1:2:1)	20.2 c	6 d	6.5 c	6.2 c	30.23 d	1.1 e
CP alone	11.5 d	6 d	4.2 d	2.2 d	6.93 e	0.8 f
Sed±	0.730	0.401	0.330	0.163	1.566	0.026
CD (P=0.05)	1.566*	0.859*	0.708*	0.349*	3.358*	0.057*

**CP - Coirpith, VC – Vermicompost, S - Sand <2 mm.*

Note: In 'Treatments' column, the values in parenthesis indicate ratio of substrates

**Means followed by the same letter are not significantly different at 5% level according to Duncan's Multiple Range Test (DMRT)*

3.3.2 | Effect of media combination on leaf length, width and area

Leaf width, leaf length, and leaf area are direct indications of plant growth. While comparing the performance of different growing media, leaf length, leaf breadth, and leaf area of Red Amaranthus exhibited significant differences. The leaf length ranged from 4.2 to 10.5 cm, leaf breadth ranged from 2.2 to 8.1 cm, and leaf area ranged from 6.93 to 63.79 cm^2. Treatment with equal proportions of coirpith and vermicompost, especially when paired together in a 1:1 ratio, showed increased leaf counts per plant (10). The lowest number of leaves per plant in CP alone (6) highlights the inadequacy of coirpith as a stand-alone medium.

Maximum leaf area (63.79 cm^2) was recorded in CP+VC (1:1), followed by CP+VC (2:1) (43.29 cm^2), which were significantly different from each other. The synergistic effect of organic matter in vermicompost and the porosity of coirpith would have likely enhanced photosynthetic surface development. Reduced leaf area in CP+VC (2:1) and CP+VC+S (2:1:1) showed that excessive coirpith might have hindered leaf expansion due to poor aeration and waterlogging. Amaranthus, being a fast-growing leafy vegetable, would have suffered from reduced chlorophyll content and stunted growth under such nutrient-deficient conditions (Epelde *et al*., 2018; Borthakur *et al*.,

2025). In the combination, CP+VC (1:2) and CP+VC+S (1:2:1), high doses of vermicompost might have raised pH, affecting nutrient solubility and microbial dynamics. Excessive vermicompost can lead to nutrient imbalances, especially elevated salts or ammonia, which may inhibit germination and seedling growth, causing phytotoxicity risks (Ceritoglu *et al*., 2021).

3.3.3 | Effect of media combination on stem girth

The highest stem girth (2.8 cm) was recorded in the CP + VC (1:1) treatment, indicating that a balanced mix of coir pith and vermicompost creates a favorable medium for stem development. Vermicompost enriched the substrate with nutrients and beneficial microbes, while coir pith would have improved aeration and water retention. In the treatment CP + VC + S (1:1:1), stem girth dropped sharply to 1.2 cm. The inclusion of sand (S) in the growing medium consistently led to reduced stem girth across all ratios. Sand would have diluted the nutrient concentration and reduced organic content, thereby limiting growth.

CP + VC (2:1) showed a moderate stem girth (2.2 cm), suggesting that increasing coir pith slightly would have reduced nutrient density but still supported decent growth. CP + VC (1:2) resulted in lower stem girth (1.4 cm), possibly due to excessive vermicompost leading to nutrient imbalance or compaction, which hindered root expansion and nutrient uptake. The lowest stem girth (0.8 cm) was observed with coir pith alone, underscoring its limited nutritive value when not supplemented with vermicompost. Though coir pith improved anchoring of the plant, it lacked the essential nutrients required for robust stem development.

3.4 | Root parameters of Red Amaranthus

3.4.1 | Root length

Root length (Table 4) exhibited a significant influence of various growing media and varied from 10.6 to 15.8 cm. The growing media comprising coirpith: vermicompost (1:1) recorded the maximum root length (15.8 cm), followed by the media combination coirpith: vermicompost in the ratio 2:1 (14.7 cm). The treatment with coirpith alone showed restricted root development (10.6 cm), indicating its limitations in sustaining healthy root architecture.

Coirpith and vermicompost media combinations would have favored better root elongation, likely due to a balanced moisture profile, root-zone porosity, and bioactive compounds from vermicompost. An optimal root-zone environment facilitates more profound and more extensive root systems and improved root architecture, which enhances nutrient and water uptake, which is critical for overall plant vigor and biomass accumulation. Similar findings were reported by Madhusree and Madhumita (2021), where media containing coirpith and vermicompost in balanced ratios significantly improved root traits in ornamental species.

3.4.2 | Root to Shoot ratio

The Root-to-Shoot Ratio serves as a valuable diagnostic tool in soilless cultivation systems. It can be used as an early indicator of substrate performance and plant stress, enabling growers to make timely adjustments to the growing medium. The media combinations were observed to have a significant effect on the root-to-shoot ratio of Red Amaranthus. Lower root-to-shoot ratios (0.59–0.61) were observed in all combinations involving VC and/or sand, indicating greater shoot biomass relative to root biomass. A lower root-to-shoot ratio is often desirable for leafy crops like Amaranthus, as it indicates efficient nutrient uptake and allocation to edible biomass. CP alone resulted in the highest ratio (0.83), indicating more root biomass relative to shoot biomass, which could often be in response to stress conditions such as nutrient deficiency or salinity. This imbalance suggests the plant is struggling to acquire sufficient resources, which can negatively impact shoot growth and overall yield. Under nutrient deficiency or drought, the root-to-shoot ratio often increases, reflecting adaptive investment in root growth for resource acquisition (Peng *et al*., 2019).

3.5 | Effect of media combination on Yield of Red Amaranthus

The highest fresh weight (61.52 g pot^{-1}) and dry weight (17.42 g pot^{-1}) were recorded in the treatment with coirpith + vermicompost (1:1), indicating optimal nutrient availability and balanced physical structure, which was a significant difference from all other combinations. The next best performance was observed in CP + VC (2:1), with a fresh weight of 43.97 g pot^{-1} and dry weight of 11.57 g pot^{-1}, suggesting that increasing coirpith slightly reduced nutrient density but still supported biomass accumulation. The lowest yield was recorded in coirpith alone, with a fresh weight of 20.32 g pot^{-1} and dry weight of 5.60 g pot^{-1}, confirming its inadequacy as a standalone medium. The lack of nutrients and microbial activity in coirpith likely restricted plant growth and biomass accumulation. (Table 5; *Fig.* 4).

Plant growth is dependent on the rate of accumulation of dry matter. Total dry matter production is the integral of crop growth rate over the entire growing period and is related to assimilatory surface area, leaf area, duration, other growth attributes, and yield (Yoshida, 1972). The dry matter accumulation influences the economic yield on one hand, while production of drymatter is dependent upon adequate supply of plant nutrients (Maghfoer *et al*., 2015).

In the present study, the growth and yield parameters were exceptionally high in growing media containing coirpith: vermicompost in the ratio of 1:1 followed by coirpith: vermicompost in the ratio 2:1. The increased dry matter under the above treatment might be mainly due to early vigour shown by the crop which was due to the availability of plant nutrients at adequate level along with sufficient moisture for early development of plant parts and roots, which might have enhanced more uptake of nutrients. This result aligns with the findings of Ramesh

(2014), who evaluated multiple media combinations for Amaranthus tricolor, where treatments with coir pith and vermicompost in a 1:1 ratio, when supplemented with organic nutrition, showed superior growth, yield, and cooking quality. Uma and Malathi (2009) reported that humic materials and other plant growth-influencing substances, such as plant growth hormones produced by microorganisms during vermicomposting, increased the growth and yield of amaranthus.

The results on the yield parameters of red amaranthus distinctly indicated the importance of combining proper fertilization with the correct composition of growing media to achieve higher production. Sande et al. (2024) observed that the combined application of vermicompost at 25% and inorganic fertilizers at 75–100% of the recommended dose yielded optimal results for biomass accumulation.

3.6 | Effect of media combination on Nutrient uptake of Red Amaranthus

The effect of composition of growing media on uptake of macronutrients by Red Amaranthus was estimated at final harvest stage. Among the growing media experimented, the highest amount of total N uptake (0.190 g pot^{-1}), total P uptake (0.085 g pot^{-1}) and total K uptake (0.160 g pot^{-1}) were observed in the growing media comprising coirpith: vermicompost in equal proportions (T_1) which was followed by growing media having coirpith: vermicompost in 2:1 proportions (T_3) (*Fig.* 5). This enhanced uptake in the CP:VC (1:1) treatment may be attributed to the balanced nutrient profile and improved root-zone conditions provided by the coir pith and vermicompost blend, which facilitated optimal nutrient absorption.

Efficient use of fertilizer nutrients is necessary for optimum growth and yield, for which making continuous availability of nutrients in the growing media is essential. During the vegetative stage, the plant vigorously absorbs nutrients to build up the plant framework, and the excess nutrients are stored within the plant and translocated to the fruit at later stages for further development (Pfluger and Mengel, 1972). Plant analysis serves as an elegant tool for understanding the growth and physiology of plants at various growth stages.

The fresh weight of Red Amaranthus raised with the growing media of coirpith: vermicompost in equal proportion recorded the highest value of nutrient content of N, P, K, and corresponding nutrient uptake. Several studies indicated that the application of organic manure along with inorganic fertilizers enhanced the mobility of nutrients around the root zone. Even though all the growing media were fertilized with a uniform dose of fertilizer solution periodically, the integrated effect of growing media with coirpith: vermicompost was reflected well in nutrient content and uptake significantly (*Fig. 6*).

TABLE 4 Effect of media composition on root length and root and shoot ratio of Red Amaranthus at harvest stage

T.No.	Root length (cm)	Root: Shoot ratio
CP+VC (1:1)	15.8 a	0.61 b
CP+VC+S (1:1:1)	12.8 c	060 b
CP+VC (2:1)	14.7 b	0.60 b
CP+VC+S (2:1:1)	13.3 c	0.59 b
CP+VC (1:2)	13.1 c	0.59 b
CP+VC+S (1:2:1)	12.1 d	0.60 b
CP alone	9.6 e	0.83 a
Sed±	0.380	0.013
CD(P=0.05)	0.815*	0.029*

*Means followed by the same letter are not significantly different at 5% level according to Duncan's Multiple Range Test (DMRT)

TABLE 5 Effect of media composition on yield parameters of Red Amaranthus at harvest stage

T.No.	Fresh Weight g pot^{-1}	Dry Weight g pot^{-1}
CP+VC (1:1)	61.52 a	17.42 a
CP+VC+S (1:1:1)	34.74 d	10.11 c
CP+VC (2:1)	43.97 b	11.57 b
CP+VC+S (2:1:1)	39.32 c	10.33 c
CP+VC (1:2)	36.14 d	10.15 c
CP+VC+S (1:2:1)	32.23 e	9.42 d
CP alone	20.32 f	5.60 e
Sed±	0.903	0.180
CD(P=0.05)	1.936*	0.387*

*Means followed by the same letter are not significantly different at 5% level according to Duncan's Multiple Range Test (DMRT)

Vermicompost, which contains nutrients such as nitrates, available P, K, Ca, and Mg, and has a large specific surface area for nutrient retention, would enhance nutrient uptake. Apart from providing mineral nutrients, particularly N and K, vermicompost also contributes to the biological fertility of soil and enhances decomposition of organic matter, composing stabilized humic substances , which would increase quick dissolution and mobility of immobile P as soluble P. Uma & Malathi (2009) also reported enhanced nutrient uptake and biomass in Amaranthus when vermicompost was used as a soil supplement. The present studies corroborate to the findings of . Yadav *et al*. (2022) demonstrated that integrated nutrient management involving vermicompost and biofertilizers significantly increased leaf number, fresh and dry weight, and nutrient uptake in *Amaranthus tricolor*. Patel *et al*. (2019) also reported that vermicompost combined with Azotobacter and PSB enhanced nitrogen and phosphorus availability, leading to higher grain and stalk yield in *Amaranthus hypochondriacus.*

TABLE 6 Effect of treatments on nutient use efficiency at harvest stage

Treatments	Response ratio (g yield g^{-1} nutrient applied)			Physiological efficiency (g yield g^{-1} nutrient absorbed)			Apparent Nutrient Recovery (%)		
	N	P	K	N	P	K	N	P	K
CP+VC (1:1)	3.046 a	13.374 a	20.507 a	323 e	725 e	383 d	5.411 a	10.587 a	30.700 a
CP+VC+S (1:1:1)	1.720 d	7.552 d	11.580 d	459 c	996 c	419 c	3.703 d	7.500 d	27.367 c
CP+VC (2:1)	2.177 b	9.559 b	14.657 b	413 d	862 d	426 c	4.559 b	9.587 b	29.733 b
CP+VC+S (2:1:1)	1.947 c	8.548 c	13.107 c	452 c	984 c	452 b	4.173 c	8.413 c	28.067 c
CP+VC (1:2)	1.789 d	7.857 d	12.047 d	454 c	1096 b	430 c	3.886 d	7.065 d	27.633 c
CP+VC+S (1:2:1)	1.596 e	7.007 e	10.743 e	487 b	1063 b	421 c	3.480 e	7.000 d	27.067 d
CP alone	1.006 f	4.417 f	6.773 f	584 a	1202 a	603 a	3.074 f	6.565 e	20.067 e
Sed±	0.057	0.1507	0.3021	11.75	20.85	10.22	0.0863	0.2035	0.5016
CD(P=0.05)	0.123*	0.3233*	0.6480*	25.21*	44.73*	21.92*	0.1849*	0.4365*	1.0757*

*Means followed by the same letter are not significantly different at 5% level according to Duncan's Multiple Range Test (DMRT)

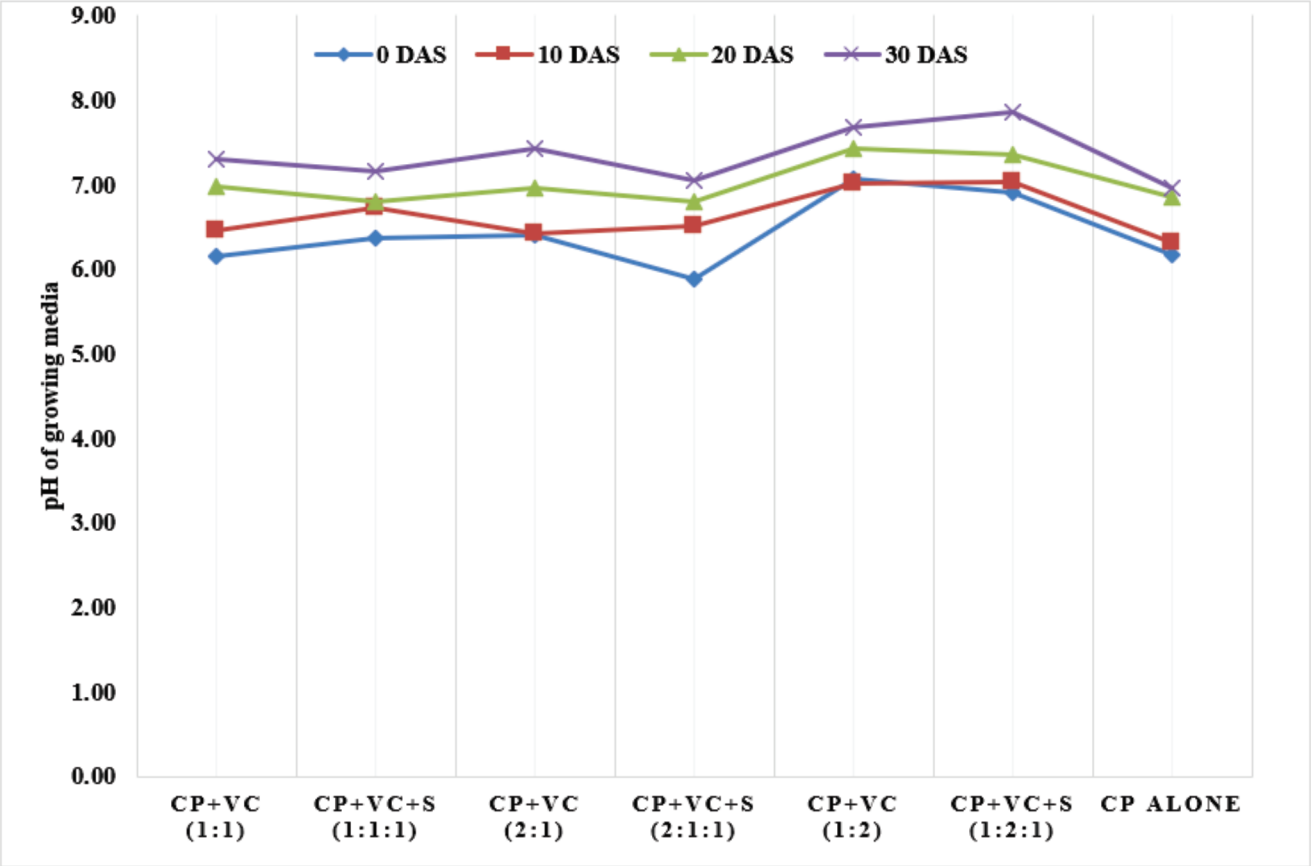


FIGURE 2 Changes in reaction state (pH) of growing media during crop growth stages

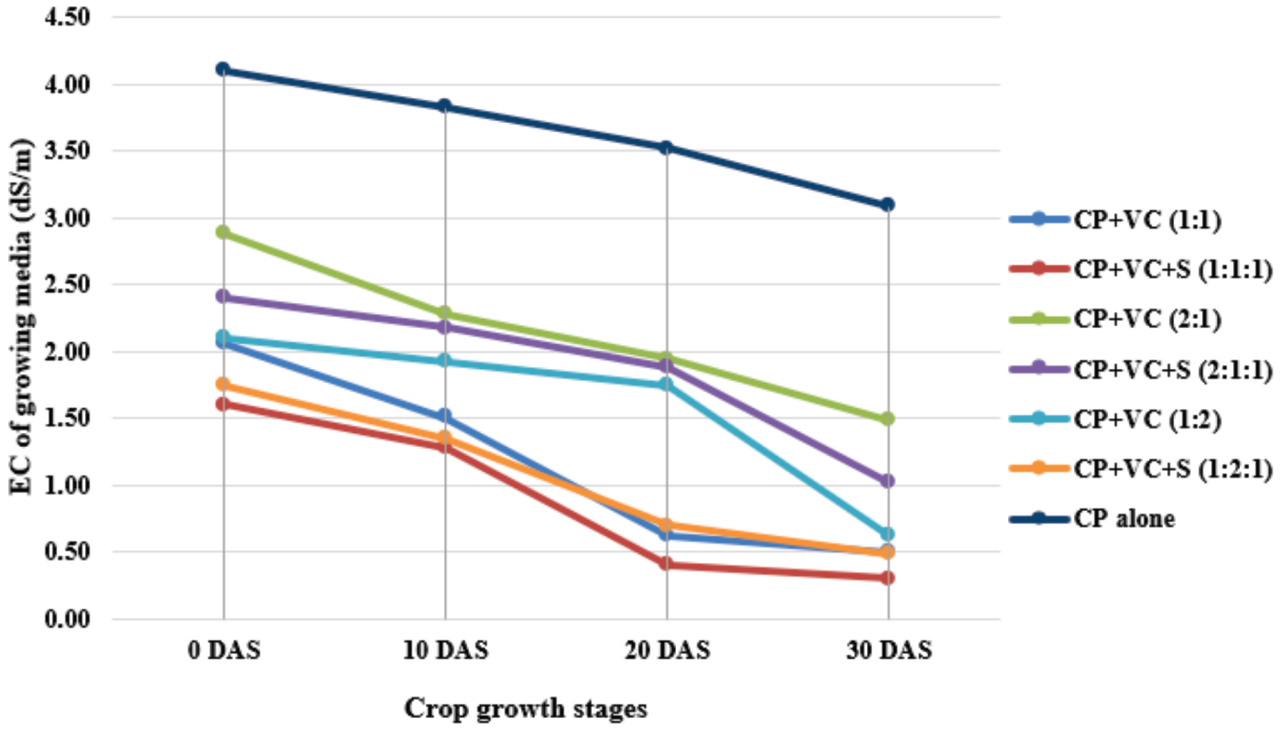


FIGURE 3 Changes in salinity (EC) of growing media during crop growth stages

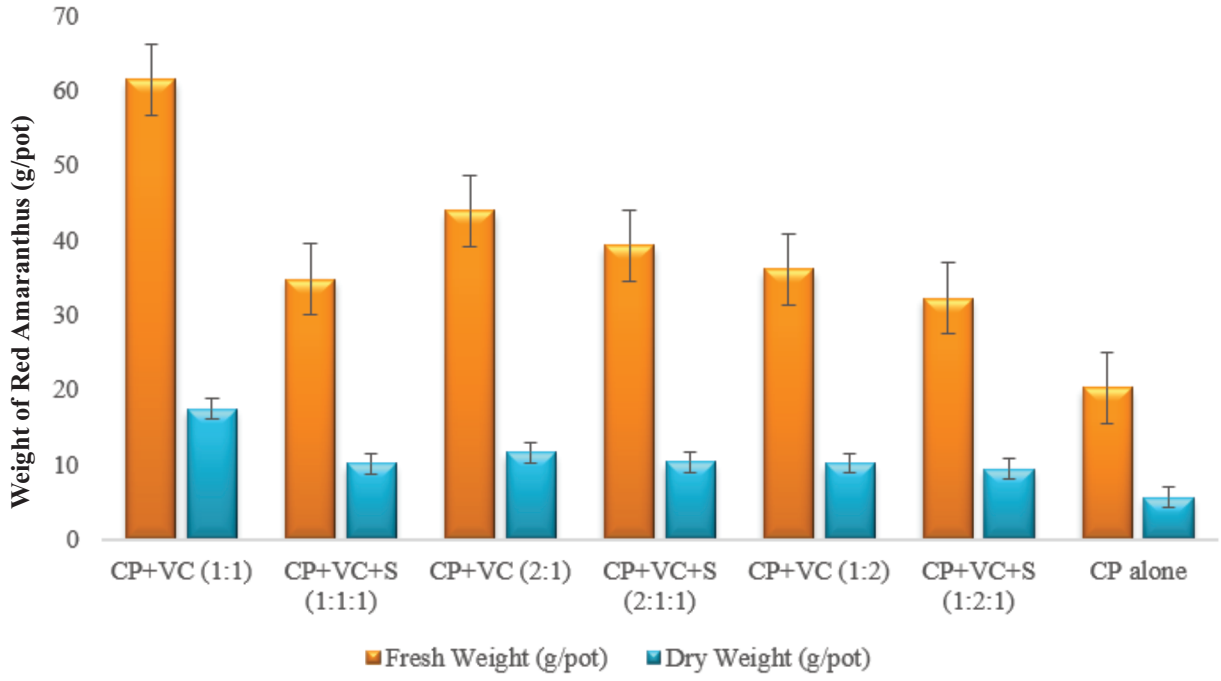


FIGURE 4 Effect of media combination on fresh weight and dry weight of Red Amaranthus

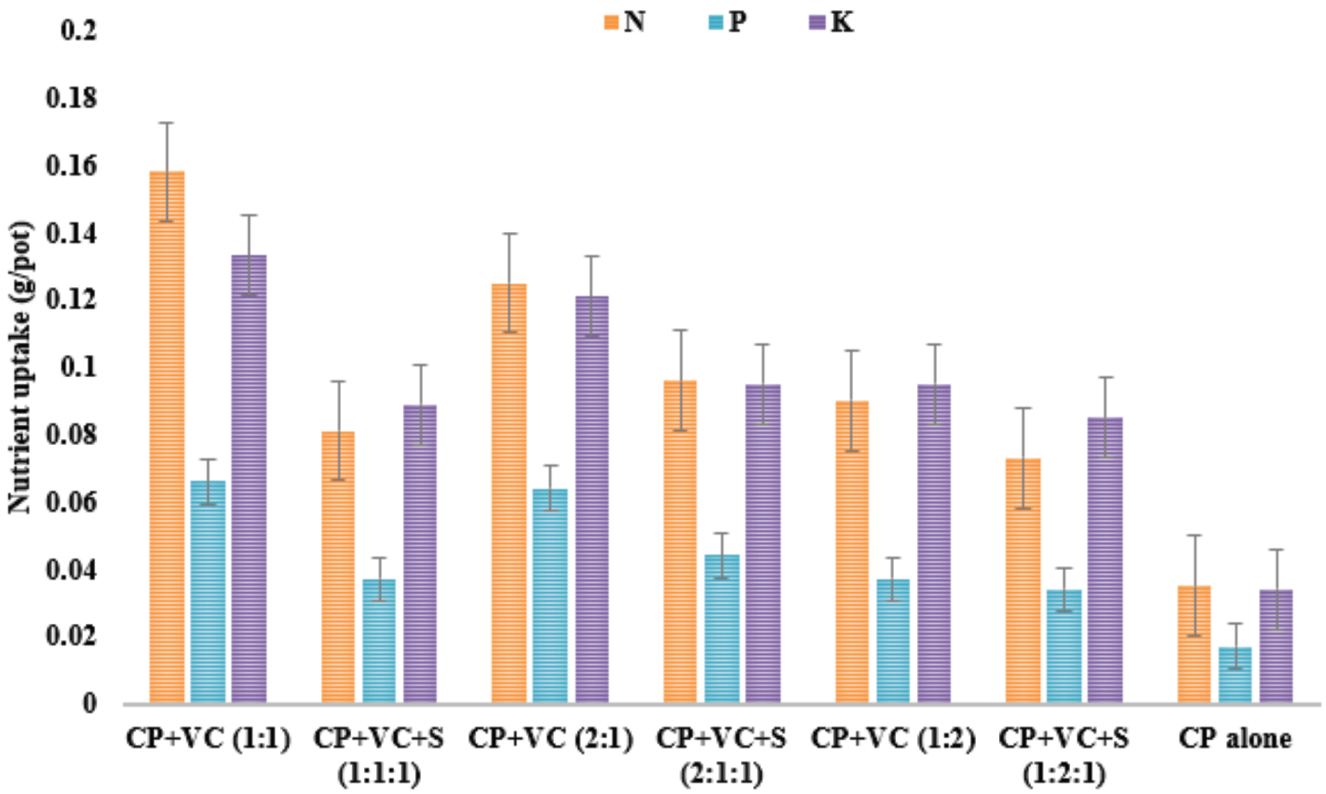


FIGURE 5 Effect of media combination on nutrient uptake of Red Amaranthus



FIGURE 6 Pot culture experiment with Red Amaranthus at 30 DAS

3.7 | Effect of media combination on Nutrient use efficiency

Based on the yield and nutrient uptake estimated for Red Amaranthus in growing media, the nutrient use efficiencies were computed in terms of response ratio, apparent nutrient recovery, and physiological efficiency for the applied N, P, and K nutrients (Table 6).

3.7.1 | Request Ratio (RR)

The coirpith and vermicompost (1:1) treatment recorded the highest RR values across all nutrients (N: 3.046, P: 13.374, K: 20.507), indicating a robust yield response per unit of nutrient applied. This aligns with previous findings that vermicompost enhances nutrient availability and microbial activity, thereby improving crop performance (Singh *et al*., 2020). In contrast, treatments incorporating sand (e.g., CP+VC+S in a 1:2:1 ratio) showed diminished RR values, which indicated that sand might have diluted nutrient concentration unfavorably for nutrient uptake.

3.7.2 | Apparent Nutrient Recovery (ANR)

CP+VC (1:1) again led in ANR for all nutrients, with potassium showing the highest recovery (K: 30.700%). This reflected that the coirpith and vermicompost combination in equal parts improved root uptake and reduced nutrient losses, likely due to better moisture retention, and microbial interactions facilitated by the compost blend (Singh *et al*., 2020; Sathiyavathi *et al*., 2023). Treatments with sand consistently showed lower ANR, suggesting that sand may reduce nutrient retention or impede root access to nutrients. However, the differences were not drastic, indicating that sand can still be a useful amendment when appropriately balanced.

3.7.3 | Physiological Efficiency (PE)

The CP-alone treatment exhibited the highest PE, particularly for phosphorus (P: 1202 g yield/g nutrient absorbed) and potassium (K: 1016 g/g). Although CP alone recorded the highest physiological efficiency, this value can be interpreted with caution due to its low absolute N uptake. The inflated PE may reflect limited nutrient acquisition rather than actual efficiency in biomass conversion. Coirpith's slow-release properties may synchronize nutrient availability with crop demand, enhancing internal nutrient utilization (Mahanta, 2017). Treatments incorporating vermicompost (VC), especially CP+VC (1:1), demonstrated balanced PE values alongside higher nutrient uptake, indicating more effective nutrient assimilation, reinforcing the role of organic matter in improving nutrient assimilation and metabolic efficiency (Sathiyavathi *et al*., 2023).

4 | CONCLUSIONS

In this study, the performance of various organic substrate combinations—mainly coirpith (CP), vermicompost (VC), and sand (S)—as growing media for Red Amaranthus in soilless cultivation is analyzed. Based on growth, yield, and nutrient use efficiency, it was found that all media supported healthy growth of Red Amaranthus despite the salinity present. The combination of coirpith and vermicompost in equal parts (1:1) emerged as the best growing medium for Red Amaranthus in soilless systems, as it strikes a good balance between physical support, nutrient supply from vermicompost, and enhanced aeration and water retention from coirpith, offering a model for sustainable urban farming. Therefore, these results provide a validated approach for optimizing soilless substrates, with implications for urban food security, resource efficiency, and sustainable production of leafy vegetables.

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CONFLICT OF INTEREST

Authors declare that there are no conflicts of interest in any form that could have influenced the research presented in this paper.

DATA AVAILABILITY STATEMENT

The data used in this study are available from the links provided in this manuscript or upon request from the authors.

AUTHOR'S CONTRIBUTION

This research work conducted by PR, SS, DRK and IA.; NE: Conceptualization, methodology, data curation, formal analysis, investigation, manuscript writing and supervision.

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ORIGINAL ARTICLE

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Potential Grass Species for Soil Conservation and Fodder Production in the Nilgiri Hills of the Western Ghats

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ABSTRACT

Soil erosion and fodder shortages on sloping terrains in the Nilgiri Hills have intensified due to grassland conversion to agriculture. While bench terracing is recommended for slopes exceeding 16%, high costs limit farmer adoption. This two-year field experiment (2019-21) at ICAR-IISWC, Udhagamandalam, evaluated eight grass species—four fodder grasses (Guinea grass, Congo signal, Cumbu Napier hybrid CO(CN) 4, Bajra Napier CO(BN) 5 and four native grasses (Weeping love grass, Guatemala grass, Vetiver, Lemon grass)—for soil conservation efficiency, biomass yield, and ecosystem services. Results showed that Bajra Napier CO(BN) 5 and Cumbu Napier CO(CN) 4 provided superior soil conservation through extensive foliage spread (150 and 146 cm), higher root mass density (1.26 and 1.20 gcc^{-1}), and greater soil binding capacity (195,613 and 180,867 cc), while delivering maximum biomass yields (310 and 262 t ha^{-1}yr^{-1}) and superior crude protein content (14%). Vetiver and Congo signal grasses enhanced soil organic carbon stocks most effectively (38.7 and 31.7 t ha^{-1} gain), with vetiver exhibiting greatest CO_2 sequestration (85.17 t ha^{-1} yr^{-1}) despite higher soil respiration. Hybrid Napier grasses proved ideal for dual purposes—erosion control and fodder production—while vetiver excelled in carbon storage. Integrating complementary grasses offers a sustainable, low-cost alternative to mechanical bench terracing in fragile hill ecosystems.

1 | INTRODUCTION

Although the issues of runoff, soil erosion, and soil degradation have long been recognized, their intensity has escalated in recent years due to mounting pressure on natural resources. The conversion of grasslands into agricultural fields has not only resulted in acute fodder shortages but has also exacerbated soil erosion and degradation, particularly on sloping terrains in hilly regions (Sun *et al.,* 2018). In the Nilgiri Hills of the Western Ghats, vegetable cultivation is practiced on slopes ranging from 5% to 40%, leading to alarming soil losses of up to 40 t ha^{-1} year^{-1}. Bench terracing is recommended for slopes exceeding 16% (Sahoo *et al.,* 2015). Yet, farmers are often reluctant to adopt it due to the high initial investment (Sudha *et al*., 2016) and the risk of reduced crop yields from subsoil exposure during the cut-and-fill process. This practice also negatively impacts soil fertility in the early years (Mesfin *et al.,* 2018).An alternative approach—natural formation of low-cost bench terraces using vegetative barriers such as medicinal plants, known as the Puerto Rican type, which was previously documented by Muralitharan et al. (2008). Many studies globally and within India demonstrate that grasses and vegetation barriers are practical tools for controlling soil erosion and enhancing carbon sequestration. For instance, Sudhishri *et al.* (2008) showed that vegetative barriers (including grasses) significantly reduced soil loss and improved soil moisture and nutrient retention under hill slopes in Orissa, India. Azis and Islam (2023) reported that vetiver grass (*Chrysopogon and zizanioides*) effectively reduced soil loss by up to 97% and runoff by over 20% under high-intensity rainfall, demonstrating its strong potential for erosion control even on steep tropical slopes with erodible soils. Do *et al.* (2023) reported that agroforestry systems integrating fruit trees, contour grass strips, and annual crops on sloping land in northwest Vietnam reduced soil, carbon, and nutrient losses by 27–84% through natural terrace formation, demonstrating the soil-conservation potential of grass-based agroforestry practices. Donjadee and Tingsanchali (2013) demonstrated that vetiver hedgerow systems reduced runoff by 31–69% and soil loss by 62–86% on steep slopes under simulated rainfall, confirming their strong effectiveness in minimizing erosion and providing reliable predictive equations for soil loss estimation.

Previous work in the region broadly examined

vegetative barriers/bench-terrace formation in isolation. It did not compare multiple grasses side-by-side for surface protection, root-mediated soil binding, SOC change/CO_2 flux, and fodder yield and quality. Evaluating ecosystem services has become an essential area of study, highlighting the vital benefits that natural environments provide to human societies (Kumar et al., 2024). Our study fills this gap by simultaneously quantifying all four dimensions in one research field experiment (plus farmer validation), providing a trait-based, species-specific basis for recommending grasses that jointly maximize fodder, erosion control, and carbon benefits in hill ecosystems with the hypothesis that improved fodder grasses such as Napier hybrids would outperform native species in erosion control and biomass production. In contrast, deep-rooted native grasses like vetiver would contribute more significantly to carbon sequestration. We selected eight grasses to reflect both farmer-used, widely available fodder types (Guinea, Congo signal, CO (CN) 4, CO (BN) 5) and native/deep-rooted species (Weeping love, Guatemala, vetiver, lemon grass) that offer contrasting functional traits relevant to hill slopes—canopy cover for ground protection, root depth/lateral spread for soil binding, and fodder quality for on-farm value. The present study was undertaken to evaluate selected fodder and native grass species for their efficiency in soil and water conservation under the sloping terrains of the Nilgiri hills, to assess their biomass yield and nutritive value for identifying high-yielding and quality fodder options suitable for hill farming systems, and to quantify the contribution of different grass species to soil organic carbon enhancement and carbon sequestration potential as an indicator of ecosystem services.

2 | MATERIALS AND METHODS

2.1 | Study Location

A field experiment was carried out during 2019–20 to 2020–21 at the ICAR–Indian Institute of Soil and Water Conservation, Research Centre, Udhagamandalam, located in The Nilgiris, Tamil Nadu, India (11°24′ N latitude, 76°41′ E longitude, 2218 m above mean sea level). The experimental site featured lateritic red soil of moderate to considerable depth, relatively fertile, with an acidic reaction (pH 5.0) and a medium to high organic carbon content (1.2%). The available nitrogen, phosphorus, and potassium levels were 276, 45, and 344 kg ha^{-1}, respectively. The region receives an average annual rainfall of approximately 1200 mm, with 53% occurring during the southwest monsoon (June to September) and 30% during the northeast monsoon (October to December). The mean maximum and minimum temperatures recorded were 19.3°C and 11.8°C, respectively.

2.2| Field Experiment

The field experiment followed a Randomized Block Design (RBD) with three replications to control spatial heterogeneity. Within each block, the eight grass species were randomly allocated to plots, ensuring that each block had one plot per species. Each plot measured 10.0 m × 5.0 m, with a 1.0 m buffer between plots and guard rows along plot perimeters to minimize edge effects. Treatments were kept on the same physical plots across years to capture temporal responses; analyses were conducted by year and pooled. Eight grass species—comprising four fodder grasses and four native grasses—were planted in a randomized block design with three replications. The fodder grasses included Guinea grass (*Megathyrsus maximus*), Congo signal grass (*Brachiaria and ruziziensis*), Cumbu Napier hybrid CO (CN) 4, and Bajra Napier CO (BN) 5. The native grasses consisted of Weeping love grass (*Eragrostiscurvula*), Guatemala grass (*Tripsacum and laxum*), Vetiver grass (*Chrysopogon and zizanioides*), and Lemon grass (*Cymbopogon citratus*). Grass slips were spaced at 50 cm × 50 cm intervals. Plant height and canopy spread were measured with a tape measure. Month-wise yield was recorded and expressed in t ha^{-1}.

HIGHLIGHTS

- Bajara Napier CO (BN)5 and Napier CO (CN) 4 provide extensive foliage spread, higher root mass density, and exceptional biomass yields.
- Vetiver grass emerged as the champion for carbon sequestration despite higher soil CO_2 emissions,
- Rapid micro-terrace formation using Bajra Napier CO (BN)5 contour hedgerows, providing evidence for scalable, low-cost biological alternatives to expensive bench terracing.

2.3 | Soil Properties

Soil organic carbon (OC) was estimated by the Walkley and Black (1934) method. Crude protein content in the biomass was estimated by the Kjeldahl method. The total nitrogen obtained was multiplied by 6.25 to express crude protein percentage on a dry matter basis. Soil organic carbon stock was computed using the method of Lal et al. (2001), based on soil organic carbon content, bulk density, and soil depth.

The SOC stock was calculated using the equation:

$$\text{SOC stock (t ha}^{-1}\text{)} = \text{SOC (\%)} \times \text{Bulk density (t m}^{-3}\text{)} \times \text{Soil depth (m)} \times 10$$

where SOC is the percentage of soil organic carbon, bulk density is expressed in t m^{-3}, and soil depth is the thickness of the sampled layer (m). The changes in SOC storage were calculated using the initial SOC storage values before the experiment and the final SOC storage values after 2 years (cumulative).

Soil conservation efficiency was calculated using the approach outlined by Manivanan et al. (2017), as follows: Net assimilation of carbon was measured using infrared gas analyzers (IRGAs), and soil carbon emission was measured using the EGM-5 Soil CO_2Analyzer.

2.4 | Measurements of the Conservation efficiency of grasses

The height of the grass was measured vertically up the main stem from the ground level with a measuring tape. The

foliage lateral spread was measured at two directions perpendicular to each other as diameters with measuring tape, and the average value was calculated as follows:

$FLS = (y1 + y2) \div 2$

Where, FLS = average foliage lateral spread

y1, y2 = foliage lateral spread in 2 directions perpendicular to each other, passing through the main stem as a vertical central axis.

The rooting depth was measured vertically from ground level after uprooting it by digging. The lateral spread of the roots was measured in 3 directions from the main stem (central) of the grasses as radii, and the average value was calculated as follows.

$RLS = (x1 + x2 + x3) \div 3$

Where, RLS = average root lateral spread

x1, x2, x3 = root lateral spread in three directions from the main stem (central)

The root volume was measured by the water-displacement method (inserting the entire root into a measuring cylinder and measuring the increase in volume). Root mass density was calculated by dividing root dry weight by soil volume and expressed in grams/cc of soil volume.

2.5 | Volume of Soil Bound by the Fibrous Roots

Grasses are shallow-rooted, and it is assumed that fibrous roots bind the soil in a cylindrical shape. It is because the greater lateral spread of the roots provides an umbrella for the soil beneath, extending up to the maximum rooting depth. So, the formula for the volume of a cylinder is used as follows:

General formula for the cylinder volume = $\pi r^2 h$

And the adopted formula for the volume of soil bound by roots = $\pi (RLS)^2 (RD)$

Where RLS = root lateral spread (radial form from the main stand of grass) ; And RD = rooting depth of grass

2.6 | Ground Surface Area Protected by Grass Foliage against Direct Raindrop Effect

The ground surface area protected by grass foliage against direct raindrop effect is calculated using the formula to calculate the area of a circle ($A = \pi d^2/4$) as follows:

Protected ground surface area = $\pi (FLS)^2/4$

Where FLS is foliage lateral spread (taking as the diameter passing through the main stand of the grass) and d is the diameter.

2.7 | Statistical Analysis

To compare the treatments, the yield data were pooled, and an analysis of variance (ANOVA) was carried out usinga randomized block design. The treatment effects were evaluated using analysis of variance (ANOVA), and significance was tested using the F-test at the 5% level in R.

3.0 | RESULTS AND DISCUSSION

3.1 | Soil Conservation Efficiency (SCE) and Ecosystem Services

Plant height, number of tillers per plant, foliage spread, and the surface area protected by grasses against raindrop impact differed significantly (Table 1). The tallest plants were recorded in Guatemala grass, followed by Bajra Napier CO (BN) 5 and Cumbu Napier hybrid CO (CN) 4. Weeping love grass produced the most tillers; however, its soil conservation efficiency was lower than that of hybrid Napier grasses and Guatemala grass due to its limited lateral foliage spread. BN CO (BN) 5 recorded 150.4 cm foliage spread, which was 5.4–40.2% greater than other species, and provided a 15.3–64.0% higher protected surface area,indicating its significantly superior canopy development and ground-cover efficiency for soil and water conservation.Cumbu Napier Co(CN) 4 produced foliage spread of 146.2 cm, which was on par with Bajra Napier Co(BN) 5.The lowest value was recorded in the Congo signal grass due to its poor foliage spread. According to Kafle et al. (2008), the lateral spread of foliage determines the extent of ground surface protection from direct raindrop impact. Both Cumbu Napier Co(CN) 4 and Bajra Napier Co(BN) 5 have significantly higher valueson surface area protected by the grass (17662 and 16733 cm^2) compared to other grasses.Thus, hybrid Napier grasses, with their wider foliage spread, provide the maximum protection by covering a larger ground surface area.

The highest root depth was recorded in vetiver grass (47 cm), which was on par with Cumbu Napier hybrid CO (CN) 4 (43.1 cm) and Bajra Napier CO (BN) 5 (43.8 cm). In contrast, root lateral spread was significantly higher in Bajra Napier CO (BN) 5 (37.8 cm), followed by Cumbu Napier hybrid CO (CN) 4 (36.6 cm), Congo signal grass (36.6 cm), and weeping love grass (35.2 cm). Both Bajra Napier CO (BN) 5 and Cumbu Napier hybrid CO (CN) 4 produced significantly greater root volume (65.3 cc and 60.6 cc, respectively) and root mass density (1.26 g/cc and 1.20 g/cc), which were on par with vetiver grass (Table 2).

The grass species significantly influenced the volume of soil bound by the roots. The highest value (195613 cc)was recorded in Bajra Napier CO (BN) 5, and on par withCumbu Napier hybrid CO (CN) 4, and it was followed by Congo signal grass (160677 cc), and vetiver grass (154923 cc). Since the volume of soil bound by roots is a function of root depth and root lateral spread, the higher values observed in hybrid Napier and Congo signal grass can be attributed to their greater root lateral spread (combined with higher root depth in hybrid Napier). Vetiver exhibited the deepest roots (47.0 cm;) but a smaller lateral spread than BN hybrids, resulting in significantly lower ($P < 0.05$) estimated soil volume bound by roots than BN CO (BN) 5 .Wang and Zhang (2017) reported that plant root systems reduced soil detachment capacity by 53.6%, of which 41.4% and 12.2% were attributed to root binding and bonding effects, respectively. However, the two-year duration likely captures early canopy and root responses but may underestimate later-phase root lateral spread/mass density and SOC accrual typical of perennial grasses; multi-year monitoring is recommended.

TABLE 1 Surface area protected by various grasses against rain

Grass	Plant height (cm)	Tillers/ Plant	Foliage Lateral Spread (cm)	Surface area protected by the grass (cm^2)
Cumbu Napier hybrid CO (CN) 4	137.6[a]	68.3[c]	146.2[a]	16733[a]
Bajra Napier CO (BN) 5	145.5[a]	75.4[b]	150.4[a]	17662[a]
Guinea grass	128.6[a]	54.0[a]	126.2[b]	12462[c]
Weeping love grass	64.8[e]	115.6[a]	138.8[a]	14950[b]
Guatemala grass	148.6[a]	46.4[e]	142.6[a]	15828[b]
Vetiver	125.6[b]	66.6[c]	120.4[b]	11304[d]
Lemon grass	110.0[c]	81.4[b]	130.2[b]	13266[c]
Congo signal grass	98.6[d]	58.3[d]	90.2[c]	6358[e]
SEm±	5.2	4.25	7.93	492
CD p≤ 0.05	14.4	11.8	22.0	1365

Means with the same alphabet are not significantly different (P ≤ 0.05).

TABLE 2 Root character and volume of soil bound by root

Grass	Root depth (cm)	Root lateral spread (RLS) (cm)	Root volume (cc)	Root mass density (gm/cc)	Volume of soil bound by roots (cc)
Cumbu Napier hybrid CO (CN) 4	43.1[a]	36.6[a]	60.6[a]	1.20[a]	180867[a]
Bajra Napier CO (BN) 5	43.8[a]	37.8[a]	65.3[a]	1.26[a]	195613a
Guinea grass	38.2[b]	31.6[a]	40.4[c]	0.82[c]	119775[d]
Weeping love grass	30.0[c]	35.2[a]	25.0[d]	0.74[d]	116717[d]
Guatemala grass	41.9[a]	32.4[b]	52.3[b]	0.88[b]	138112[c]
Vetiver	47.0[a]	32.4[b]	55.0[b]	1.24[a]	154923[b]
Lemon grass	40.2[b]	30.6[b]	30.0[d]	0.66[d]	118194[d]
Congo signal grass	38.2[b]	36.6[a]	55.8[b]	0.91[b]	160677[b]
SEm±	1.3	1.0	2.60	0.03	5335
CD (p≤ 0.05)	3.6	2.6	7.2	0.07	14810

Means with the same alphabet are not significantly different (P ≤ 0.05).

3.2 | Soil Ecosystem Function

The increase in soil organic carbon stock over the initial value was the highest under vetiver grass (38.7 t ha^{-1}), which was significantly (*P≤0.05*) superior to all other grasses (*Fig.1*). It was followed by Cumbu Napier Co(CN) 4 (33.7 t ha^{-1}), and was statistically on par with Bajra Napier Co(BN) 5 (32.3 t ha^{-1}), Weeping love grass (32.7 t ha^{-1}), and Congo signal grass (31.7 t ha^{-1}). Although Congo signal grass contributed relatively little to surface area protection against raindrops, its wider lateral root spread and dense root mats led to higher soil organic carbon accumulation. Similar findings were reported by Anup *et al*. (2019), who observed higher soil organic carbon stock under Congo signal grass and hybrid Napier grasses in the Tripura hills.

Soil CO_2 emission (*Fig. 2*) varied significantly among the grasses. The highest emission was recorded in soils under vetiver grass (34.73 t ha^{-1} yr^{-1}), followed by soils under Guatemala grass (32.34 t ha^{-1} yr^{-1}). In contrast, soils under Cumbu Napier hybrid CO (CN) 4 released the least amount of CO_2 (18.55 t ha^{-1} yr^{-1}), as estimated using the EGM-5 Soil CO_2 Analyzer. With respect to sequestration (*Fig. 2*), vetiver grass absorbed the most significant amount of atmospheric CO_2 (85.17 t ha^{-1} yr^{-1}), followed by lemon grass (78.35 t ha^{-1} yr^{-1}) and CO 5 (68.24 t ha^{-1} yr^{-1}). These results clearly indicate that all the grasses studied acted as strong sinks for atmospheric CO_2, except Cumbu Napier hybrid CO (CN) 4, which had comparatively lower sequestration potential. The observed higher CO_2 emission under vetiver and Guatemala grasses aligns with earlier reports that deep-rooted perennial grasses enhance microbial activity and root respiration, thereby increasing CO_2 efflux (Singh et al., 2009). However, these species also exhibited strong carbon sequestration potential, consistent with the findings of Conant et al. (2017), who reported that perennial grasses are effective atmospheric CO_2 sinks.

3.3 | Biomass Yield and Fodder Quality

Biomass yield and fodder quality (*Fig. 3*) varied considerably among the grasses studied. Bajra Napier hybrid CO (BN) 5. Month-wise analysis indicated that biomass production was generally higher during the rainy

season, while in winter, Bajra Napier CO (BN) 5 maintained superior yield due to its greater tolerance to frost (*Fig. 4*). In terms of nutritive value, hybrid Napier exhibited the highest crude protein content (14%), followed by Cumbu Napier CO 4, whereas native grasses recorded relatively lower protein levels. These findings are in line with the report by Gupta et al. (2019), who observed that hybrid Napier grass produced significantly higher biomass than native grasses under the humid tropical conditions of Eastern India. Similarly, studies by Pathan *et al*. (2012) and Kumar *et al*. (2023) have highlighted that improved Napier hybrids not only yield higher biomass but also have higher crude protein and digestibility than traditional grasses, making them highly suitable for fodder production under intensive livestock systems. Napier (Napier–bajra hybrids) provides a threefold benefit: fodder value, soil conservation effectiveness, and carbon sequestration that aligns with national and international research. Multi-location fodder evaluations in India report that hybrid Napier consistently delivers higher biomass and superior forage quality than many competing grasses (Gupta et al., 2019). On sloping land, Napier hedgerows and grass strips serve as effective vegetative barriers, reducing runoff and soil erosion while promoting terrace formation—a process observed across Asia and Africa and measured under simulated storms (Kafle & Balla, 2008; Do et al., 2023). Beyond controlling erosion, perennial grass systems—including those with Napier-based strips—build soil organic carbon (SOC) through continuous root inputs and litter, functioning as net carbon sinks when managed with minimal disturbance (Conant et al., 2017; Do et al., 2023; Singh & Sharma, 2019). Together, these studies reinforce our Nilgiris findings that Napier hybrids simultaneously maximize fodder yield, stabilize slopes, and enhance SOC, making them a scalable, nature-based solution for hill farming systems.

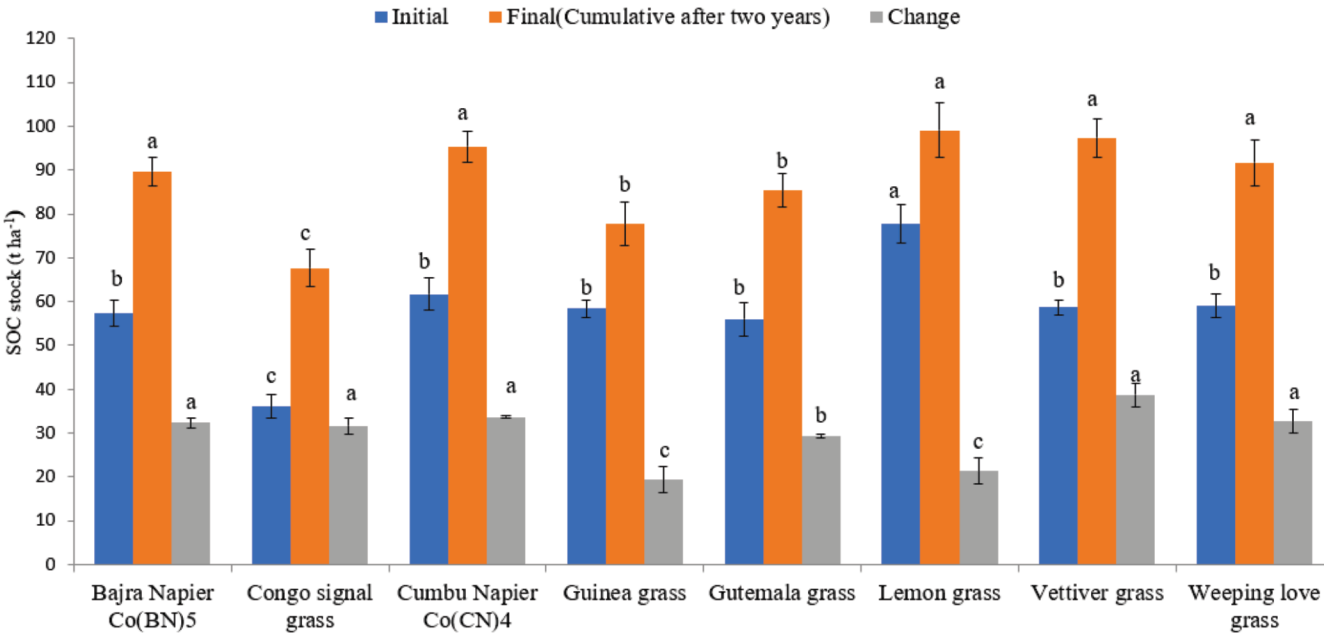


FIGURE 1 Effect of perennial grass species on soil organic Carbon (SOC) stock (t ha^{-1}) over two years. Error bars represent SEM (*n=3*). Columns followed by different letters differ significantly at P≤ 0.05 (DMRT)

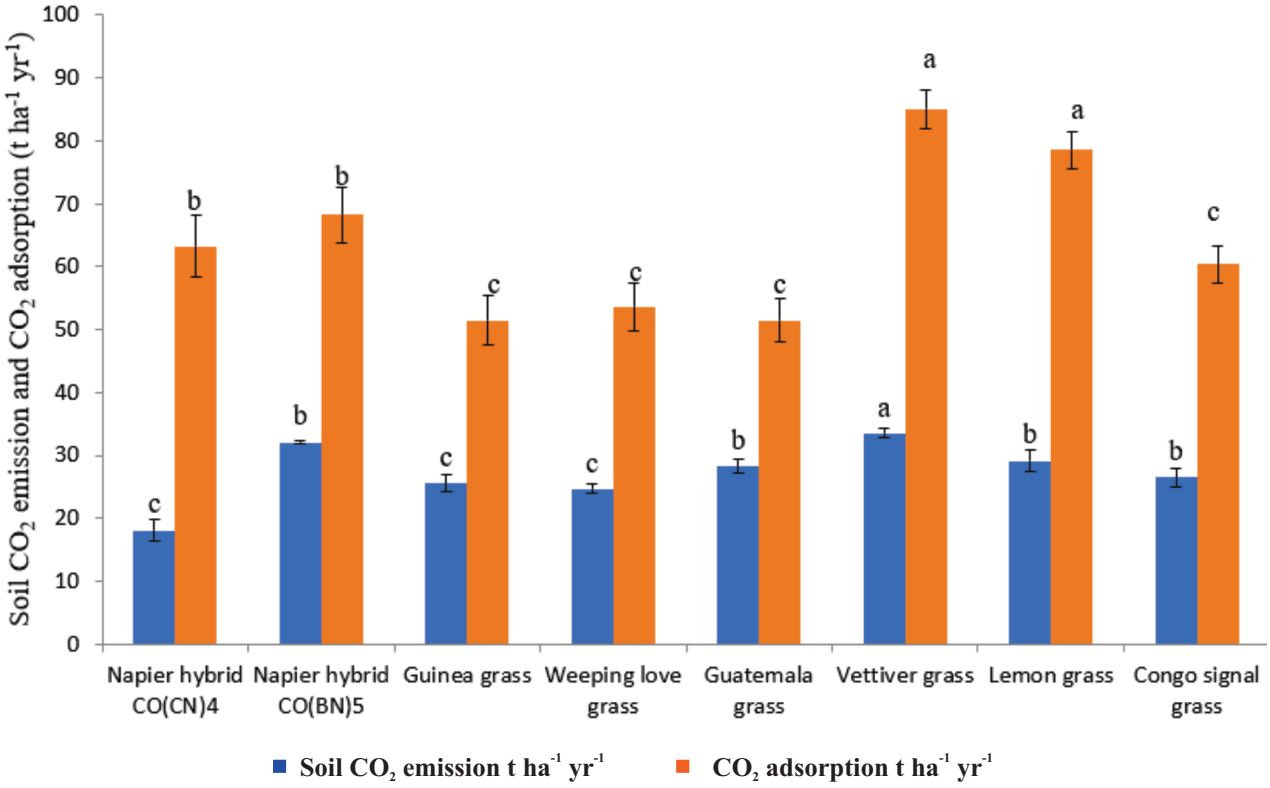


FIGURE 2 **Soil CO_2 emission and atmospheric CO_2 adsorption (t ha^{-1} yr^{-1}) under different perennial grasses. Errors bars represent mean ± SEM (n = 3). Bars followed by different letters differ significantly at $P \leq 0.05$ according to DMRT**

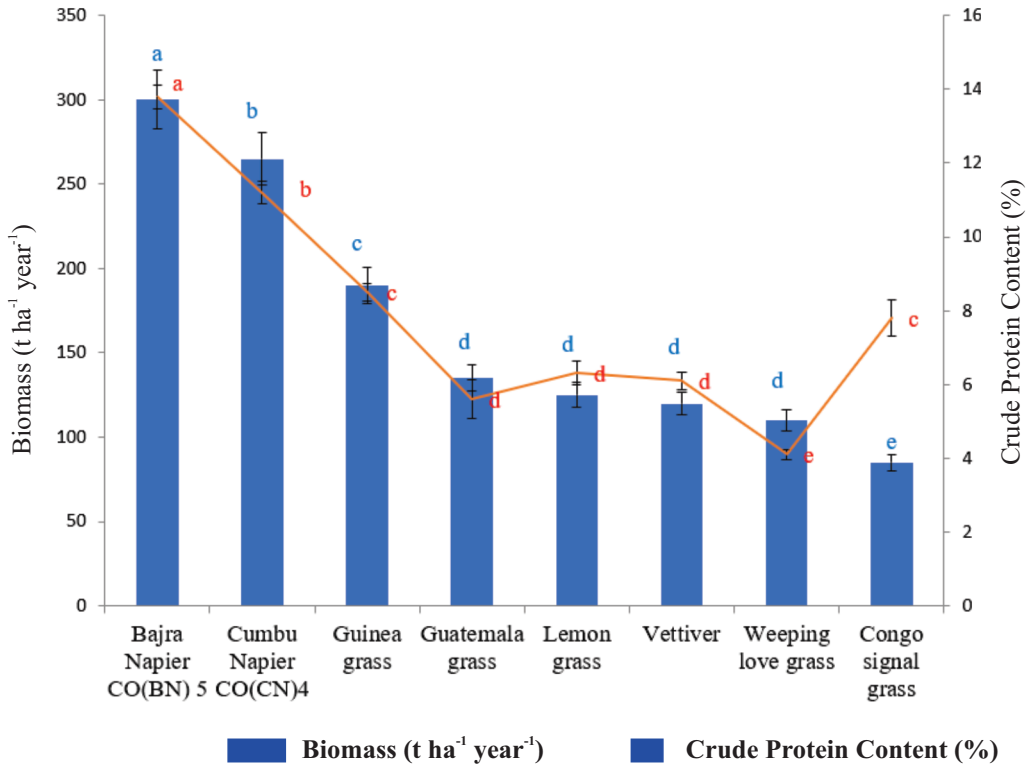


FIGURE 3 Biomass yield and crude protein content of various perennial grasses (mean ± SEM, *n* = 3).

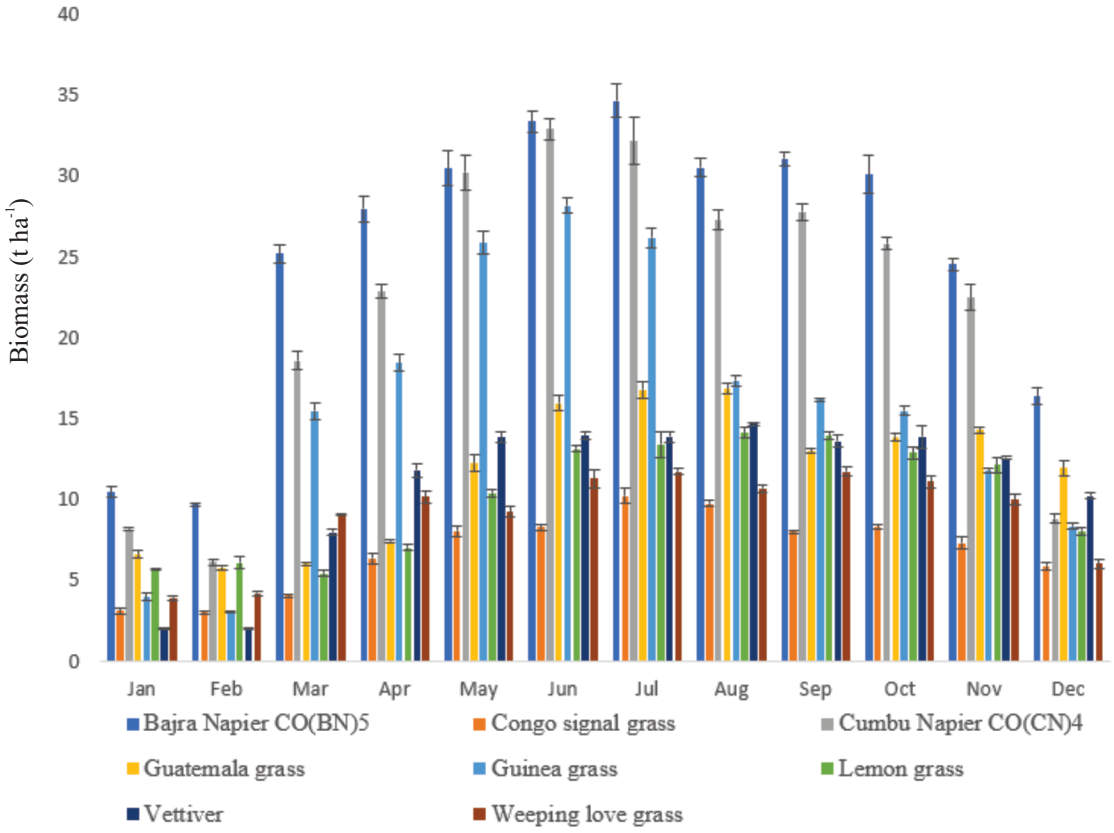


FIGURE 4 Monthly biomass production of various perennial grasses (mean ± SEM, *n* = *3*).

4.0 | CONCLUSIONS

This study demonstrates that grass species differ significantly in soil conservation efficiency, biomass production, and ecosystem services, offering distinct functional advantages for hill agriculture. Bajra Napier CO (BN) 5 and Cumbu Napier CO (CN) 4 emerged as optimal dual-purpose species, excelling in both erosion control—through wider foliage spread, higher root mass density, and greater soil volume bound by roots—and fodder production, delivering superior biomass yields and nutritive quality. In contrast, vetiver and Congo signal grasses contributed more substantially to soil organic carbon accumulation and sequestration, with vetiver achieving the highest atmospheric CO_2 uptake (85.17 t ha^{-1} yr^{-1}) despite elevated soil respiration rates.

These findings support a species-specific integration strategy: combining high-yielding Napier hybrids for immediate fodder and surface protection with deep-rooted grasses like vetiver for long-term carbon storage provides a comprehensive solution to soil erosion, fodder scarcity, and climate mitigation in sloping terrains. Such vegetative barrier systems represent a sustainable, economically viable alternative to conventional bench terracing, particularly suitable for smallholder farmers in the Nilgiri hills and similar fragile ecosystems.

However, the two-year study duration may underestimate longer-term root system development and soil organic carbon accrual typical of perennial grasses. Future research should include multi-year monitoring across diverse sites and slopes, with direct measurement of runoff and sediment yield under natural and simulated rainfall events. Additionally, optimizing fodder harvest intervals to balance biomass production with continuous ground cover for erosion control warrants investigation. Integration of these grasses into watershed development programs, supported by performance-linked incentives and monitoring frameworks for carbon and soil credits, could enhance adoption and remunerate farmers for verified environmental benefits.

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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 paper.

DATA AVAILABILITY STATEMENT

All data supporting the findings of this study are available from the corresponding author upon reasonable request. Summary datasets generated or analyzed during the current study are included in the article.

AUTHOR'S CONTRIBUTION

KK: Project execution, biometric observations, soil conservation efficiency estimation, and manuscript preparation; CB: Species selection, cultivation practice standardization, protein analysis, and result interpretation; PS: Field demonstrations, farmer training, and result interpretation; KR: Soil physical and chemical analysis, soil organic carbon stock estimation, and data interpretation; PR: Measurement of soil CO_2 flux, atmospheric carbon absorption by grasses, and data interpretation.

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ORIGINAL ARTICLE

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Economic Viability of Underground Pipeline Irrigation System Projects in Punjab: Evidences from Randomized Control Trials

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ABSTRACT

Present study aims to evaluate the economics of Underground Pipeline Irrigation System (UGPS) installations completed in recent years in two districts of Punjab. Benefit-Cost Analysis (BCA) of Underground Pipeline System (UGPS) projects implemented in Patiala and Sangrur districts of Punjab during 2020–21 were evaluated The evaluation employed Randomized Control Trial (RCT) technique to assess economic and agronomic impacts of UGPS schemes implemented at both community and individual farmer levels. Beneficiary and control groups were randomly selected from an eligible farming population. Data was collected through structured interviews using pre-tested questionnaires. The primary indicators for impact assessment were Wheat Equivalent Yield (WEY), Benefit-Cost Ratio (BCR), and Payback Period (PBP), calculated based on Minimum Support Price of wheat and paddy. In Patiala, community-level UGPS projects showed improvements in WEY ranging from 8.91% to 20.32% over control farms, with BCR values between 1.28 and 1.38, and payback periods of 5 to 7 years. For individual farmer projects, WEY gains ranged from 3.5% to 25.6%, BCRs from 1.26 to 1.36, and PBP from 4 to 9 years. In Sangrur, community-level projects achieved WEY increases of 1.97% to 5.55%, BCRs from 1.27 to 1.32, and PBP from 4 to 10 years. Individual projects showed 3.45% to 17.24% higher WEY than controls, with BCRs between 1.27 and 1.34, and PBP ranging from 4 to 9 years. Overall, the study confirmed that UGPS significantly enhances crop productivity and offer favourable economic returns, making it a viable intervention for sustainable agricultural water management in Punjab.

1 | INTRODUCTION

Punjab has severely exploited its groundwater resources, raising major concerns for sustainability of its agriculture and food security (Roul *et al.*, 2021). Increasing dependence on groundwater has led to declining water tables, higher tube-well installation and operation costs, greater electricity usage, and deteriorating ground/irrigation water quality. Farmers have been tackling steep expenses for investment and maintenance of tube-wells, *i.e.* the cost of energy has escalated. An estimated ₹ 97.56 billion is needed to replace approximately one million centrifugal tube-wells with submersible pumps due to declining groundwater table. Groundwater depletion has also driven a sharp rise in energy demand, with agricultural electricity consumption increasing from 463.4 million kWh in 1970 to 10,248.6 million kWh in 2012 (ESO, 2013). Meanwhile, groundwater extraction efficiency declined from 5.19 m³/kWh in 2004 to 3.85 m³/kWh in 2009 (Singh, 2009). In-situ water harvesting techniques offers promise to address issue of water scarcity mitigation in this region (Bhat *et al*., 2020).

At a global scale, growing water demand amid shrinking supplies is intensifying the search for alternative sources. In low-rainfall regions like Punjab (less than 1000 mm annually), paddy cultivation has raised serious concerns about water sustainability. Without intervention, groundwater depletion could reach 75% by 2050. Field unevenness further causes poor irrigation efficiency, leading to wastage of water, energy, and labour. Traditional water conveyance through earthen channels (*kuchha khals*) results in significant seepage and maintenance costs that particularly harm farm economics of tail-end users.

Punjab is a food bowl of India and has a prevalent wheat-rice cropping system. If the paddy–wheat rotation continues, the groundwater level in central Punjab is expected to decline sharply by 2023, it may fall below 70 feet in 66% of the area, below 100 feet in 34%, and below 130 feet in 7% (Sidhu *et al.*, 2010). Consequently, the sustainability of irrigated farming in the state faces a serious

threat. To rejuvenate Punjab's agriculture, especially by identifying alternatives to the rice–wheat system and improving irrigation management, several expert committees and research groups have been working on possible solutions.

For combating these issues, government subsidy programs have promoted efficient water-saving/usage technologies, with reportedly mixed success. Subsidies aim to reduce groundwater extraction and stabilize water tables. In this regard, one of the technologies promoted by Punjab Department of Soil and Water Conservation is Under Ground Pipeline Systems (UGPS) through projects supported by NABARD, PIDB, MoA&FW, and others. The study aimed to achieve the following objectives i)To evaluate the economics of installed UGPS in two districts of Punjab ii) To compare the economics of installed UGPS with non-UGPS based agriculture. iii) To evaluate indirect benefits of UGPS.

2 | METHODOLOGY

Economic evaluation of underground pipeline systems (UGPS) implemented by Soil and Water Conservation Department, Government of Punjab under various central and state government funded schemes was undertaken under a consultancy project through Benefit-Cost Analysis (BCA) of samples selected following Randomized Control Trial (RCT) approach. Randomized control trial (RCT) is a way of doing impact evaluation in which the population receiving or has received the programme or policy intervention (beneficiary group) is chosen at random from the eligible population, and a control group that will not receive or has not received the intervention is also chosen at random from the same eligible population. The random assignment of members of the population eligible for treatment to either one or more treatment groups (who received the intervention treatment or variations of it) or to the control group (who received either no intervention or the usual intervention if the treatment is an innovation to an existing intervention) renders them comparable, and any difference between them is the effect of the treatment (Banerjee and Duflo, 2012). For the evaluation study, a selected eligible population at a location (sub-division of a chosen district) consisted of individual/group of farmers (as per subsidy scheme) that received the intervention (beneficiary group), namely the underground pipeline systems (UGPS), or did not receive the intervention (control group) due to certain administrative or local reasons, but can receive in the future when the constraints to implementing the interventions are removed.

2.1 | Sampling

For selection of the primary sampling units, i.e. beneficiary and control farmers, to be studied, multistage stratification was adopted. Though UGPS were implemented in many districts of Punjab state, only two districts were purposively chosen – Patiala and Sangrur – as they are among the most groundwater exploited districts of Punjab (Fig. 1) where groundwater level was reported to have fallen by more than

HIGHLIGHTS

- The study evaluates the economic viability of underground pipeline irrigation systems (UGPS) in punjab using a Randomized Control Trial (RCT) and Benefit-Cost Analysis (BCA).
- UGPS adoption enhanced Wheat Equivalent Yield (WEY) by 1.97-25.6 %, with BCRs of 1.26-1.38 and payback periods of 4-10 years, confirming strong feasibility.
- The system reclaimed cultivable land, reduced water and energy losses, and replaced inefficient open channels.
- Findings, establish UGPS as a scalable, sustainable intervention for improving agricultural profitability and groundwater management.

4.0 m during 2009-2019 (CGWB, 2021). In the first sub-strata, four tehsils of the chosen districts were purposively chosen –Nabha, Patiala, Patran and Rajpura –outof six (i.e. 66% sampling) in case of Patiala, and two (namely Sunam and Sangrur) out of seven (i.e. 28% sampling) in case of Sangrur – being among the highest groundwater exploited tehsils in their respective districts.For the next sub-strata, lists of implemented UGPS at different locations within the previous/higher substrata (i.e. in selected tehsils of the two districts) under two government funded schemes offering different percentages of subsidy depending upon the project being for individual farmer (50% subsidy) or group of farmers (90% subsidy) were procured from secondary sources. Out of the list of a tehsil, certain number of implemented UGPS projects were randomly selected as the second sub-strata. The percentage of sampling of implemented UGPS from the lists varied 11-30% and 20-33% in case of 50% and 90% subsidy schemes, respectively from Patiala district. In case of Sangrur district, the percentage was 20-21% and 20% in case of 50% and 90% subsidy schemes, respectively. In the last/third sub-strata, beneficiaries of installed UGPS with 50% subsidy were automatically selected being the sole beneficiary of 50% subsidized UGPS. In case of schemes giving 90% subsidy, which was for a group of more than ten benefitting farmers that were supplied irrigation water through a long distance UGPS from single node of a canal, three sampling units were randomly selected, one each from near, middle and farthest end of the UGPS for better representation of the beneficiary farmers. An equal number of respective controls were also selected from the control group of that location. The distribution of sampling units is given in Table 1. In total, 96 sampling units were utilized for the evaluation study.

2.2 | Data for benefit cost analysis

For undertaking benefit-cost analysis (BCA) of the UGPS installed under schemes offering different percentages of subsidy through the selected primary sampling units, their long-term data was required. Accordingly, provision was made for collection of the data through personal interviews of the randomly selected farmers of both beneficiary and control kind on a well-structured pre-tested questionnaire (Annexure-1). For pre-testing the questionnaire, a

TABLE 1 Sampling Units Distribution

District	Tehsil	Scheme Subsidy 90%		Scheme Subsidy 50%	
		Beneficiary	Control	Beneficiary	Control
Patiala	Nabha	3	3	3	3
	Patiala	3	3	3	3
	Patran	3	3	3	3
	Rajpura	3	3	3	3
Sangrur	Sunam	6	6	6	6
	Sangrur	6	6	6	6

Divisional office ofeach of the two selected districts tested it through personal interview of farmers. The questionnaire was then modified as per discussion with pre-testing Divisional offices. Total number of years of data collected for a UGPS project was as per data availability, depending upon the year of data collection after the UGPS started functioning. Secondary data such as information regarding schemes and the beneficiaries were obtained from Head office or Divisional offices of the Department.

As the evaluation was to be undertaken on RCT basis, the with/without project approach was utilized for the BCA. Therefore, the analysis took the difference in respective costs and benefits of the beneficiary farmers (i.e. with project) versus control farmers (i.e. without project) as the additional costs and benefits, respectively due to the UGPS intervention at a location in a scheme.

For each farmer's kind, data was collected of crop and livestock production activities, as these are the main sources of livelihood of the farmers of the study area. All physical outputs produced and purchased/hired inputs utilized for the crop and livestock production activities by the sampled farmers were included in the analysis. However, cost and benefits of intermediate outputs produced and consumed within the farming system like dry/green fodder from crops and manure from livestock were not considered in the BCA; nevertheless, any quantity of these purchased as an input from market were utilized for the analysis. Constant prices were utilized of all inputs and outputs for estimating the costs and benefits for the 96 sampled farmers. These costs and benefits were constantly discounted at 7%, the average of best interest rates available for more than 5 years long term deposits in banks of the country, during the period of analysis. Externality in the form of the area freed from old open channel system by laying down of UGPS and cultivated as irrigated area was included in the BCA. The productive life of a UGPS was taken to be 15 years for the BCA, as beyond 15 years what maintenance cost will be incurred is not known. Hence the period of analysis of BCA was 15 years.

In case of livestock component, owned livestock of the sampled farmers were first converted into standard livestock unit (SLU). As command area of each studied UGPS was uniformly extrapolated to a bigger size of 100 acre, the size of the livestock component was also expected to be larger. Therefore, the actual size of the livestock component of each beneficiary farmer was also extrapolated to a larger herd size in proportion to the 100 acre size of the UGPS Command Area, and that herd size was utilized for the respective control farmer. The extrapolated herd size varied across UGPS benefitting farmers as the actual herd size varied across these farmers. In two 50% subsidy cases, where a benefitting farmer did not own livestock, the respective control farmer was also assumed not to own livestock to maintain comparability. In case of 90% subsidized UGPS, wherein one out of three beneficiary (three such cases) or control (one such case) did not own livestock, the effect of zero livestock was nullified by utilizing average of the other two beneficiary / control farmers'. In case of four 50% subsidized UGPS, where the lone control farmer did not own livestock (while the beneficiary farmer owned livestock), and so its income from livestock component of farming was zero, for comparability, the BCR was estimated from only the crop component of both the control and corresponding beneficiary for comparability.

In addition to BCA, wheat equivalent yield (WEY) following Bhattacharyya *et al.* (2010) and Ghosh *et al.* (2012) were estimated to set apart overall impact of UGPS from its non-usage in terms of comparable yield data. The yield of paddy was converted into wheat equivalent yield (WEY). The converted paddy yield of a year was then added to the actual yield of wheat in that year. Therefore, WEY expresses total yield (productivity) for the paddy–wheat crop sequence. It is the yield of wheat plus yield of paddy expressed in terms of wheat yield.Wheat equivalent yield (WEY) was estimated using the following formula:

$$WEY_x = Y_x(P_x/P_w)$$

where, WEY_x is the wheat equivalent yield of crop x (paddy)in kg per acre, Y_x is the economic yield of crop x (paddy) in kg per acre, P_x is the price of crop x (paddy)in Rs per kg, and P_w is the price of wheat in Rs per kg.

2.3 | UGPS Projects

Department of Soil and Water Conservation, Punjab implemented the UGPS projects under a subsidy scheme that provided 90% subsidy (scheme subsidy 90:10) in the

total sanctioned amount of the project for group or community of beneficiaries. A summary of the UGPS projects installed with 90% subsidy scheme in the selected two districts of Punjab that were surveyed and evaluated in this study is presented in Table 2.

Department of Soil and Water Conservation, Punjab also implemented UGPS projects under a subsidy scheme that provided 50% subsidy in the total sanctioned amount of the project for a single beneficiary i.e. individual farmer. A summary of the UGPS projects installed with 50% subsidy scheme in the selected two districts of Punjab that were surveyed and evaluated in this study is presented in Table 3 and Fig. 1.

TABLE 2 Brief data of studied UGPS projects funded for community based irrigation system (scheme subsidy 90:10)

District/Tehsil	Village	Area covered under scheme (ha)	Length of pipeline laid (km)
		District Patiala	
Patiala	Sanour	161	3.9
Nabha	Tarkheti Kalan	11.68	0.9
Rajpura	Rurka Ghanaur	31.72	2.6
Patran	Haryau Kalan	113.94	3.2
		District Sangrur	
Sunam	Ramgarh Jawanda	129.2	5.3
	Chhahar	134.4	3.9
Sangrur	Rupaheri	187.2	4.6
	Saaron	104	2.2

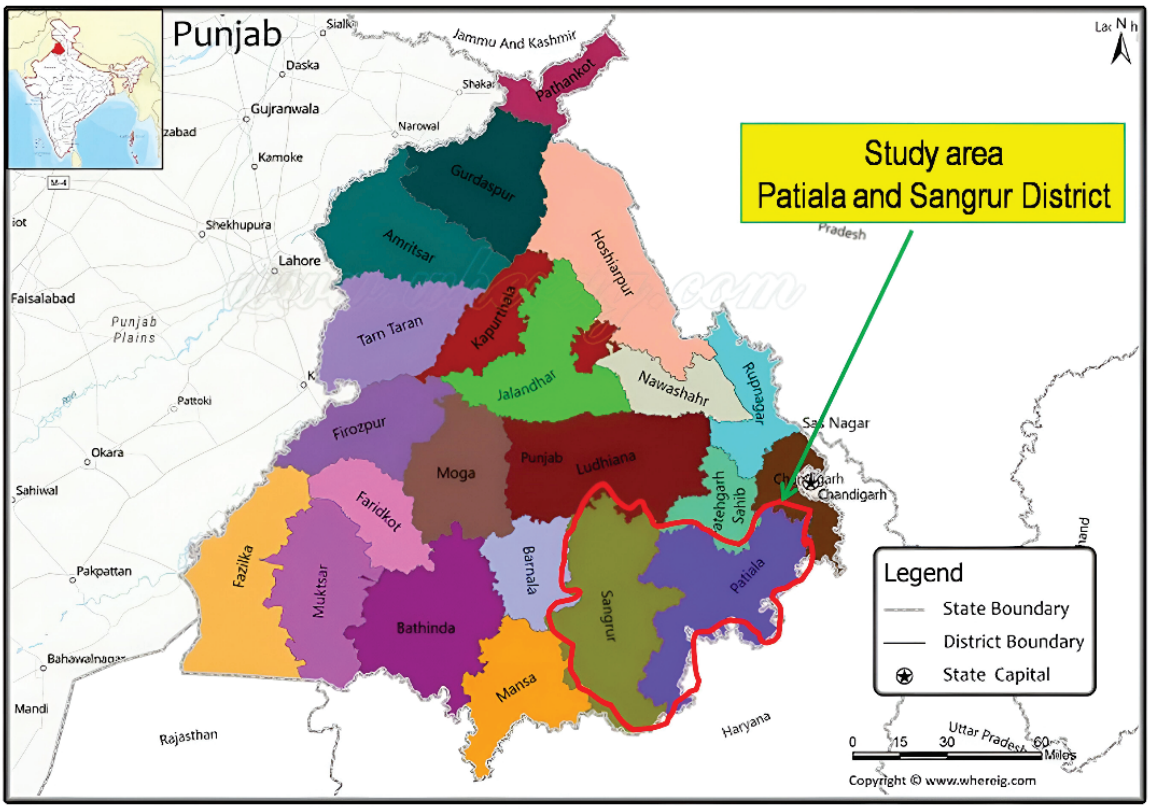


FIGURE 1 Selected Study area

TABLE 3 Brief data of location of studied UGPS projects for individual farmer based irrigation system (scheme subsidy 50:50)

District/Tehsil	Village	District/Tehsil	Village
Patiala		Sangrur	
Patiala	Kathmatti Chhamarkheri	Sunam	Sheron -1 Sheron -2
Nabha	Chana - Nathuwalia Chahal Khizarpur		Sheron -3 Sheron -4 Chhahar Biggarwal
Rajpura	Kheri-Mandalan Sehra Khutha-kheri	Sangrur	Fatehgarh Channa 1 Fatehgarh Channa 2
Patran	Duggal Kalan Shutrana Dodra		Fatehgarh Channa 3 Fatehgarh Channa 4 Banera

3 | RESULTS AND DISCUSSION

3.1 | Wheat Equivalent Yield

3.1.1 | District Patiala (scheme subsidy 90:10)

The WEY for beneficiary farmers averaged 4535kg per acre, 9.72% higher than the control group's 4133 kg per acre (*Fig. 2.a*). In Tarkheri Kalan (Nabha), 972 m of UGPS covered 11.68 ha, benefiting six farmers with an average WEY of 5139 kg per acre, 16.27% above the control. Overall, beneficiaries achieved a 20.32% higher WEY. In Haryau Kalan (Patran), 3220 m of pipeline irrigated 113.94 ha for 33 farmers, yielding 5108 kg per acre, a 9.38% gain over the control (*Fig. 2a*).

3.2 | District Patiala (scheme subsidy 50:50)

Farmers in Punjab who installed UGPS under the 50:50 subsidy schemes showed notable yield improvements (*Fig. 2b*). In Nabha tehsil (Channa Nathuwalia, Chahal, Khizarpur), yields rose 8.1% to 19.1%; in Rajpura tehsil (Kheri Mandalan, Sehra, Kuthakheri), WEY was 5.34% to 16% higher; and in Patran tehsil (Shutrana, Dugal Kalan, Dodra), yields increased 4.10% to 24.25% compared to controls.

3.3 | Sangrur (Scheme subsidy 90:10)

In Ramgarh Jawanda, 5380 m of underground pipeline benefited 58 farmers, achieving a WEY of 4429 kg per acre, 5.55% higher than the control group. In Chhahar, 3985 m of UGPS served 48 farmers, with a WEY of 47.99 quntals per acre, 1.97% higher than control. In Rupaheri, UGPS covered 187.2 ha, benefiting 33 farmers and yielding 5367 kg per acre, a 4.84% increase. In Saaron, 2295 m of pipeline benefited 30 farmers, achieving 4853 kg per acre, 3.36% higher than control (*F ig. 3a*).

3.4 | Sangrur (Scheme subsidy 50:50)

In the Sangrur subdivision/tehsil, Banera and Fatehgarh Chhana villages were randomly selected, and beneficiary farmers from these villages were surveyed. The WEY among these farmers ranged from 5128 to 5667 kg per acre (*Fig. 2b*), which was higher than that of the respective control farmers, indicating the positive impact of the UGPS installation. The percentage increase in WEY attributed to the UGPS intervention ranged from 3.44% to 12.18%, as shown in *Fig. 3b*.

The adoption of UGPS made available additional cultivable area by replacing unlined 2 metre wide irrigation channels with narrow 1–1.5 foot bunds. In Patiala, 12696 m of pipeline were installed across 15 projects (four under 90:10 and eleven under 50:50 subsidy schemes), reclaiming 6348 m² of land. Similarly, in Sangrur, 20035 meters of UGPS were laid under 16 projects, making 10017 m² of land available for cultivation. Given a square acre, about 47.4 m² was saved per acre, enabling an additional 62 kg per acre of WEY, with the average WEY being 5261 kg per acre under the paddy-wheat system.

The findings of this study confirm that Underground Pipeline Systems (UGPS) are a technically and economically viable irrigation solution for Punjab,particularly in regions experiencing severe groundwater stress. The application of the Randomized Control Trial (RCT) technique provided credible empirical evidence, demonstrating significant improvements in crop yield and economic efficiency. In both Patiala and Sangrur districts, the WEY of UGPS beneficiaries consistently outperformed control groups, with yield increases ranging from 1.97% to 25.6%. These results are consistent with prior studies indicating that underground and pressurized pipeline systems reduce water loss that occurs in the form of seepage and evaporation from open irrigation channels being used for cultivation, thereby improving irrigation efficiency and crop response (Narayanamoorthy, 2005).

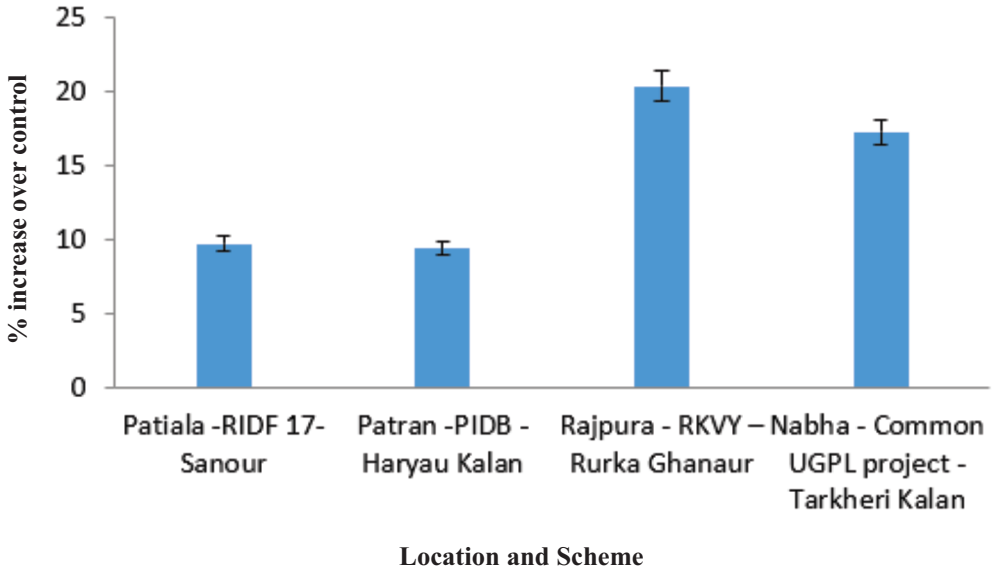


FIGURE 2a Percent increase of WEY over control (Scheme subsidy 90:10) in district Patiala. Line on the bars are error bars (5 % level)

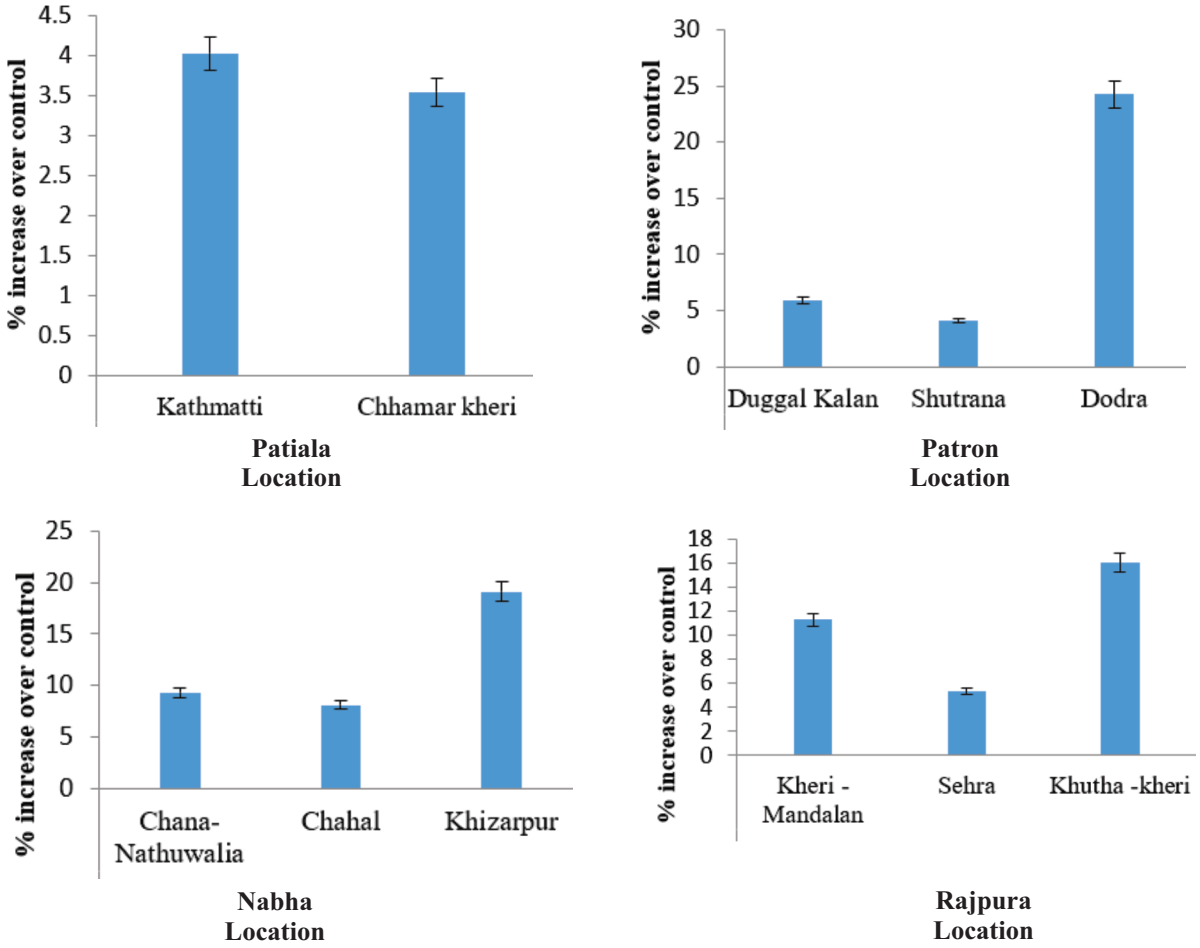


FIGURE 2b Percent increase of WEY over control (scheme subsidy 50:50) in district Patiala. Line on the bars are error bars (5% level)

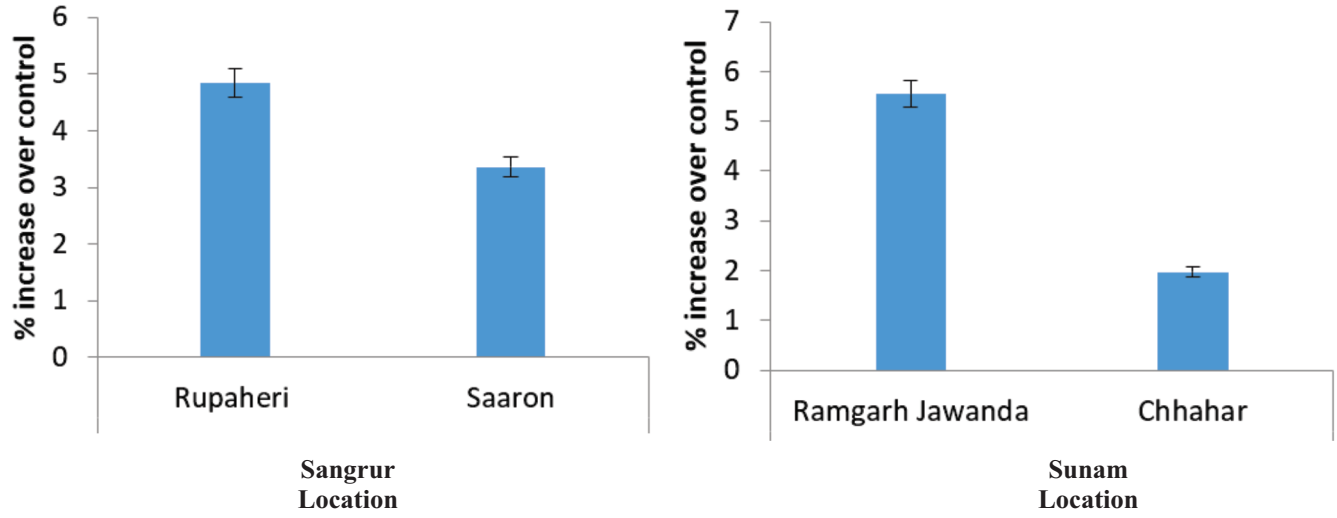


FIGURE 3a Percent increase of WEY over control (scheme subsidy 90:10) in district Sangrur. Line on the bars are error bars (5% level)

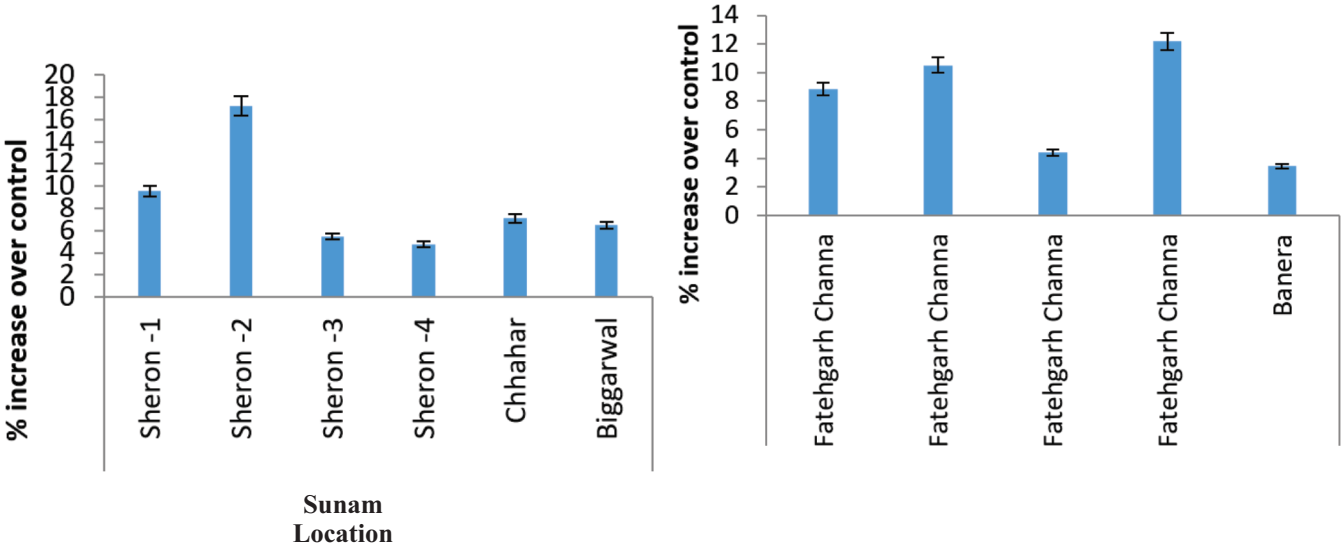


FIGURE 3b Percent increase of WEY over control (scheme subsidy 50:50) in district Sangrur. Line on the bars are error bars (5% level)

3.5 | Benefit-cost analysis
District Patiala (Scheme subsidy 90:10 and 50:50

Benefit-cost analysis, following the described methodology wherein the UGPS command area were standardized by extrapolating the results to a 100-acre landholding, was undertaken in terms of Benefit-Cost Ratio (BCR) and Payback Period (PBP). This allowed uniform assessment of economic viability across all surveyed beneficiary and control farmers of different landholding sizes. BCR ranged from 1.26 to 1.36 (Table 4), indicating a positive return on investment. The PBP was observed to range between 4 and 9 years, reflecting the time required to recover the initial investment through increased agricultural returns.

TABLE 4 Brief cost analysis of installing UGPS under different subsidy schemes for conveyance of canal water in district Patiala

Tehsil	Village	BCR	PBP (years)
	Scheme subsidy 90:10		
Patiala	Sanour	1.35	3
Nabha	Tarkheri Kalan	1.33	4
Rajpura	Rurka Ghanaur	1.30	7
Patran	Haryau Kalan	1.38	5
	Scheme subsidy 50:50		
Patiala	Kathmati	1.26	3
	Chhamarkheri	1.33	9
Patran	Duggal Kalan	1.32	8
	Shutrana	1.28	4
	Dodra	1.35	9
Rajpura	Kheri-Mandalan	1.34	6
	Khutha-kheri	1.31	5
	Sehra	1.26	8
Nabha	Chana-Nathuwalia	1.34	6
	Chahal	1.36	5
	Khizarpur	1.29	4

TABLE 5 Benefit cost analysis of installing UGPS for conveyance of canal water under different subsidy schemes for conveyance of canal water in district Patiala

Sub-division	Village	BCR	PBP (years)
	Scheme subsidy 90:10		
Sunam	Ramgarh Jawanda	1.32	9
	Chhahar	1.29	7
Sangrur	Rupaheri	1.30	5
	Saaron	1.27	4
	Scheme subsidy 50:50		
Sunam	Sheron -1	1.34	7
	Sheron -2	1.34	8
	Sheron -3	1.33	9
	Sheron -4	1.30	9
	Chhahar	1.33	4
	Biggarwal	1.27	8
Sangrur	Fatehgarh Channa -1	1.31	6
	Fatehgarh Channa -2	1.30	6
	Fatehgarh Channa -3	1.33	9
	Fatehgarh Channa -4	1.31	5
	Banera	1.31	7

3.6 | District Sangrur (scheme subsidy 90:10 and 50:50)

The economic analysis in Sunam region revealed that BCR ranged between 1.27 and 1.34, while the PBP varied from 4 to 9 years. In comparison, the Sangrur region recorded BCR values between 1.30 and 1.33, with the Payback Period ranging from 5 to 9 years. These findings are summarized in Table 5.

The observed BCR, ranging from 1.26 to 1.38 across different schemes, further validate the economic justification for UGPS investment. A BCR greater than 1.0 suggests that the benefits of the project outweigh its costs, even without considering long-term environmental externalities. These findings align with FAO (2020), which emphasizes the role of modern irrigation infrastructure in improving input-use efficiency and farm profitability. Furthermore, the variation in PBP (4–10 years) underscores the importance of tailoring subsidy levels and implementation models (community *vs* individual) to local conditions, as community-managed systems appeared to yield more consistent outcomes, echoing the results of Meinzen-Dick *et al.* (2002).

From a policy standpoint, these results support scaling up UGPS through targeted subsidies and farmer education programmes. However, complementary strategies—such as promoting crop diversification and efficient water-use practices—are essential for maximizing the long-term sustainability of such infrastructure. Continued evaluation is also critical to assess system durability, maintenance behavior, and broader environmental impacts over time.

4 | CONCLUSIONS

The implementation of Underground Pipeline Systems (UGPS) in Punjab's Patiala and Sangrur districts has yielded notable agronomic and economic gains. This study based on Randomized Control Trial (RCT) showed Wheat Equivalent Yield (WEY) improvements of 1.97% to 25.6% and Benefit-Cost Ratio (BCR) between 1.26 and 1.38, confirming economic viability with Payback Period (PBP) of 4 to 10 years. The study underscores the value of RCT based approach in assessing agricultural interventions. It suggests scaling UGPS to similar regions to improve water efficiency, farm income, and long-term resilience in water-scarce areas.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data will be provided on request.

AUTHOR'S CONTRIBUTION

PP designed and executed the study and prepared the manuscript. SP and PD contibuted to data collection and manuscript preparation. OP Premi, Manoj Kumar and OPS Khola assisted in data collection.

Supplementary data available in online version.

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ORIGINAL ARTICLE

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Study the Socio-Economic Dynamics of Farming Communities Practicing Agroforestry in upstream Catchment area of Gobind Sagar Reservoir

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ABSTRACT

The present investigation aimed to explore the socio-economic transformations experienced by farming communities under the influence of the nearby water reservoir. The socio-economic dynamics of 375 households across 25 villages in upstream catchment area of the Gobind Sagar Reservoir in Bilaspur district, Himachal Pradesh, were examined to assess the influence of reservoir proximity on agroforestry adoption and livelihoods. Households were grouped into seven distance classes (D1 = 0-2 km, D2 = 2-4 km, D3 = 4-6 km, D4 = 6-8 km, D5 = 8-10 km, D6 = 10-12 km, and D7 = 12-14 km) at 2 km intervals. The highest number of households was in D4 (372) and D5 (361), with family sizes ranging from 5.5 to 6.5 members. D4 also had the largest population (911 males, 883 females), while literacy peaked at 80.67% in D6. Households in D1 held the largest land (1.92 ha) and cultivated land (1.25 ha), whereas fodder consumption was highest in D5 (70.56 kg day^{-1} household^{-1}) and D4 (70.17 kg day^{-1} household^{-1}). Fuelwood use was greater among households near the reservoir. Agroforestry knowledge was highest in wider distance classes i.e. D7 and D5 (42.50%), compared to closer distance classes like D1 (30.67%) and D2 (30.33%). Positive correlations were found between cultivated land and *ghasni* (grassland), and between livestock population and fodder use, while agroforestry knowledge negatively correlated with fuelwood consumption. These findings suggest that reservoir proximity influences landholding, resource use, and agroforestry practices, shaping household adaptation strategies and socio-economic outcomes. The findings of this study can be utilized to design location-specific agroforestry and livelihood enhancement programs for communities influenced by water reservoirs.

1 | INTRODUCTION

The construction of large dams significantly impacts the socioeconomic situations of farming communities in its upstream catchment areas and downstream areas (Shi *et al.,* 2019; Liu *et al.,* 2023). These infrastructures provide crucial irrigation resources, which can enhance agricultural productivity and lead to more stable crop yields. Increased access to water allows farmers to diversify their crop patterns and engage in multiple cropping cycles, thereby improving food security and increasing household incomes (Sarvade *et al.,* 2014; Wable *et al.,* 2021; Rajkhowa, 2024). Additionally, the presence of a dam often fosters ancillary economic activities, such as transportation and agro-processing, which create job opportunities and contribute to local economic growth (Ampadu *et al.,* 2015). However, these benefits can be unevenly distributed, leading to income disparities within communities, especially if wealthier farmers or landowners gain more access to resources compared to marginal and smallholder farmers.

On the flip side, the socio-economic dynamics of these communities can also be adversely affected. The displacement caused by dam construction can disrupt traditional livelihoods and displace entire communities, leading to loss of agricultural land and local cultural heritage (Huang *et al.,* 2018). Moreover, the influx of external labour and capital can alter social structures, potentially undermining social cohesion and traditional practices (Krammer *et al.,* 2023). Environmental changes resulting from dam operations, such as altered water flow and sedimentation patterns, can negatively impact local ecosystems, further challenging the livelihoods of farming communities that depend on natural resources (Foudi *et al.,* 2023). Therefore, while big dams can offer substantial benefits for agricultural development, careful consideration

of their socio-economic consequences is essential to ensure equitable growth and the sustainable management of resources in upstream catchment areas (Strobl and Strobl, 2011).

The socio-economic conditions of communities around the Gobind Sagar Reservoir are closely tied to the availability of critical resources such as water, soil, and vegetation. These factors not only affect agricultural productivity but also contribute to the overall well-being of local residents (Parizanganesh *et al.,* 2008). In the hilly terrain of the upstream catchment area, water scarcity presents significant challenges, directly impacting soil health, vegetation, and the socio-economic conditions of the populace (Dwivedi *et al.,* 2007; Su *et al.,* 2012).

Agriculture and cattle rearing serve as the primary livelihoods for these communities; however, limited water resources constrain agricultural yields, leading to changes in land use and natural vegetation (Sarvade *et al.,* 2016b; Ingrao *et al.,* 2023). Education, transport, and employment significantly influence land-use transformations, with educated farmers often seeking to optimize land productivity by utilizing knowledge from government initiatives and research institutions (Lovell, 2010). The size of landholdings and human resources further shape agricultural practices, with smaller landowners typically opting to plant multi-purpose trees (MPTs) to enhance their income. In contrast, traditional practices often involve retaining MPTs within farm boundaries for long-term benefits (Nair, 1989; Sarvade *et al.,* 2020). Agroforestry, which integrates trees with crops and livestock, emerges as a crucial system for promoting socio-economic development in these regions, providing avenues for improved livelihoods and environmental sustainability (Nair, 1989; Nair, 2011). These types of studies are limited but very useful for the planning of well-being of the farming community residing nearby dam sites. Therefore, the present investigation was carried out to study the impact of constructing big dams on socio-economic situation of farming communities situated in upstream catchment area of the water reservoir with the following objectives: 1. To analyze the influence of reservoir proximity on the socio-economic status and livelihood patterns of farming communities residing around the Gobind Sagar Reservoir. 2. To assess the variations in landholding size, resource utilization, and extent of agroforestry adoption across different distance zones from the reservoir. 3. To identify and establish relationships among key socio-economic parameters affecting household adaptation strategies and resource management practices in the region.

2 | MATERIALS AND METHODS

2.1 | Study Area

The study was conducted in the upstream catchment area of the Gobind Sagar Reservoir, which is situated on the 'Sutlej River' in the Bilaspur district of Himachal Pradesh. The Gobind Sagar Dam, also known as the Bhakra Dam, is one of the largest gravity dams in India, constructed across the Sutlej River. Commissioned in 1963, the dam stands about

HIGHLIGHTS

- Examined socio-economic variations among villages at different distances from the Gobind Sagar Reservoir in Himachal Pradesh
- Reservoir proximity influenced household characteristics , resource dependence and livelihood diversification.
- Near-reservoir communities relied more on natural resources, while distant ones showed greater adoption of agroforestry.
- Results call for location-speciifc agroforestry and livelihood interventions to enhance community resilience

226-meter-high and stretches approximately 518 meter in length, creating a vast reservoir with a storage capacity of around 9.34 billion cubic meters. The reservoir extends over 90 kilometers in length and covers an area of nearly 170 square kilometers, serving multiple purposes including hydroelectric power generation, irrigation, and fisheries, while also shaping the socio-economic landscape of surrounding rural communities. This region spans an area of 1,167 km^2, representing 2.1% of the state's total geographical expanse. The elevation in this area varies significantly, ranging from 290 m to 1,980 m above mean sea level, with a substantial portion of the district lying below 650 m. The geographical coordinates for this site are approximately 31° 12' 30" to 31° 35' 45" N and 76° 23' 45" to 76° 55' 40" E (Sarvade *et al.,* 2016a).

2.2 | Sampling Method

A multistage stratified random sampling design was employed to identify communities involved in agroforestry, which were regarded as the basic study units for this research. This method blended purposive and stratified random sampling techniques, ensuring a detailed and representative selection of participants (van Hoeven et al., 2015). A total of 25 villages were included in the study, with 15 households randomly selected from each village. To minimize bias in household selection, we enlisted the help of a local guide who assisted in identifying households that fit the specified farmer categories within each village. These study sites were distributed randomly across seven concentric rings (distance classes), each 2-kilometer-wide, in upstream catchment area of the Gobind Sagar Reservoir (*Table 1 and Fig. 1*).

Households serve as the primary decision-making units in cultivating fodder, fuelwood, and fruit trees on their own lands, whether through natural growth or intentional planting. To gather primary data on various socio-economic attributes, face-to-face interviews were conducted with the heads of households in the chosen villages using a pre-tested questionnaire (online available) (Marshall 2005). The selection of these villages was informed by secondary data from the 2011 Census (Census, 2011).

TABLE 1 Details of the study sites

Distance classes	Study sites	Latitude and Longitude (Degree, decimal, seconds)
D1	2-Jai Shri Devi	31˚25'27.2"N and 76˚29'57.3"E
	3-Badgaon	31˚26'43.9"N and 76˚29'53.5"E
	5-Jaddu	31˚22'22.1"N and 76˚33'25.0"E
	6-Malroan	31˚19'22.5"N and 76˚35'42.6"E
	19-Fugogh	31˚20'28.8"N and 76˚38'47.86"E
	13-Dhanola	31˚16'28.20"N and 76˚37'58.4"E
D2	9-Paploh	31˚18'34.9"N and 76˚37'55.5"E
	12-Kharli	31˚16'02.8"N and 76˚39'19.9"E
	11-Kukrehar	31˚16'25.1"N and 76˚39'43.3"E
	10-Silwin	31˚18'21.4"N and 76˚39'06.7"E
	7-Tihri	31˚21'15.1"N and 76˚35'07.4"E
	8-Jhunjnu	31˚20'03.2"N and 76˚36'21.3"E
D3	1-Jol	31˚24'58.2"N and 76˚32'23.5"E
	4-Gangloh	31˚23'58.5"N and 76˚33'11.0"E
	18-Baloh	31˚20'43.91"N and 76˚43'22.72"E
D4	14-Beharan	31˚22'41.50"N and 76˚38'26.80"E
	22-Kuthera	31˚23'26.70"N and 76˚36'02.70"E
	24-Talai	31˚27'17.95"N and 76˚31'25.31"E
D5	15-Ser	31˚22'49.0"N and 76˚40'24.70"E
	25-Jhabola	31˚27'0.20"N and 76˚32'13.50"E
D6	20-Balsina	31˚22'15.99"N and 76˚43'7.726"E
	23-Gujrera	31˚25'09.40"N and 76˚34'15.30"E
	21-Malari	31˚24'46.00"N and 76˚36'32.20"E
D7	16-Dhroti	31˚24'47.7"N and 76˚39'16.30"E
	17-Singaswin	31˚25'12.60"N and 76˚37'38.30"E

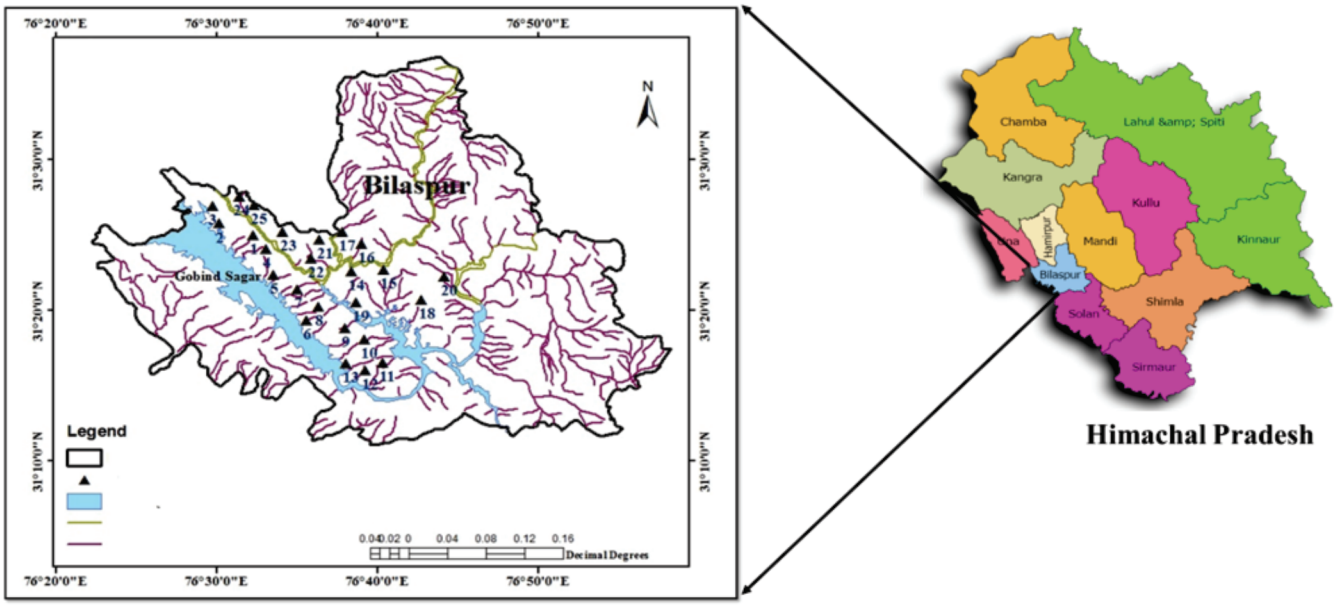


FIGURE 1 Study sites selected in upstream catchment area of Gobind Sagar reservoir (Source : Sarvade *et al.*, 2016b)

2.3 | Statistical Analysis

Descriptive statistics, encompassing mean values and standard deviations at a 95% confidence interval, were computed in accordance with the procedures described by Lindman (1992). To ensure greater precision and conformity with modern social survey standards, the analytical framework was further refined by incorporating the updated methodological recommendations of Dillman *et al.* (2014). Z- test was carried out for percent data and t-test for demography, literacy, land use, livestock at 0.05 level of probability. The Pearson correlation between different socioeconomic variables was carried out at 0.01 & 0.05 level of probability. All analysis was carried out by using SPSS (Version 23) statistical software package (IBM Corp, 2015).

3 | RESULTS AND DISCUSSION

3.1 | Demographic features of the farm families

An analysis of the demographic data of farming families from villages located around the Gobind Sagar reservoir reveals notable trends in household distribution based on proximity to the water source. Table 2 indicates that households are most concentrated in equidistant areas from the reservoir, particularly in zones D4 (average of 371.67 HH) and D5 (360.50 HH). In contrast, areas closer or further away, such as D3 (149.33), D6 (140.67), D1 (88), D7 (87.50), and D2 (60.17), exhibit significantly lower household counts.

The demographic analysis reveals that the highest population figures were observed at distance D4, with a total of 1,794 individuals - comprising 911 males and 883 females. Interestingly, the sex ratio in households located near the Gobind Sagar reservoir indicated a slight male predominance, with ratios of 935.37 at D1 and 935.22 at D2. In contrast, areas further from the reservoir, such as D3 (1,056.58), D6 (1,031.95), D5 (1,026.22), and D7 (1,012.32), reported higher female populations than male, suggesting a shift in gender dynamics.

The demographic profile of farm families surrounding the Gobind Sagar reservoir presents a nuanced understanding of rural livelihoods shaped by both ecological and infrastructural variables. The evident disparity in development indicators among the study sites appears to stem from the varying degrees of influence exerted by the reservoir, which has indirectly shaped access to essential services like transportation, education, healthcare, irrigation, and market linkages, thereby redefining the socio-economic landscape of the surrounding communities. This aligns with the perspectives of Adesina and Chianu (2002) and Neupane and Thapa (2001), who underscored the catalytic role of infrastructure in shaping household dynamics in rural landscapes. Chavez *et al.* (2013) further supported this, noting that proximity to essential services strongly influences demographic composition and settlement stability.

Family size, a critical demographic marker, exhibited only marginal variation across the study sites, averaging between 5.50 to 6.50 members. Interestingly, the largest average family size was recorded in D5, suggesting that variations in household structures are not random but are strongly shaped by local socio-economic dynamics. Factors such as income levels, livelihood options, educational opportunities, and resource accessibility collectively influence how families are organized. Hence, the composition and functioning of households reflect the broader socio-economic context in which they exist. These trends are consistent with the findings of Masoodi (2010) and Sharma (2012) in Himachal Pradesh, where educational attainment and occupational shifts were linked to family size. Notably, Joshi (2011) and Nisha (2013) also observed similar household sizes in different agro-ecological zones of the region. The Bundelkhand region, with much larger household sizes (Kareemulla *et al.,* 2002), and smaller average sizes in Chinese villages (Demurger and Martin, 2010), reflect the diversity of family structures shaped by regional socio-economic and cultural contexts.

The observed improvements in sex ratios across certain sites point towards a progressive shift in societal attitudes concerning gender roles. Vepa (2007) and Bhattacharya (2012) emphasized such evolving perceptions as instrumental in fostering gender parity, supported by national-level trends documented by Echavarri and Ezcurra (2010). These findings indicate that improvements in socio-economic conditions, coupled with targeted advocacy, education, and awareness initiatives, have started to produce tangible demographic benefits for women, reflecting their enhanced participation and empowerment within the community.

3.2 | Literacy Rate

The literacy rates among residents of villages surrounding the Gobind Sagar reservoir, as illustrated in Table 3, reveal that educational attainment is highest in areas located equidistant from the reservoir, particularly at distances D5 (8-10 km) and D4 (6-8 km). These villages outperformed others in terms of primary, middle, high school, intermediate, graduate, and postgraduate education levels. Notably, D5 recorded the highest number of individuals with secondary education, yet it also had the highest illiteracy rate, with 540 illiterate individuals, followed closely by D4, D3, D6, D1, D7, and D2. The overall literacy rate across surveyed households exhibited no distinct pattern related to proximity to the reservoir. The highest literacy rate was found in D6 at 80.67%, while D3 had the lowest at 68.67%.

Literacy levels in the study area also provide insights into intergenerational educational shifts. A notable share of illiterate individuals was observed among the older population, while younger generations exhibited higher literacy levels, likely reflecting both expanded access to education and the indirect effects of the reservoir, which, by

improving local economic conditions, enabled families to invest more in schooling and educational opportunities. This positive trend is likely linked to increased household income, better access to schools, and changing aspirations, echoing the assertions of Archer *et al.* (2010), Hanasaki *et al.* (2013), and Singh (2014). The influence of household economic status on children's educational attainment, as described by Chevalier *et al.* (2013), reinforces the need for holistic approaches that integrate economic development with educational policies.

3.3 | Land Management

The land use patterns among farmers in the upstream catchment area of the Gobind Sagar reservoir, as detailed in Table 4, reveal varying land holdings across different distance classes. Average land holdings ranged from 1.29 ha to 1.92 ha, with the largest holdings found in D1 (1.92 ha) and D3 (1.82 ha), while smaller holdings were noted in D2 (1.29 ha) and D4 (1.30 ha). Interestingly, the amount of land leased for cultivation and other purposes was greatest in the distance classes farther from the reservoir, particularly in D7 (0.09 ha) and D3 (0.06 ha). In contrast, the least leased land was found in the proximity of the reservoir, specifically D1 (0.02 ha) and D2 (0.005 ha). The analysis indicated that farmers in D3 also reported the highest irrigated land (0.14 ha), whereas D1 had the most un-irrigated land, totaling 1.85 ha. Additionally, D1 farmers maintained the largest cultivated area (1.25 ha) compared to those in other distance classes. The areas dedicated to orchards (0.06 ha) and *ghasni* (0.50 ha), (it is a local term for a patch of land covered with grass, known generally as a grassland) were most prominent in D5 and D3, respectively. Barren land was most prevalent in D6 (0.19 ha), followed by D1 (0.17 ha) and D3 (0.14 ha).

The patterns of land management around the reservoir reflect the combined influence of population pressures, socio-economic demands, policy regulations, and the pursuit of environmental sustainability, illustrating how communities adapt their practices in response to both ecological and livelihood challenges. The encroachment of land for infrastructure and education facilities, coupled with policy-induced land use regulations, has transformed traditional practices, supporting findings by Jayakumar *et al.* (2013) and Garg *et al.* (2020). A move towards climate-adaptive and resource-conserving strategies is evident, emphasizing the need for inclusive land-use planning to safeguard both ecological and human systems.

TABLE 2 Demography of villages at different distance classes from reservoir

Distance classes	Demograhpy					
	Average number of households/ villages	Average family size/ household	Population/ village	Male/ village	Female/ village	Sex ratio
D1	88.00^{c}	5.67^{a}	439.33^{c}	227.00^{c}	212.33^{c}	935.37^{b}
D2	60.17^{c}	6.17^{a}	303.50^{d}	156.83^{d}	146.67^{d}	935.22^{b}
D3	149.33^{b}	6.00^{a}	751.33^{b}	365.33^{b}	386.00^{b}	1056.58^{a}
D4	371.67^{a}	5.67^{a}	1794.33^{a}	911.00^{a}	883.33^{a}	969.63^{ab}
D5	360.50^{a}	6.50^{a}	1738.50^{a}	858.00^{a}	880.50^{a}	1026.22^{a}
D6	140.67^{b}	6.00^{a}	678.67^{b}	334.00^{b}	344.67^{b}	1031.95^{a}
D7	87.50^{c}	5.50^{a}	408.50^{c}	203.00^{c}	205.50^{c}	1012.32^{a}
Mean	179.69	5.93^{a}	873.45	436.45	437	995.33^{ab}
P Value	0.031	0.33	0.027	0.023	0.022	0.041

Different upper case small letter showed statistical difference in different distance classes using t-test at 0.05 probability level.

3.4 | Livestock population, consumption of fodder and fuelwood

The data presented in Table 5 and Appendix I reveal notable variations in livestock numbers and the consumption of fodder and fuelwood among farmers residing at different distances from the Gobind Sagar reservoir. At a distance of D5, the average number of cows per household reached its peak at 2.5, representing 38.46% of the total livestock population. However, the number of cows tended to decrease with increasing distance from the reservoir: D4 (2.33), D6 (2.00), D2 (1.50), D7 (1.50), D3 (1.33), and D1 (1.17). In contrast, the average number of bullocks was highest at D1 (1.50), while the goat population was most abundant in D6 (3.33). Sheep were predominantly found at D1 and D3, each recording an average of 1.00 sheep per household. Buffalo numbers were consistent across several distances, with an average of 1.00 at D3, D5, D6, and D7. Overall, total livestock per household ranged from 5.50 at D7 to 8.00 at D3. Fodder consumption varied significantly across distances, ranging from 42.28 to 70.56 kg per day. The highest fodder intake was observed in areas further from the reservoir, such as D5 (70.56 kg) and D4 (70.17 kg), with consumption decreasing as the distance to the reservoir shortened: D6 (63.34 kg), D2 (56.93 kg), D7 (51.56 kg), D3 (47.11 kg), and D1 (42.28 kg). Conversely, fuelwood consumption was highest in households closer to the reservoir, particularly at D2 (21.31 kg) and D1 (20.46 kg),

with lower consumption noted at greater distances: D4 (19.63 kg), D5 (19.50 kg), D3 (19.18 kg), D7 (17.17 kg), and D6 (16.52 kg).

Livestock dynamics emerged as another crucial indicator of rural sustainability. The correlation between fodder resource availability and livestock numbers was apparent across sites, affirming observations by Dwivedi *et al.* (2007), Radha and Kumar (2022), and Sharma and Omena (2024). Consumption patterns for fuelwood and fodder also varied with proximity to urban centers, where modernization and access to cleaner energy alternatives gradually shift households away from traditional biomass dependency (Arya *et al.,* 2012; Singh *et al.,* 2010; Hussain *et al.,* 2017). This shift in energy use reflects the gradual transformation of rural economies, increasingly shaped by connections to urban markets, infrastructure, and lifestyle influences.

3.5 | Sources of employment and income

The data presented in Table 6 illustrates the contribution of various income sources to household earnings as distances from the Gobind Sagar reservoir change. Agriculture accounted for about 50% of total household income. This was complemented by other income sources: small businesses and private jobs contributed 27.40%, dairy farming provided 14.90%, government jobs contributed 4.90%, and fishery activities made up 2.70%. Notably, households in the D1 distance class exhibited a higher reliance on agriculture, which constituted 56% of their income, along with contributions from dairy (19.30%), fishery (7%), and government jobs (6.30%). In contrast, households in D7 showed a greater reliance on alternative income sources, with small businesses and private jobs contributing significantly (45%).

The reservoir's role as an economic catalyst was notable, with diverse livelihood strategies emerging in its vicinity. From agriculture to fisheries, tourism, and allied sectors, the resource base created new opportunities for income generation, which not only reduced economic vulnerability but also bolstered resilience (Birthal *et al.,* 2014; Vatta and Budhiraja, 2020). These transformations validate the assertion that water bodies, if sustainably managed, can serve as engines of rural development. The present study's findings are consistent with earlier research emphasizing the socio-economic consequences of dam construction and management on local communities. Ampadu *et al.* (2015) reported that the establishment of dams in Ghana significantly influenced the livelihoods of downstream populations by altering water availability, agricultural productivity, and income patterns. Similarly, Huang *et al.* (2018) highlighted that dam-induced changes in hydrological regimes often lead to shifts in land use, resource accessibility, and settlement structures, affecting the overall socio-economic resilience of rural households. These observations reinforce the need for inclusive development planning and participatory water resource governance to ensure that the benefits of dam projects are equitably distributed while minimizing adverse impacts on local economies and social well-being.

TABLE 3 Literacy of people at different distance classes from reservoir

Distance classes	Qualification							Literacy (%)
	Primary	Middle	High School	Intermediate	Graduate	Post graduate	Illiterate	
	Number of people (Mean)							
D1	101.17^{d}	102.83^{e}	94.17^{e}	43.17^{d}	8.83^{cd}	3.00^{d}	123.00^{d}	75.33^{a}
D2	79.50^{e}	57.17^{de}	87.50^{e}	39.67^{d}	17.67^{c}	0.00	77.83^{e}	78.17^{a}
D3	187.00^{c}	211.67^{b}	130.33^{d}	47.33^{d}	10.33^{cd}	0.00	275.00^{c}	68.67^{b}
D4	346.67^{a}	304.00^{a}	480.67^{b}	401.67^{a}	84.67^{a}	161.33^{a}	442.00^{b}	78.67^{a}
D5	368.50^{a}	310.50^{a}	631.00^{a}	331.50^{b}	50.00^{b}	30.50^{c}	540.00^{a}	75.50^{a}
D6	213.33^{b}	79.33^{d}	200.67^{c}	102.33^{c}	18.33^{c}	71.00^{b}	155.33^{d}	80.67^{a}
D7	134.50^{d}	25.00^{e}	115.50^{d}	55.50^{d}	14.00^{c}	25.00^{c}	117.00^{d}	76.00^{a}
Mean	204.38	155.79	248.55	145.88	29.12	41.55	247.17	76.14
P Value	0.026	0.022	0.021	0.034	0.037	0.025	0.024	0.041

*Different upper case small letter showed statistical difference in different distance classes using t-test at 0.05 probability level; *Z-test used at 0.05.*

3.6 | Knowledge of Agroforestry

The assessment of households regarding their knowledge of agroforestry and its adoption, as detailed in Tables 7, reveals significant insights into the understanding of agroforestry systems among different communities. Households located arther from the Gobind Sagar reservoir, specifically in D7 and D5, demonstrated a higher level of knowledge about agroforestry, with approximately 42.50% of these households being informed about various agroforestry practices. In contrast, households closer to the reservoir, such as those in D1 (30.67%) and D2 (30.33%), exhibited lower awareness levels.

Awareness and knowledge of agroforestry practices were widespread among the surveyed families,

demonstrating that it is not an alien concept but rather a historically ingrained practice supported by modern institutional interventions. Government and NGO-led training and extension programs have played an instrumental role in disseminating agroforestry knowledge (Dhyani, 2009; Berry *et al.,* 2021). Such interventions bridge traditional wisdom with scientific innovations, promoting long-term sustainability and improved livelihoods.

TABLE 4 Land management at different classes from reservoir

Distance classes	Land use per house hold (ha HH^{-1})							
	Average land owned	Leased	Irrigated	Un-Irrigated	Cultivated*	Orchard	Ghasni (grassland)	Barren
D1	1.917^{a} ± 0.60	0.020^{a}	0.097^{b}	1.848^{a}	1.25^{a} (64.44)	0.03^{a} (1.29)	0.47^{a} (24.17)	0.17^{a} (8.78)
D2	1.292^{a} ± 0.35	0.005^{b}	0.030^{b}	1.268^{a}	0.89^{a} (68.48)	0.02^{a} (1.39)	0.30^{a} (23.37)	0.09^{b} (6.79)
D3	1.820^{a} ± 0.50	0.057^{a}	0.137^{a}	1.737^{a}	1.13^{a} (60.21)	0.02^{a} (1.23)	0.50^{a} (26.64)	0.14^{a} (7.46)
D4	1.297^{a} ± 0.11	-	0.067^{b}	1.230^{a}	0.87^{a} (67.09)	0.04^{a} (2.85)	0.31^{a} (23.68)	0.11^{a} (8.25)
D5	1.350^{a} ± 0.10	0.030^{a}	0.100^{a}	1.280^{a}	0.98^{a} (71.01)	0.06^{a} (3.99)	0.24^{a} (17.03)	0.11^{a} (7.97)
D6	1.467^{a} ± 0.08	0.040^{a}	0.047^{b}	1.463^{a}	1.02^{a} (67.90)	0.01^{a} (0.86)	0.28^{a} (18.58)	0.19^{a} (12.41)
D7	1.330^{a} ± 0.04	0.085^{a}	0.075^{b}	1.345^{a}	0.99^{a} (69.61)	0.04^{a} (2.83)	0.29^{a} (20.14)	0.11^{a} (7.42)
Mean	1.496 ± 0.21	0.034	0.079	1.453	1.019 (68.11)	0.03 (2.00)	0.34 (22.72)	0.13 (8.69)
P Value	0.067	0.049	0.038	0.064	0.057	0.260	0.052	0.045

*± Standard deviation (SD); *Cultivated land includes agroforestry systems also; values in parenthesis are the percent of the average land owned (ha HH^{-1}); different upper case small letter showed statistical difference in different distance classes using t-test at 0.05 probability level.*

TABLE 5 Livestock number, consumption of fodder and fuelwood per household at different distance classes from reservoir distances

Distance classes	Average livestock number per household						Fodder (kg day^{-1} HH^{-1}	Fuelwood (kg day^{-1} HH^{-1}
	Cow	Bullock	Goat	Sheep	Buffaloes	Total		
D1	1.17^{b} (17.07)	1.50^{a} (21.95)	2.50^{ab} (36.59)	1.00^{a} (14.63)	0.67^{a} (9.76)	6.83^{ab}±0.98	42.28^{c}±17.94	20.46^{ab}±4.53
D2	1.50^{b} (21.43)	1.17^{a} (16.67)	2.67^{ab} (38.10)	0.83^{a} (11.90)	0.83^{a} (11.90)	7.00^{ab}±0.89	56.93^{c}±18.77	21.31^{a}±1.87
D3	1.33^{b} (21.05)	1.33^{a} (21.05)	1.67^{c} (26.32)	1.00^{a} (15.79)	1.00^{a} (15.79)	6.33^{ab}±1.15	47.11^{d}±27.89	19.18^{b}±3.31
D4	2.33^{a} (31.82)	1.00^{ab} (13.64)	3.00^{a} (40.91)	0.33^{b} (4.55)	0.67^{a} (9.09)	7.33^{a}±0.58	70.17^{a}±3.64	19.63^{b}±2.53
D5	2.50^{a} (38.46)	1.00^{ab} (15.38)	2.50^{ab} (38.46)	-	1.00^{a} (15.38)	6.50^{ab}±0.71	70.56^{a}±11.55	19.50^{b}±0.08
D6	2.00^{a} (25.00)	1.00^{ab} (12.50)	3.33^{a} (41.67)	0.67^{a} (8.33)	1.00^{a} (12.50)	8.00^{a}±1.73	63.34^{b}±12.70	16.52^{c}±1.83
D7	1.50^{b} (27.27)	0.50^{c} (9.09)	2.50^{ab} (45.45)	-	1.00^{a} (18.18)	5.50^{b}±0.71	51.56^{c}±7.54	17.17^{bc}±1.18
P Value	0.041	0.036	0.034	0.041	0.190	0.044	0.032	0.046

± Standard deviation (SD), values in parenthesis are the per cent of total number of animals; different upper case small letter showed statistical difference in different distance classes using t-test at 0.05 probability level.

3.7 | Correlation Study

The interrelations among various socioeconomic factors near water reservoirs are intricate, reflecting a web of connections between economic growth, environmental sustainability, social dynamics, and policy influences. To explore these interconnections, we conducted a correlation analysis of 14 key variables, as shown in Table 8. The findings indicate that the total number of households is positively correlated with both the total human population and the number of agricultural laborers per household. Notably, a significant positive correlation exists between the total human population and agricultural labor per household, highlighting how population density can drive labor needs in agriculture. Additionally, the total land owned per household exhibits a strong positive correlation with both cultivated and *ghasni* (grassland) land. This suggests that larger landholdings may facilitate more extensive agricultural activities. There are also significant positive correlations between cultivated land and *ghasni*, as well as between the literacy rate and agricultural labor per household. Moreover, a positive relationship is noted between average livestock population and average fodder consumption, reinforcing the idea that increased agricultural activities generate employment opportunities not only in farming but also in ancillary sectors like processing, transportation, and marketing. However, the analysis revealed some negative correlations as well. The literacy rate is negatively correlated with *ghasni*, while total owned land, cultivated land, and *ghasni* are negatively correlated with average fodder consumption. Interestingly, a negative correlation was also observed between the knowledge of agroforestry and fuelwood consumption. Family size and sex ratio did not show any correlation with the other socioeconomic variables, indicating that these factors may operate independently in this context.

TABLE 7 Farmers keeping knowledge of agroforestry at different distance classes from reservoir

Distance Classes	Household having knowledge of agroforestry (%)
D1	30.67[d]
D2	30.33[d]
D3	33.33[c]
D4	33.33[c]
D5	42.50[a]
D6	40.00[b]
D7	42.50[a]
Mean	36.09
P Value	0.034

*Z-test used to find statistical difference; small case letters denote significant difference at 0.05 probability level.

TABLE 6 Share of different sources of income in total household income at different at different distance classes from reservoir

Distance classes	Share %				
	Income from agriculture	Income from Gov. Job	Income from Fishery	Income from Dairy	Other Sources
D1	56.00[a]	6.30[a]	7.00[a]	19.30[a]	11.30[e]
D2	50.00[c]	4.80[b]	3.70[b]	15.00[c]	26.50[c]
D3	48.30[c]	3.00[c]	2.30[b]	13.30[d]	33.00[b]
D4	48.30[c]	5.70[ab]	0.70[c]	13.30[d]	32.00[b]
D5	52.50[b]	5.50[ab]	3.00[b]	17.50[b]	21.50[d]
D6	53.30[b]	4.70[b]	1.70[c]	18.30[b]	22.00[d]
D7	42.50[d]	4.00[b]	0.50[c]	7.50[e]	45.50[a]
P Value	0.021	0.047	0.030	0.026	0.019

**Z-test used to find statistical difference; upper case small letters denote significant difference at 0.05 probability level.*

The correlation analyses revealed that while economic development associated with reservoir proximity spurs growth, it may inadvertently widen income disparities if gains are not equitably distributed. This mirrors findings by Konwar (2015) and underscores the importance of inclusive development. Agroforestry has shown promise as a balancing mechanism by uplifting marginalized groups through enhanced income, gender empowerment, and ecological stability (Mukhlis *et al.,* 2022). Shi *et al.* (2019) reinforced the notion that dams and large infrastructure must be accompanied by equitable resource-sharing policies to avoid social fragmentation.

4 | CONCLUSIONS

A detailed assessment of the socio-economic landscape around the 'Gobind Sagar Reservoir' revealed that households located in close proximity to the reservoir generally hold larger land parcels, likely benefiting from better access to water resources for irrigation and associated agricultural advantages. In contrast, households farther from the reservoir tend to demonstrate greater familiarity with agroforestry practices and utilize more fodder, reflecting adaptive strategies to optimize limited resources. Agriculture remains the principal livelihood for these communities, supplemented by income from small businesses, dairy farming, government employment, and fisheries-activities often bolstered by the reservoir's influence on water availability and economic opportunities. Farmers actively cultivate woody perennials and bamboo species, establishing diversified agroforestry systems that

not only enhance economic returns but also promote environmental sustainability. These patterns illustrate how the reservoir shapes both land use and resource management decisions, highlighting the adaptive measures households employ to navigate socio-economic and ecological challenges in the region.

TABLE 8 Pearson correlation matrix between different socioeconomic variables of farm families at different distance classes from reservoir

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.00													
2	0.99**													
3	-0.02	0.01												
4	-0.10	-012	-0.16											
5	0.13	0.12	-0.20	-0.12										
6	-0.04	-0.01	0.16	-0.27	-0.35									
7	-0.05	-0.03	0.15	-0.26	-0.24	0.97**								
8	-0.06	-0.03	0.19	-0.30	-0.51**	0.89**	0.79**							
9	0.08	0.06	-0.23	-0.03	0.33	-0.25	-0.26	-0.33						
10	-010	-0.10	0.06	-0.01	-0.20	0.29	0.29	0.33	-0.18					
11	0.23	0.23	-0.08	0.23	0.03	-0.15	-0.09	-0.18	-0.30	-0.11				
12	0.67**	0.68**	0.00	-0.24	0.42*	0.10	0.12	-0.07	0.08	-0.28	0.11			
13	0.32	0.30	-0.03	0.21	0.29	-0.76**	-0.72**	-0.81**	0.52**	-0.36	0.16	0.15		
14	0.00	0.00	-0.08	-0.07	0.13	0.03	0.03	0.03	-0.06	0.28	-0.43*	0.05	-0.22	1.00

***. Correlation is significant at the 0.01 level; *. Correlation is significant at the 0.05 level.*

Where, 1-Total number of households, 2-Total human population, 3-Family size, 4-Sex ratio, 5-Literacy rate, 6-Total land owned, 7-Cultivated land, 8-*Ghasni* (grassland), 9-Av. Livestock population, 10-Income from agriculture, 11-Knowledge of agroforestry, 12-Agriculture labour HH^{-1}, 13-Av. fodder consumption and 14-Av. fuelwood consumption.

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CONFLICT OF INTEREST

The authors state that they have no financial or personal connections that could have influenced the work in this paper.

DATA AVAILABILITY STATEMENT

Data will be provided upon request.

AUTHOR'S CONTRIBUTION

SS: Investigation, resources, formal analysis, visualization, writing - original draft; BG & DRB: Supervision, conceptualization, writing - review and editing; PP, DK ,CL and PS: Review and editing.

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Short Communication

ORIGINAL ARTICLE

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Efficacy of Foliar Nutrient Applications on Growth, Yield and Economics of Mung Bean (*Vigna radiata L.*) under Hot Arid Conditions of Rajasthan

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ABSTRACT

The hot, arid conditions of Rajasthan often face multiple challenges such as low soil fertility, high temperatures, erratic rainfall, and poor nutrient-use efficiency. Conventional soil application of fertilizers is less effective because nutrient mobility is restricted due to limited soil moisture. To address these issues, foliar nutrition emerges as a potential solution for direct and rapid absorption of nutrients and to mitigate the impact of dry spells. Against this backdrop, a field experiment was conducted at the Agricultural Research Sub-Station, Nagaur, Agriculture University, Jodhpur, during Kharif 2021 to investigate the effect of foliar application of nutrients on enhancing growth, yield, and productivity, as well as mitigating the effects of dry spells during flower initiation (FI) and pod formation (PF) stages in mung bean (Vigna radiata L.). The eleven treatments included: absolute control (no foliar application); two foliar sprays of nitrogen urea @ 1% at FI and PF stages; two foliar sprays of water- soluble NPK (19: 19: 19) @ 1% at FI and PF stages; two foliar sprays of soluble KNO 3 @ 0.5% at FI and PF stages; two foliar sprays of borate @ 0.5% at FI and PF stages; and two foliar sprays of micronutrient six elements (Fe, Zn, Mn, Cu, Mo, B) @ 0.5% at FI and PF stages. The treatments were laid out in a randomized block design (RBD) with three replications. Results revealed that foliar application of the micronutrient six elements at 0. 5% concentration at FI and PF stages exhibited the highest growth and yield attributes of mung bean, including plant height at maturity (78. 1 cm), number of branches per plant (8. 2), number of active nodules at flowering (24. 6), number of pods per plant (61. 7), number of seeds per pod (13. 2), and 1000- grain weight (43. 8 g), leading to a grain yield of 1420 kg ha- 1. This treatment also resulted in significant improvements in net returns (₹ 71, 555 ha- 1), B:C ratio (2. 25), production efficiency (20. 9 kg ha- 1 day- 1), and monetary efficiency (₹1052 ha- 1 day- 1). The lowest values were observed in the no foliar application treatment. It was concluded that foliar application of six micronutrient elements at 0.5% concentration at FI and PF stages produces superior growth, yields, and returns under the hot, arid conditions of Rajasthan.

1 | INTRODUCTION

Mung bean (*Vigna radiata L.*), also known as green gram, green bean, moong bean, or golden gram, belongs to the Leguminaceae family. It is an important pulse crop in India and is believed to have originated there. India is the world's leading producer and consumer of pulses. With an area of 31.94 lakh hectares, mung bean is the third most important pulse crop in India, cultivated in nearly 10 % of the country's total pulse area. In India, the total production of mung bean is 15.06 lakh tonnes (Anonymous, ICAR-IIPR-2023-24a). Rajasthan has the highest area, production, and yield productivity of mung bean, with about 22.12 lakh hectares, 10.56 lakh tonnes, and 477 kg ha^{-1}, respectively (Anonymous, ICAR-IIPR-2023-24b). The main contributors to mung bean cultivation in terms of area and production are Rajasthan (46 % and 45% respectively), followed by Madhya Pradesh (9% and 14%), Maharashtra (9% and 8%), Karnataka (9% and 6%), Odisha (5% and 4%), Bihar (4% and 5%), Tamil Nadu (4% and 3%), Gujarat (3% and 4%), Andhra Pradesh (3% for both), and Telangana (2% for both) (Anonymous, Annual Report, ICAR-IIPR, 2022-23). In Rajasthan, the districts with the largest mung bean cultivation area are Nagaur (27%), Jodhpur (13.57%), and Pali (12.18%). Together, Nagaur, Jodhpur, and Pali account for more than 50% of Rajasthan's total mung bean cultivation area (Sharma *et al*. 2017).

It plays an important role as a food security crop due to its high nutritional value and ability to survive in severe environmental conditions such as arid and semiarid lands. According to the Food and Agriculture Organization

.(FAO, 2017), by 2050, the world's population is expected to surpass 10 billion, leading to a 50 percent increase in food demand, mainly in developing countries. Globally, micronutrient deficiencies affect about 38% of pregnant women and 43% of preschool-aged children. Reports indicate that over 30% of the world's population is anemic and suffers from hidden hunger (Dogra *et al.*, 2024). The global challenge lies in adopting sustainable crop production approaches to prevent soil and environmental degradation, which results in the loss of both major and micronutrients (Ram *et al*., 2022). Indian soils are deficient in micronutrients such as Zn, Fe, Mn, Cu, B, Mo, and S, with deficiency rates of 48, 12, 5, 4, 33, 13, and 41%, respectively (Boradkar *et al*., 2022). These crops are mainly cultivated for human consumption, flour production, and as sprouts or immature pods used as vegetables. The grains contain roughly 25-28% protein, 3.5-4.5% fiber, 4.5-5.5% ash, and 60-65% carbohydrates on a dry weight basis. They also provide nutrients such as vitamin A (94 µg), vitamin C (8 mg), iron (7.3 mg), calcium (124 mg), magnesium (189 mg), phosphorus (367 mg), and folate (549 mg) (Muchomba *et al*., 2023). In addition to being a rich source of protein, green gram roots are vital for soil nitrogen enrichment. The roots form nodules that facilitate atmospheric nitrogen fixation through rhizobium bacteria, enabling the crop to add approximately 30-40 kg N ha^{-1} in a single season. The vegetative parts, stalks, and husks also serve as valuable leguminous fodder for livestock. Furthermore, the crop functions as an important cover crop and is used in crop rotation systems (Dhakal *et al.*, 2016).

The hot, arid region of western Rajasthan presents a unique challenge for mungbean cultivation due to nutrient deficiencies (Basir *et al*., 2022), which are intensified by limited water availability, high temperatures, and poor soil conditions such as salinity or extreme pH. These conditions impede root-based nutrient uptake, making foliar nutrition an effective approach to overcome fixation and immobilization issues, thereby improving nutrient efficiency, especially for short-duration crops (Pochampally *et al*., 2021). Considering these factors, the present study was conducted to examine growth, yield, productivity, profitability, and to address the dry spell effect through foliar application of nutrients during the flower initiation and pod formation stages of mungbean under the hot, arid conditions of Rajasthan (India).

2 | MATERIALS AND METHOD

2.1 | Experimental Site and Weather Conditions

A field experiment was conducted during the Kharif (Rainy) season of 2021 at the Research farm of Agricultural Research Sub-Station, Nagaur, Agriculture University, Jodhpur, Rajasthan, situated at 27° 12' 7.24" N latitude, 73° 44' 2.18 E longitude, at an altitude of 302 m above the mean sea level. This location falls within agro-climatic zone II A, characterized as an arid and semi-arid transitional plain of the inland drainage zone in Rajasthan. The climate of this region is distinctly arid and semi-arid, marked by significant temperature fluctuations throughout

HIGHLIGHTS

- Foliar spray of micronutrients (Fe, Zn, Mn, Cu) @ 0.5% during flowering and pod formation improved mung bean growth and yields.
- The recommended fertilizer dose with foliar application of 0.5% micronutrients (Fe, Zn, Mn, Cu, Mo, B) at flower initiation and pod formation showed the highest growth, yield, returns, and efficiency compared to no spray.

the year. Average annual rainfall of 385 mm, about 80% of which falls during July–September from the southwest monsoon, while the rest is more or less equally distributed during the rest of the year. Weather data during the whole experimental period was recorded and presented as per -

TABLE 1 Weather data during experiment period

Months and Years	Mean monthly maximum temperature (°C)	Mean monthly minimum temperature (°C)	Totally monthly rainfall (mm)	**Mean** Pet (mm)
July 2021	37	29	130	155
August 2021	36	28	126	131
Sept., 2021	33	26	175	109

2.2 | Soil Analysis and Status

The soil samples were drawn from the top 15 cm of soil depth. The experimental soil was sandy loam in texture, and soil pH, electrical conductivity (EC), organic matter, available phosphorus, potassium, and six element micronutrients are presented in Table 2.

TABLE 2 Initial soil nutrient status of the experimental site

Parameters	Parameters
Soil type	Sandy loam Soil
pH	8.2
EC (dSm^{-1})	0.35
OC (%)	0.15
N ($kg\ ha^{-1}$)	219
P_2O_5 ($kg\ ha^{-1}$)	15
K_2O ($kg\ ha^{-1}$)	217
Fe ($mg\ kg^{-1}$)	2.56
Zn ($mg\ kg^{-1}$)	0.504
Cu ($mg\ kg^{-1}$)	0.178
Mn ($mg\ kg^{-1}$)	2.21
B ($mg\ kg^{-1}$)	2.34
Mo ($mg\ kg^{-1}$)	0.64

2.3 | Treatments and Experimental Details

Eleven treatments were applied in a randomized block design (RBD) with three replications. These included: T1, an untreated control; T2, a single foliar spray of 1% nitrogen urea at flower initiation (FI); T3, two sprays of 1% nitrogen urea at FI and pod formation (PF); T4, one spray of 1% soluble NPK (19:19:19) at FI; T5, two NPK sprays at FI and PF; T6, one spray of 0.5% soluble KNO3 at FI; T7, two KNO3 sprays at FI and PF; T8, one spray of 0.5% borate at FI; T9, two borate sprays at FI and PF; T10, one spray of 0.5% micronutrient mix of Fe, Zn, Mn, Cu, Mo, and B at FI;

T11, two micronutrient sprays at FI and PF. Each plot measured 4 x 3 m² (gross) and 3 x 2.6 m² (net). The micronutrient mix was a ready-made combination with Zn 5%, Fe 2%, Mn 2%, Cu 0.5%, B 0.5%, and Mo 0.05%. Borate was di sodium tetra borate penta hydrate (20%), with potassium nitrate (13% nitrate N, 46% K_2O), and soluble urea nitrogen (46%) in water. Applications were made at 500 liters per hectare, using a knapsack sprayer with a flat-fan nozzle, at FI and PF stages, with a 0.5% solution.

2.4 | Crop Management Practices

Certified seeds of Mung bean variety "GM-4" were obtained from the Agricultural Research Sub-station, Nagaur, and manually sown using a 30 x 10 cm planting grid with a seed rate of 15 kg per hectare on July 18, 2021. The crop was grown entirely under rainfed conditions. A recommended fertilizer dose of 40:20 kg N:P_2O_5 per hectare was applied as a basal dose through Urea and Di-ammonium phosphate (DAP), following the local crop management practices. Cultural practices suitable for the agro-climatic zone were maintained throughout the mung bean growth cycle, except for the experimental foliar nutrient management technique. Activities such as gap filling, thinning, irrigation, weeding, mulching, and pest control were carried out as needed to promote optimal plant growth and development.

2.5 | Data Recording

Observations on the number of nodules/plants, plant height (cm), number of branches/plants, number of pods/plants, and number of seeds/pods were conducted by randomly selecting five representative plants from each plot within each replication according to Idnani and Singh (2008). Additionally, test weight (g) and overall yield were documented. The important growth parameters, yield attributes, and yield were recorded following standard procedures. To calculate the net returns for each treatment, the total cost of cultivation was subtracted from the gross returns. The total cost of cultivation was calculated based on input and labor requirements during the experiment. Gross returns were estimated according to the minimum support price of the last three years prevailing at the time of the experiment, and the benefit-cost ratio was calculated from gross returns to the cost of cultivation. Harvesting took place on October 4, 2021. Grain and straw yields were recorded from the net plot area of each treatment. Harvest index (HI) was calculated as:

$$\text{Harvest Index (\%)} = \left[\frac{\text{Grain yield } (\frac{kg}{ha})}{\text{Biological yield } (\frac{kg}{ha})}\right] \times 100$$

Benefit-cost (B:C) ratio was computed to assess the economic viability of different treatment combinations as:

$$\text{B:C Ratio} = \frac{\text{Net Returns (₹ ha}^{-1})}{\text{Cost of cultivation (₹ ha}^{-1})}$$

Monetary Efficiency was calculated as:

$$\text{Monetary efficiency (₹ ha}^{-1}\text{ day}^{-1}) = \frac{\text{Net returns obtained (₹ ha}^{-1})}{\text{Number of growing days (Days)}}$$

2.6 | Statistical Analysis

The experimental data were subjected to statistical analysis employing standard techniques of analysis of variance (ANOVA). Mean analysis of the data was conducted, adhering to the methodology outlined by Gomez and Gomez (1984). Furthermore, mean comparison was carried out based on critical differences at the 5% probability level.

3 | RESULTS AND DISCUSSION

3.1 | Effect of Foliar Application of Nutrients on Growth and Yield traits

Foliar application of different nutrients at flower initiation (FI) and pod formation (PF) stages significantly affected the growth, yield attributes, and yield parameters of mungbean. Among various treatments, foliar application of soluble nitrogen urea, NPK, KNO_3, borate, and micronutrient six elements showed a significant increase in plant growth, yield attributes, economic returns, production, and efficiency over the control (Table 3). The highest values of plant height at maturity (78.1 cm), number of branches per plant (8.2), active nodules at flowering (24.6), pods per plant (61.7), seeds per pod (13.2), and 1000-grain weight (43.8 g) were observed when treated with foliar application of micronutrient six elements (Fe, Zn, Mn, Cu, Mo, B) at 0.5% concentration during flower initiation and pod formation stages (Table 3). Conversely, the lowest values for plant height (63.4 cm), branches per plant (6.7), active nodules at flowering (21.8), pods per plant (46.7), seeds per pod (10.9), and 1000-grain weight (40.5 g) were found in mungbean grown without foliar application. This improvement can be attributed to the increased availability of both macro and micronutrients to the plants through foliar nutrient application. This enhanced nutrient availability facilitated early root growth, cell multiplication, and nutrient absorption from deeper soil layers. Consequently, these factors contributed to increased plant height, improved food synthesis, and better resource partitioning (Dhaliwal et al. 2023). These findings align with those of Zafar et al. (2023), who reported significant improvements in the number of branches, plant height, pods per plant, pod length, seeds per pod, 1000-grain weight, and grain yield of mungbean with foliar application of Zn at 0.3%. Zinc plays a complex role in plant physiology by regulating water uptake and its effective utilization by plants (Bahadari *et al.* 2020).

The yield data showed that applying micronutrient elements (Fe, Zn, Mn, Cu, Mo, B) at 0.5% concentration during flower initiation and pod formation stages resulted in the highest seed yield of 1420 kg ha^{-1} (Table 3). These treatments also significantly improved stalk yield (2290 kg ha^{-1}), biological yield (3710 kg ha^{-1}), and harvest index (38.3%). Following this, foliar application of borate at 0.5% during the same stages yielded 1270 kg ha^{-1} of seed, 2310 kg ha^{-1} of straw, a biological yield of 3580 kg ha^{-1}, and a harvest index of 35.5%. The lowest values for seed yield (1061 kg ha^{-1}), straw yield (2040 kg ha^{-1}), biological yield (3410 kg ha^{-1}), and harvest index (32.6%) were observed in mungbean grown without foliar nutrient application (Table 1 & 2).

Foliar application of microelements might have increased plant height, leaf area index, 1000-grain weight, totalchlorophyll content, grain protein percentage, proline accumulation, under both stress and non-stress conditions (Amirani and Kasraei, 2015). Applying micronutrient elements (Fe, Zn, Mn, Cu, Mo, B) at 0.5% during flower initiation and pod formation significantly increased the number of branches per plant, pods per plant, seeds per plant, active nodules per plant, seed yield, and harvest index, showing respective increases of 21.8%, 32.1%, 21.1%, 12.8%, 33.9%, and 11.9% over plants without foliar nutrient application.

TABLE 3 Effect of foliar nutrient application on growth and yield traits of mungbean

Treatments	Plant height at maturity (cm)	Number of branches/ plants	Number of active nodules at flowering	Number of pod/plant	Number of seeds/pod	1000-grain weight (gm)	Seed yield ($kgha^{-1}$)	Stalk yield ($kgha^{-1}$)	Biological yield ($kgha^{-1}$)	Harvest index
Absolute control (Without foliar application)	63.4	6.7	21.8	46.7	10.9	40.5	1061	2040	3100	34.2
Foliar spray of nitrogen Urea @ 1% at FI stage	72.7	7.8	23.6	50.5	11.4	40.7	1185	2150	3335	35.5
Foliar spray of nitrogen Urea @ 1% at FI and PF stage	73.5	7.9	23.9	51.5	11.6	41.9	1205	2150	3355	35.9
Foliar spray soluble NPK (19:19:19) @ 1% at FI stage	73.1	7.9	24.3	50.3	11.7	42.1	1205	2260	3465	34.8
Foliar spray soluble NPK (19:19:19) @ 1% at FI and PF stage	75.7	8.0	24.3	51.9	12.1	41.7	1230	2270	3500	35.1
Foliar spray of soluble KNO_3 @ 0.5% at FI stage	71.1	8.0	24.4	51.2	12.2	41.9	1200	2320	3520	34.1
Foliar spray of soluble KNO_3 @ 0.5% at FI and PF stage	72.1	8.0	24.5	53.0	11.9	42.4	1240	2260	3500	35.4
Foliar spray of borate @0.5 % at FI stage	73.7	8.1	24.6	53.6	12.1	44.4	1230	2300	3530	34.8
Foliar spray of borate @ 0.5 % at FI and PF stage	74.8	8.1	24.6	53.9	12.3	43.3	1270	2310	3580	35.5
Foliar spray of micronutrient 6's element (Fe, Zn, Mn, Cu, Mo, B) @0.5 % at FI stage	72.9	8.1	24.9	54.2	12.4	43.6	1275	2240	3515	36.3
Foliar spray of micronutrient 6's element (Fe, Zn, Mn, Cu, Mo, B) @0.5 % at FI and PF stage	78.1	8.2	24.6	61.7	13.2	43.8	1420	2290	3710	38.3
Sem±	2.5	0.33	0.81	2	0.24	0.34	41	62	74	0.84
CD (*P*=0.05)	7.6	1.06	2.51	6.1	0.71	1.03	123	165	221	2.53

TABLE 4 Effect of foliar nutrient application on Economics of mungbean production

Treatments	Cost of Cultivation (₹ ha^{-1})	Gross return (₹ ha^{-1})	Net return (₹ ha^{-1})	Benefit cost ratio	Production efficiency (kg ha^{-1} day^{-1}	Monetary efficiency (₹ ha^{-1} day^{-1})
Absolute control (Without foliar application)	26000	77115	5115	1.97	15.6	752
Foliar spray of nitrogen Urea @ 1% at FI stage	27530	86209	58679	2.13	17.4	863
Foliar spray of nitrogen Urea @ 1% at FI and PF stage	29060	87664	58604	2.02	17.7	862
Foliar spray soluble NPK (19:19:19) @ 1% at FI stage	27600	87664	60064	2.18	17.7	883
Foliar spray soluble NPK (19:19:19) @ 1% at FI and PF stage	29200	89483	60283	2.06	18.1	887
Foliar spray of soluble KNO_3 @ 0.5% at FI stage	27600	87300	59700	2.16	17.6	878
Foliar spray of soluble KNO_3 @ 0.5% at FI and PF stage	29200	90210	61010	2.09	18.2	897
Foliar spray of borate @0.5 % at FI stage	27950	89483	61533	2.20	18.1	905
Foliar spray of borate @ 0.5 % at FI and PF stage	29950	92393	62443	2.08	18.7	918
Foliar spray of borate @ 0.5 % at FI and PF stage	28875	92756	63881	2.21	18.8	939
Foliar spray of micronutrient 6^{is} element (Fe, Zn, Mn, Cu, Mo, B) @0.5 % at FI and PF stage	31750	103305	71555	2.25	20.9	1052
Sem±	-	-	-	-	0.41	28.6
CD (*P*=0.05)	-	-	-	-	1.25	85.8

**Gross return calculated based on MSP prevalent in kharif -2021 (₹7,275 per quintal) of mung bean*
Input cost: One foliar spray cost (₹ 1500 ha^{-1}): Micronutrient 6, s element (₹ 550 liter^{-1}): Boron (₹ 180 kg^{-1}): Urea (₹ 5.5 kg^{-1}): NPK (₹ 10 kg^{-1}) and KNO_3 (₹ 10 kg^{-1})

The same results were obtained under the combined application of ZnSO4.7H2O (0.5%), FeSO4.7H2O (0.5%), and borax (0.1%), which could be considered the most effective combination for enhancing yield, nutritional quality, and economic returns of mung bean (Dhaliwal *et al*., 2023). A significant increase in yield and yield attributes due to foliar application of ferrous sulfate, zinc sulfate, and borax might be attributed to increased leaf area (Ali *et al*., 2008). The addition of zinc and ferrous to the soil may also have caused higher activation of micronutrients, mainly due to their positive effects in mobilizing native nutrients to improve their availability, as well as providing better nutrition over a longer period. The coactive effect of both nutrients on yield components (Bahadari *et al*., 2020) could also contribute to this improvement. Such effects might also be attributed to the favorable influence of these nutrients on metabolism and biological activity, as well as their stimulatory effects on photosynthetic pigments and enzymatic activity, which in turn increase vegetative growth (Ali *et al*., 2014). Similarly, foliar fertilization of NPK with Fe, Zn, and Mn has been shown to increase vegetative growth, yield components, and nutrient concentrations in cowpea plants (Ali *et al.*, 2014).

3.2 | Effect of foliar spray of nutrients on economics, production and monetary efficiency

The economic analysis of mung bean cultivation as influenced by foliar application of various soluble nutrients such as nitrogen urea, NPK, KNO3, borate, and micronutrient 6's element showed that the highest cost of cultivation was observed for micro nutrient 6's element (₹ 31,750 ha^{-1}), followed by borate application (₹ 29,950 ha^{-1}). Conversely, the lowest cost was seen in plots without foliar application (₹ 26,000 ha^{-1}) during flower initiation and pod formation stages. The highest gross return (₹1,03,305 ha^{-1}) and net return (₹71,555 ha^{-1}) were achieved with foliar application of micro nutrient 6's element (Fe, Zn, Mn, Cu, Mo, B) at 0.5% concentration during flower initiation and pod formation stages, while the lowest gross return (₹77,115 ha^{-1}) and net return (₹51,115 ha^{-1}) occurred in plots without foliar application (Table 4). Similar findings were reported by Diwedi *et al*. (2024). The highest B:C ratio (2.25), production efficiency (20.9 kg ha^{-1} day^{-1}), and monetary efficiency (₹1052 ha^{-1} day^{-1}) were also observed with foliar application of micronutrient 6's element at 0.5% concentration during flowering initiation and pod formation stages. This was followed by foliar application of borate, which resulted in production efficiency of 18.7 kg ha^{-1} day^{-1} and monetary efficiency of ₹918 ha^{-1} day^{-1}. The minimum production efficiency (15.5 kg ha^{-1} day^{-1}) and monetary efficiency (₹752 ha^{-1} day^{-1}) were recorded in plots without foliar application. Similar results were also reported by Dhaliwal et al. (2023), emphasizing the benefits of integrated nutrient management combined with an optimum irrigation level of 0.8 IW/CPE to enhance input efficiency (Bandyopadhyay *et al*., 2021).

4 | CONCLUSIONS

The study clearly emphasizes the importance of foliar nutrient application during flowering and pod formation in

mungbean to boost growth, yield, and profitability. The recommended fertilizer doses with foliar application of soluble nutrients at these stages—such as urea @ 1%, NPK (19:19:19) @ 1%, KNO3 @ 0.5%, and micronutrients including Fe, Zn, Mn, Cu, Mo, B at 0.5%—showed superior performance in growth, yield, economic returns, and production efficiency compared to the control. Therefore, applying a 0.5% solution of micronutrient 6's element (Fe, Zn, Mn, Cu, Mo, B) during flowering and pod formation can be an effective strategy for increasing growth, yield, and economic returns of mungbean, especially under the hot, arid conditions of Rajasthan (India).

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CONFLICT OF INTEREST

This research is conducted ethically and in compliance with relevant guidelines and regulations. We, all the authors, have declared that no conflict of interest exists that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

Available with the author on request.

AUTHOR CONTRIBUTION

This work was carried out as an in-house activity under the ZREAC recommendation by RB.

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