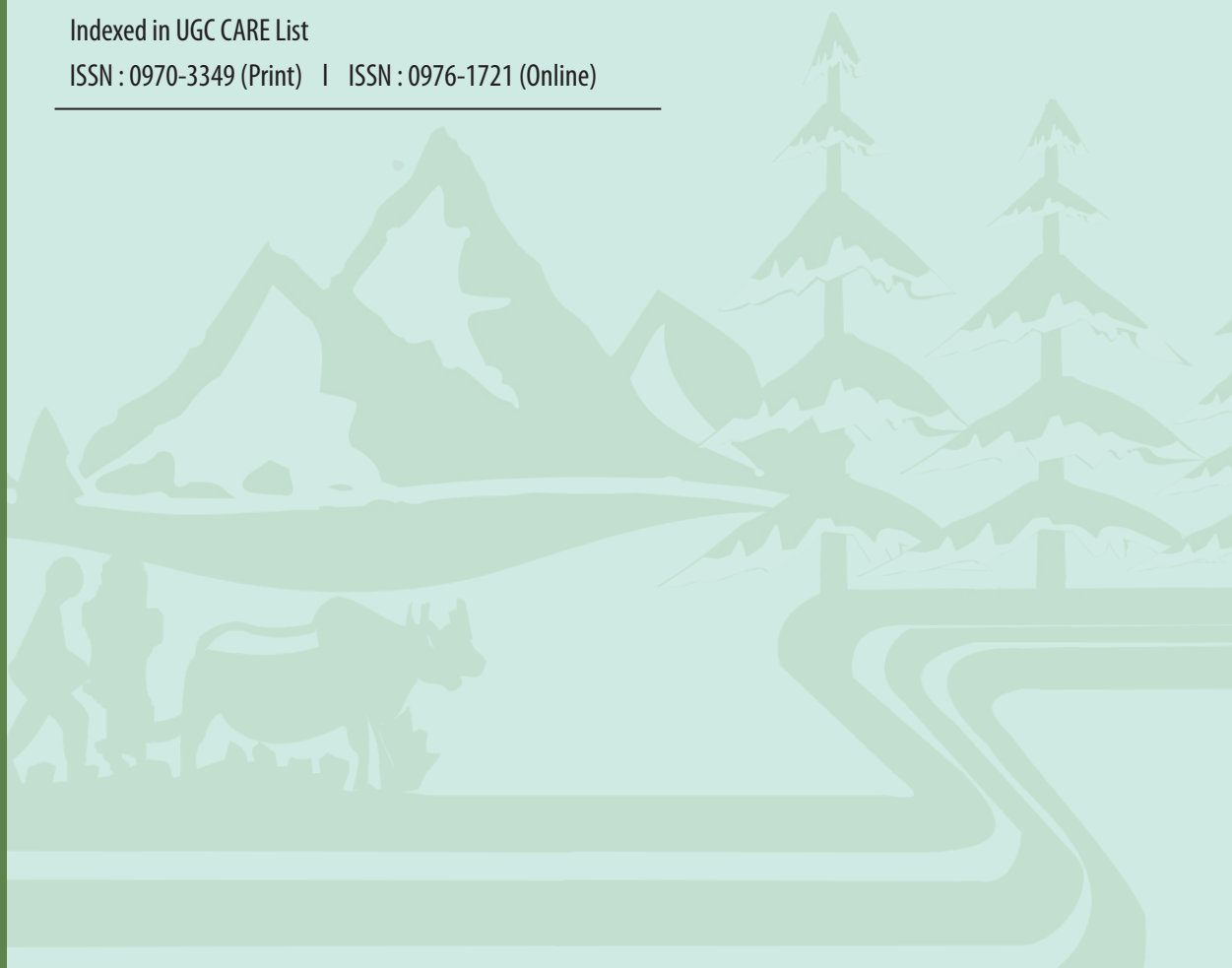




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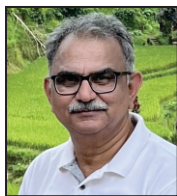
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Hydrological Modeling for Environmental Flow Estimation under Data-Scarce Condition

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Key words:Environmental flow
EMC
Flow duration curve
GEFC
Sankh river
SWAT model**ABSTRACT**

Estimating environmental flows is crucial for mitigating anthropogenic impacts and restoring their ecological functions; however, such assessments remain challenging, particularly in data-scarce and regulated basins. This study addresses this gap by estimating environmental flows for the Sankh River (4,027.4 km²), a regulated and hydrologically data-limited tributary in eastern India, using an integrated Soil and Water Assessment Tool (SWAT)– Global Environmental Flow Calculator (GEFC) modeling framework. Despite its widespread use, the SWAT-GEFC approach is limited in small- to medium-sized Indian basins, especially in ecologically sensitive and under-monitored rivers such as the Sankh. The SWAT model performed satisfactorily in simulating streamflow, as evidenced by the test statistics obtained during calibration and validation (NSE: 0.81 and 0.90; R²: 0.81 and 0.92; RSR: 0.44 and 0.32, respectively). To assess ecological flow requirements, the GEFC was used to derive environmental flow regimes through Flow Duration Curves (FDCs) and Environmental Management Classes (EMCs). Results indicate a systematic decline in Mean Annual Runoff (MAR) allocations from EMC “A” to “F”, with SWAT-simulated values (39.5 to 0.9%) closely matching with the observed trends (47.1 to 1%), thereby supporting the model robustness. Seasonal analysis identified December and January as the most flow-stressed months, with a minimum ecological flow threshold of 5.72 m³ s⁻¹ required to sustain riverine health. The findings offer practical benchmarks for integrating environmental flows into reservoir management, regional water allocation, and policy planning, particularly within the framework of India's National Water Policy (2012). Integrating hydrological modeling with ecological considerations can lead to sustainable river management. Future research should integrate habitat simulation models and climate-change-driven flow scenarios to support resilient and adaptive environmental flow management.

1 | INTRODUCTION

Disruption of the river's natural flow, especially downstream, threatens aquatic habitats, water quality, ecosystems, and local stakeholders relying on the river. This mainly results from non-compliance with environmental flow regulations, which were inadequately addressed during project planning. Environmental flows (E-flows) replenish groundwater and support ecosystems, benefiting all flow aspects-high, medium, and low. Low flows maintain river connectivity and water quality; medium flows aid fish development and migration; high flows are vital for channel flushing, flooding, and riparian vegetation. Although E-flows are recognized as valuable by water planners, they are often overlooked in practice, possibly due to a lack of discharge data (Arthington *et al.*, 2023).

A 2003 global survey showed 88% of respondents saw environmental flow assessment as vital for sustainable

water management. The Brisbane Declaration (2007), backed by over 750 practitioners from 50+ countries, reinforced this. By 2010, many nations adopted environmental flow regulations, but practical implementation remains limited. In India, despite advances, implementation is still early (Acreman *et al.*, 2014). India has nine of the 30 priority river basins for aquatic biodiversity, mostly affected by flow regulation. Recognizing environmental flows as key in water management is growing (Bussettini, 2018). Approaches to flow assessment include Standard-Setting, which prescribes fixed flows, and Incremental methods that assess habitat responses via field data (Dunbar *et al.*, 1998). Tharme and Smakhtin (2003) classify methods as hydrological, hydraulic, habitat-simulation, and holistic. Hydrological methods, used in data-limited basins, rely on discharge records and often use flow duration curves or express e-flows as a proportion of mean flow.

After reviewing hydrology-based techniques, Smakhtin and Anputhas (2006) proposed an FDC-based strategy linking e-flow needs to Environmental Management Classes (EMCs). This approach is used in applications like the Global Environmental Flow Calculator (GEFC), which uses FDC–EMC analysis to recommend flows based on duration and ecology (Kumar *et al.*, 2021). Rivers are categorized into EMCs based on ecological and management needs. Researchers like Govind *et al.*, (2024) combined the Sustainable Management of Hydrological Alteration with Bayesian Belief Networks and FDC analysis. Kumar and Jayakumar (2020) studied dam impacts on hydrology and flow. Gleeson *et al.*, (2020) offered methods for estimating flows in data-scarce regions. These studies highlight the importance of environmental flows for ecosystems and communities (Sahoo *et al.*, 2016).

The SWAT–GEFC approach has been used globally to estimate environmental flows in regulated and unregulated rivers (Smakhtin & Anputhas, 2006; Gleeson *et al.*, 2020). Later studies confirmed its usefulness in reconstructing natural flow patterns, evaluating flow changes, and aiding environmental flow decisions with limited data (Kumar & Jayakumar, 2020; Govind *et al.*, 2024). These studies show that the framework can combine hydrological models with flow-duration ecological classification, enabling flow assessments even without long-term pristine data. While widely used, SWAT–GEFC's application in small to medium Indian basins, especially ecologically sensitive and under-monitored rivers like the Sankh, is limited. This method is particularly relevant for the Sankh River basin, which has significant flow regulation, seasonal variability, and limited data. The basin faces increasing pressures from mining, deforestation, and water abstraction but lacks prior environmental flow assessments or ecological thresholds (JSPCB, 2019; Sharma & Singh, 2024). In these data-scarce, regulated contexts, relying only on observed flow data may underestimate ecological water needs. By combining SWAT-predicted natural flows with GEFC-based ecological classifications, this study provides a scientific basis for defining suitable flow regimes, tailored to the Sankh's conditions. This approach demonstrates the transferability of the SWAT–GEFC framework to less-studied rivers and offers a model for regulated Indian rivers lacking flow or ecological data monitoring.

SWAT has been used to assess ecological flow and water shortages in basin-scale hydrology, linking simulated flows with environmental flow methods (Fang *et al.*, 2025). It is also applied in ecosystem services like water yield, soil retention, and flow regulation under changing environments (Zhao *et al.*, 2024). SWAT+ improves streamflow simulations under climate change scenarios in regulated basins (Mishra *et al.*, 2025). The model helps simulate hydrological balance and component distribution, such as in Wadi Mina (Mebarki *et al.*, 2024). The SWAT model has been used across various hydrological environments (Singh, 2015). This study focuses on the Sankh River, originating in Gumla, Jharkhand, flowing

HIGHLIGHTS

- A coupled SWAT–GEFC framework enables environmental flow estimation in regulated, data-limited basins.
- Consistent MAR reduction across EMC classes (A–F) confirms close agreement between simulated and observed flows.
- The methodology is adaptable for reservoir operation and environmental flow planning in India.

through Odisha and Jharkhand, and joining the South Koel River to form the Brahmani River. Its environmental flow is estimated using the Global Environmental Flow Calculator (GEFC), which uses hydrological data and FDC analysis. In data-scarce conditions, flows are determined by applying GEFC to SWAT-simulated and observed data. Unlike earlier large-basin studies, this research applies SWAT–GEFC to the ecologically sensitive, regulated, and data-scarce Sankh River basin, a tributary of the Brahmani system in Eastern India.

2 | MATERIALS AND METHODS

2.1 | Study Area

The Sankh River lies between latitudes 22°0' N and 23°17' N and longitudes 83°55' E and 84°46' E. It originates at an elevation of 1,020 meters above sea level in Lupungpat village of Gumla district, Jharkhand. The river flows approximately 67.5 km within the state before entering Chhattisgarh. Along its course, it passes through the districts of Gumla and Simdega in Jharkhand and Jashpur in Chhattisgarh. When it enters Odisha's Sundargarh district, the Sankh River joins the South Koel River at Vedvyas, near Rourkela, where the combined flow is called the Brahmani River. The catchment area of the Sankh River Basin (SRB) before entering Odisha is about 4,027.4 km², with an additional 1,319 km² within Odisha (Malik, 2014). The region receives an average annual rainfall of around 1,460 mm, mainly during the southwest monsoon from June to October. Three major irrigation projects — the Upper Sankh Reservoir Project, Ramrekha Reservoir Project, and Kansjore Reservoir Project — are located along the river. They provide irrigation coverage of approximately 7.07, 4.39, and 6.26 thousand hectares, respectively, and play a key role in regional economic growth (Fig. 1). Two main canal systems covering a Culturable Command Area (CCA) of 7.069 thousand hectares are positioned on the left and right banks of the river.

2.2 | Data Preparations

NASA's POWER program provided meteorological datasets for 1998–2021, including temperature, humidity, solar radiation, wind, and precipitation. Bias correction was not applied due to lack of long-term in-basin observations; uncertainties were addressed through SWAT calibration and sensitivity analysis. Discharge data from the Tilga gauge station (2001–2021) was provided by the Central Water Commission, Bhubaneswar. A 30-m DEM from SRTM was

used for watershed delineation and stream generation. Land use/cover data were derived from Landsat-8 imagery at 30-m resolution, soil data from FAO's database at ~1 km (Table 1). All datasets were projected to a common coordinate system and resampled to DEM resolution before HRU definition in SWAT. Variations in land use, soil, and slope

were represented through HRU discretization within sub-basins. Data was projected to Zone-45 N, UTM 1984. LULC maps were created using the support vector machine (Chowdhury, 2024), a robust machine learning algorithm for classifying land features (Jamsran *et al.*, 2019).

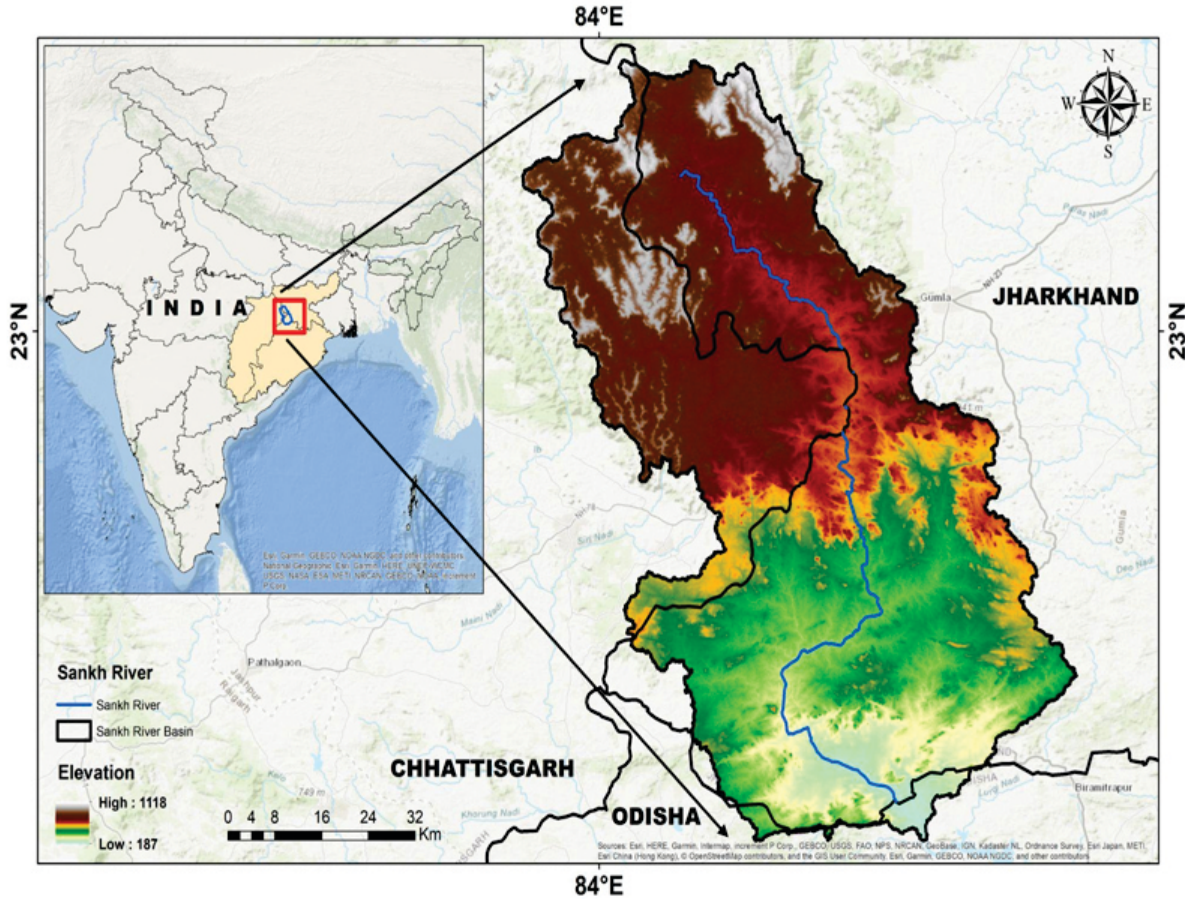


FIGURE 1 Geographical location of the Study area

2.3 | SWAT Model Development, Calibration and Validation

The SWAT model is a freely available, physically based model utilised globally to assess the impact of different land management practices on water flow, soil erosion, and chemical runoff in large and complex watersheds (Singh *et al.*, 2012). It operates continuously over time and calculates the water balance for each Hydrologic Response Unit (HRU), combines it at the sub-basin level, and then sends it to the basin outlet via the stream network. To accurately model the hydrological processes, each HRU is handled separately (Piniewski *et al.*, 2017).

Four HRUs were created across the entire catchment based on slope, soil type, and land use. This was done by overlaying LULC, soil, and DEM maps. The SWAT 2012 version with an ArcGIS interface (ArcSWAT 2012.10.5.24) was used to simulate river discharge. The model simulates streamflow using a water balance equation that depends on

rainfall and temperature.

The equation is :

$$SW_t = SW_0 + \sum_{i=1}^t (P_{day} - R_{surf} - ET_{day} - W_{seep} - R_{gw}) \quad \dots (1)$$

where,

SW_t and SW_0 reflect the final and initial soil moisture levels,

P_{day} represents daily precipitation,

R_{surf} is surface runoff,

ET_{day} is daily evapotranspiration (ET),

W_{seep} is GW seepage, and

R_{gw} is GW return flow

All values are in mm. The following formula is used by the model to estimate surface runoff using the SCS-Curve Number method:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \quad \dots (2)$$

where,

Q = runoff depth (mm),

S = maximum retention potential,

I_a = water abstraction (initial) (mm), and

P = effective precipitation (mm).

Evapotranspiration was calculated with the Penman-Monteith (PM) method. The SWAT model was calibrated and validated using SWAT-CUP with the SUFI-2 algorithm, which provides a framework for automatic calibration, sensitivity analysis, and uncertainty quantification via Monte Carlo simulations (Abbaspour, 2015). SUFI-2 accounts for model uncertainty and observational errors by generating and refining multiple parameter sets. Calibration spanned 2001–2015, validated for 2016–2021, using monthly discharge data from the Tilga gauge station. A three-year warm-up (1998–2000) initialized conditions (Kumari *et al.*, 2024). The process included 1000

simulations, with model performance assessed by NSE, R^2 , PBIAS, and RSR (Singh *et al.*, 2012). Sensitivity analysis used key hydrological parameters identified from prior studies on SWAT modeling in Indian basins (Rahman *et al.*, 2022), focusing on those influencing streamflow and groundwater. Details are in (Table 2). To strengthen future calibration, using local sensitivity analysis methods like the Morris method is recommended. This global, one-at-a-time screening tool examines parameter influence by exploring elementary effects with low computational effort (Campolongo *et al.*, 2007). Combining such methods with SUFI-2 can identify key local basin parameters, reduce model uncertainty, and improve predictions. Morris-based screening would supplement the current literature approach and support more reliable environmental flow estimates in data-scarce, regulated basins like the Sankh.

TABLE 1 Summary of datasets used in the study

Dataset	Description	Source
Meteorological	Tmax and Tmin, relative humidity, solar radiation, wind speed, precipitation.	NASA Power
Hydrological	Discharge data from Tilga rain gauge station	CWC Bhubaneswar
DEM	30 m resolution	USGS SRTM
LULC map	2021	Landsat-8
Soil map	1km resolution	FAO

2.4 | Environmental Flow Estimation

Smakhtin and Anputhas (2006) evaluated several hydrology-based techniques for evaluating environmental flows and their applicability in India (Table 3). They developed an approach that combines FDCs with EMCs. The GEFC is open-source software created by the International Water Management Institute. The GEFC uses flow duration curves and EMCs. To analyse environmental flows, GEFC model requires monthly discharge data from rivers for an extended length of time (Kumar & Jayakumar, 2020).

To determine environmental water requirements, the first step is calculating the FDC for sites. Source sites have

flow data; destination sites need FDC and time series estimates for EF. The FDC approach used flow values at various exceedance probabilities (0.01% to 99.9%), representing flow variability. FDCs were derived from data from 2001-2021, using nearby upstream site data. Environmental flows aim to maintain or restore river ecosystems, classified as EMCs (A to F). Higher EMCs (e.g., Class A) need more water, while lower classes indicate more human impact. The reference FDC is later adjusted to determine EMCs. After determining the FDC from observed and SWAT data, it was converted into an average monthly flow series.

TABLE 2 Model parameters used for sensitivity analysis

Parameters	Description	Min_Value	Max_Value
r_CN2.mgt	SCS runoff curve number	-0.531206	-0.178936
v_ALPHA_BF.gw	Base flow alpha factor (days)	0.000000	0.000002
v_GW_DELAY.gw	Groundwater delay (days)	1.792297	50.562866
v_GWQMN_gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	250.431952	1000.634944
v_GW_REVAP.gw	Groundwater revap coefficient	0.115274	0.135258
v_ESCO.hru	Soil evaporation compensation factor	0.710739	0.746337
v_CH_N2.rte	Manning coefficient for main channel	0.001182	0.076940
v_CH_K2.rte	Effective hydraulic conductivity of the channel (mm hr ⁻¹)	0.045151	0.951453

continued on next page

table 2 continued

v_ALPHA_BNK.rte	Base flow alpha factor for bank storage	0.074282	0.271848
r_SOL_AWC(..).sol	Available water capacity of soil layer (mm H ₂ O mm soil ⁻¹)	-0.616933	-0.444881
r_SOL_K(..).sol	Saturated hydraulic conductivity (mm hr ⁻¹)	0.063346	0.207018
r_SOL_BD(..).sol	Moist bulk density	0.168974	0.927353
v_SFTMP.bsn	Snowmelt base temperature (C ⁰)	0.719767	5.310936
v_SURLAG.bsn	Lag time for surface runoff (days)	0.138594	0.950639

TABLE 3 EMCs Classes (Smakhtin & Anputhas, 2006)

EMC	Ecological Description	Management perspective
A: Natural	Original state or least alteration in river stream and riparian territory.	Applied for safeguarded rivers and basins, Natural reserves, and parks. No new water projects, such as dams, canals, or deviations, are allowed.
B: Slightly modified	Mostly unbroken biodiversity & altered habitats despite water resources expansion and basin amendments.	Agricultural development and water supply structures are present or tolerable.
C: Moderately modified	The environments and dynamics of the changed biota are a concern, but basic ecosystem functions remain. Some sensitive species are lost or diminished, and alien species are present.	Several problems and complexities belong with the requirement of socio-economic development projects (Dams and decline in water quality)
D: Largely modified	Big alterations and modifications in basic natural ecosystems/ habitats have occurred. Species and their population were found to be less than expected. Species that have low tolerance levels are found in much lower numbers. Alien species prevail	Potential and observable problems attached to various water supply and resource development programs (including dams, diversions, transfers, habitat modification, and water quality degradation)
E: Seriously modified	Diversity in habitat was found to have declined extensively, with species richness at a minimum; intolerant species vanished, and only tolerable species remained. Indigenous species in ecosystems are unable to breed. Alien species have almost overtaken the ecosystem	Very high human population density and extreme exploitation of water resources.
F: Critically modified	Modifications have reached a critical level, and the ecosystem has been completely altered, with almost total loss of natural habitat and biota. In the worst case, the basic ecosystem functions have been destroyed, and the changes are irreversible	This status is unacceptable from management's perspective. Management interventions are necessary to restore flow patterns, river habitats, etc. (if still possible/feasible) – to 'move' a river to a higher management category.

3 | RESULTS AND DISCUSSION

3.1 | SWAT Model

The yearly hydrological water balance of the watershed was calculated and compared with observed data. (Fig. 2) shows the observed and simulated discharges during calibration and validation periods, along with their corresponding scatter plots. The calibration and validation periods achieved R^2 values of 0.82 and 0.92, respectively. The model results are highly convincing, as indicated by NSE values of 0.81 during calibration and 0.90 during validation. The SWAT model was calibrated and validated using the SUFI-2 algorithm in SWAT-CUP, with 1, 1000 Monte Carlo simulations per iteration over three calibration cycles, allowing parameters to be refined progressively and model fit to improve. The 95 PPU was assessed using the P-Factor (percentage of observed data within the uncertainty band) and R-factor (average thickness of the band normalized by the observed data standard deviation), ensuring a balance between predictive accuracy and uncertainty. The SUFI-2 calibration and uncertainty analysis setup used in this study is detailed below and in Appendix 1. Table 4 summarizes statistical results, while Table 5 lists the calibrated SWAT parameters. Additionally, the low RSR values of 0.44 and 0.32 further support the SWAT model's effectiveness, indicating minimal differences between observed and simulated data. Collectively, these results confirm the reliability of the model outputs for water resource management in the Sankh river basin. The model's PBIAS values of -8.9 and -19.1 suggest that, on average, the model slightly overestimates observed values by 8.9% during calibration and 19.1% during validation. The robustness of the SWAT results improves our understanding of the basin's hydrology and aids in sustainable water planning. The catchment is forested, as reflected by the average curve number of 35.02. Discharges over 250 m³/s were not accurately simulated, especially in 2001 and 2011, though lower flows were modeled more precisely. This mismatch may stem from antecedent moisture conditions. The model assumes a constant soil storage capacity, but in reality, heavy rainfall events can increase infiltration. The static soil storage capacity may therefore cause inaccuracies during high-discharge events, as it does not reflect dynamic field conditions.

Although the SWAT model demonstrated generally satisfactory performance, the validation phase revealed a relatively high PBIAS of -19.1%, indicating that the model tends to overpredict streamflow compared to observed data. NSE, R^2 , and RSR are primarily influenced by the model's ability to reproduce flow variability and peak discharges, as these metrics emphasize larger deviations that typically occur during high-flow events. In contrast, PBIAS is influenced by the cumulative water balance and indicates systematic over- or underestimation of total runoff volume throughout the simulation period. This consistent overestimation could lead to inflated environmental flow (e-flow) values, particularly under low-flow Environmental

Management Classes (EMCs), where precision is essential. Despite this bias, the NSE (0.90) and R^2 (0.92) values suggest strong agreement and predictive accuracy. Nonetheless, the level of bias warrants additional statistical analysis to confirm the reliability of e-flow estimates.

A paired t-test on monthly observed and simulated discharge values ($n=12$) showed a mean difference of 3.12 cumecs, a standard deviation of 27.49, and a t-statistic of 0.39 with 11 degrees of freedom. The p-value (0.702) exceeds 0.05, indicating no significant difference at 95% confidence. Despite a negative PBIAS, the model is statistically sound for estimating monthly flows, capturing patterns and seasonality (high NSE/ R^2). Its positive bias may lead to overestimation of e-flow volumes in lean months if used directly, especially under altered scenarios like EMC "E" or "F," which could cause conservative ecological recommendations. Future improvements like bias correction or multi-model ensembles are recommended to reduce uncertainty and enhance accuracy in data-limited conditions (Table 6).

TABLE 4 Summary statistics for the calibration and validation period

Statistic	Calibration period (2001-2015)	Validation period (2016-2021)
NSE	0.81	0.90
R^2	0.81	0.92
RSR	0.44	0.32
PBIAS	-8.9	-19.1

TABLE 5 SWAT model parameter and their calibrated values

Parameter	Calibrated value	Parameter	Calibrated value
CN2	38.37	GW_REVAP	0.13
SOL_AWC	0.04	ESCO	0.71
SOL_K	12.31	CH_N2	0.04
SOL_BD	2.49	CH_K2	0.22
ALPHA_BF	0	ALPHA_BNK	0.10
GW_DELAY	8.49	SFTMP	3.86
GWQMN	996.50	SURLAG	0.52

TABLE 6 Summary of Paired t-Test

Parameter	Value
Number of Observation (n)	12
Mean Difference (Observed-Simulated)	3.12 cumecs
Standard Deviation of Differences	27.49 cumecs
Standard Error	7.94 cumecs
t-statistic	0.39
Degree of freedom (df)	11
p-value (two-tailed)	0.702
Statistical Significance	Not significant

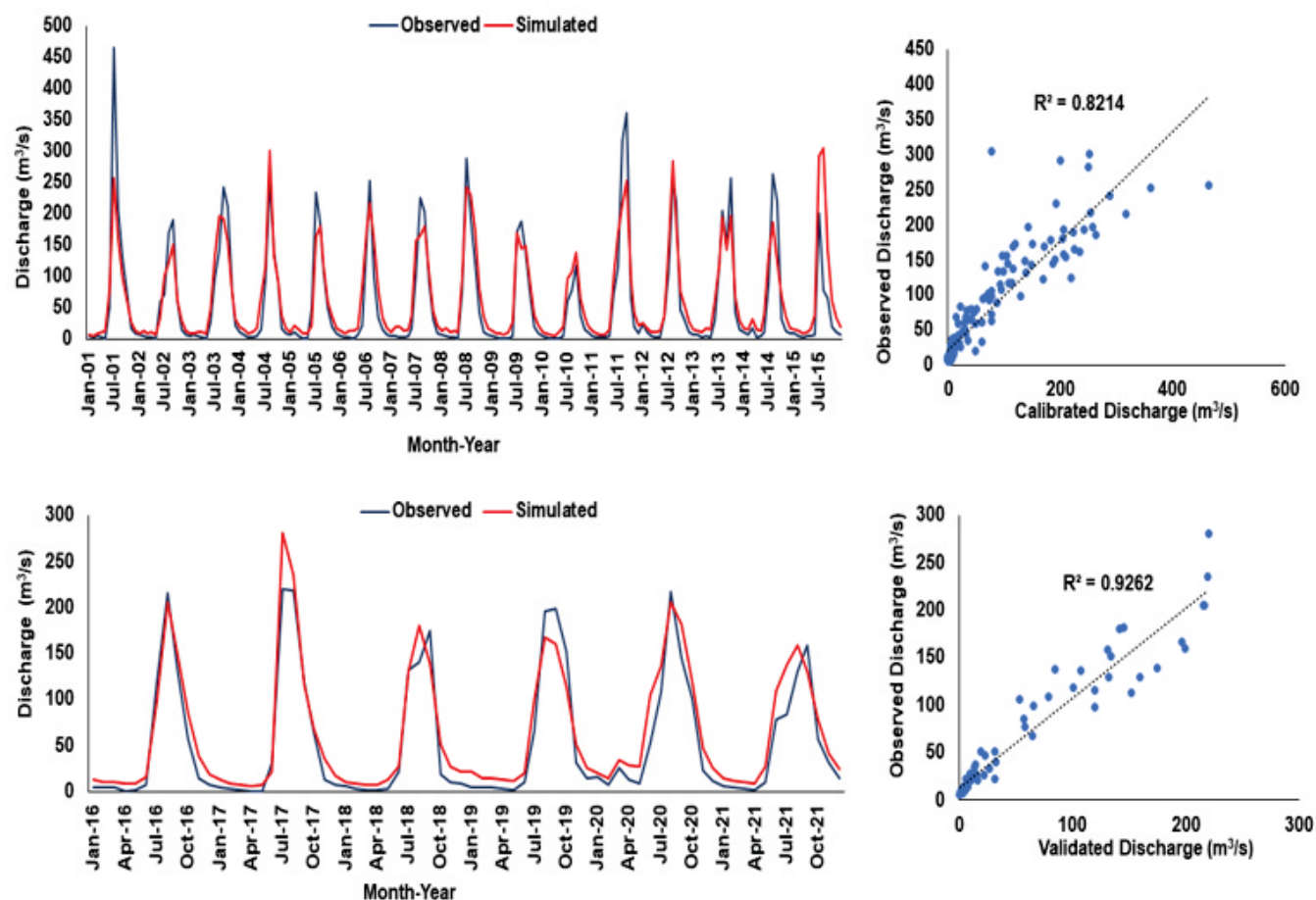


FIGURE 2 Comparison of observed and SWAT-simulated monthly discharge for the Sankh River during calibration (2001–2015) and validation (2016–2021) periods

3.2 | Environmental Flow Analysis

The study used monthly discharge data to analyze environmental flows. Fig. 3 shows FDCs for various EMCs along Sankh River. Discharges drop from EMC A to EMC F and remain steady during lean season. EMC "A" has the least discrepancy between estimated and natural flows, which widens from EMC "A" to EMC "F," indicating greater flow deviation at F. Flow values across EMCs are comparable. Fig. 4 displays Sankh river's environmental flows using observed data, with MAR percentage decreasing from EMC A (47.1%) to EMC F (1%). Flows are lowest in December. Fig. 5 shows FDCs based on simulated discharge, with discharges declining from EMC "A" to EMC "F" during lean season with little fluctuation. Fig. 6 shows average monthly environmental flows from simulated SWAT data, with the smallest deviation between estimated and natural flows in EMC "A." Deviation increases from EMC "A" to EMC "F," indicating more flow alteration at lower management levels. MAR percentage declines from EMC "A" (39.5%) to EMC "F" (0.9%), with flows lowest in December. For EMC "A," observed e-flows are about 50% of a 435.04 cumec peak, while simulated e-flows are about 44% of a 455.04 cumec peak.

Environmental flow estimates derived from both observed and SWAT-simulated discharge data exhibit a consistent trend across EMCs. The simulated data indicate that the MAR percentage decreases steadily from EMC "A" to EMC "F," with EMC "A" having the highest allocation at 39.5% and EMC "F" the lowest at 0.9%. Similarly, results obtained from observed data follow the same pattern, with EMC "A" showing a MAR of 47.1% and EMC "F" showing the lowest at 1%. This close alignment of observed and simulated data demonstrates the SWAT model's capacity to estimate environmental flows, especially in data-scarce locations. Fig. 7 shows that the flow regime generated from SWAT-simulated data closely matches the pattern observed in discharge records. This high level of agreement confirms the SWAT model's ability to accurately replicate natural flow dynamics, which is essential for environmental flow estimation. The consistency between the two datasets validates the application of SWAT in regions with limited hydrological data and enhances the credibility of GEFC-derived environmental flow assessments.

To assess the accuracy of environmental flows estimated from SWAT-simulated discharges, a statistical comparison was conducted against observed values over the full calendar year, from January to December. Three key

metrics were employed: Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and the Pearson Correlation Coefficient (R^2), all based on monthly environmental flow estimates. The RMSE was calculated at 26.51 cumecs, reflecting the average deviation between simulated and observed flow values. The MAE, representing the average of absolute errors over the year, was 13.77 cumecs. A high Pearson correlation coefficient of 0.984 indicates a very strong positive relationship between observed and simulated flows, suggesting that the SWAT model

effectively captures seasonal flow variations in the Sankh River. These metrics fall within acceptable ranges for hydrological modeling and are noteworthy given the presence of extreme flow events, such as the simulated peak of 455.04 cumecs in March. The performance summary is presented in (Table 7), reinforcing the suitability of the SWAT-GEFC approach for monthly-scale environmental flow planning and assessment, particularly in regulated, data-constrained river basins such as the Sankh.

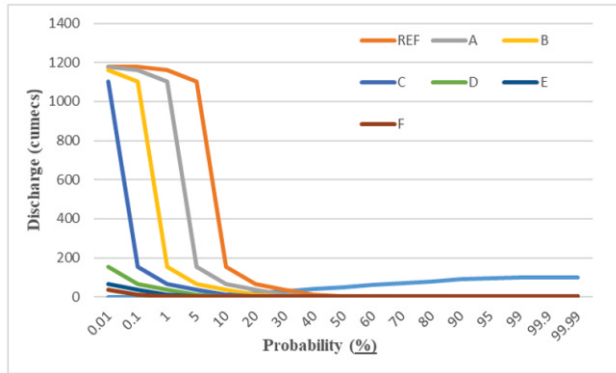


FIGURE 3 Flow Duration Curves (FDCs) for different Environmental Management Classes (EMCs) based on observed discharge data for the Sankh River

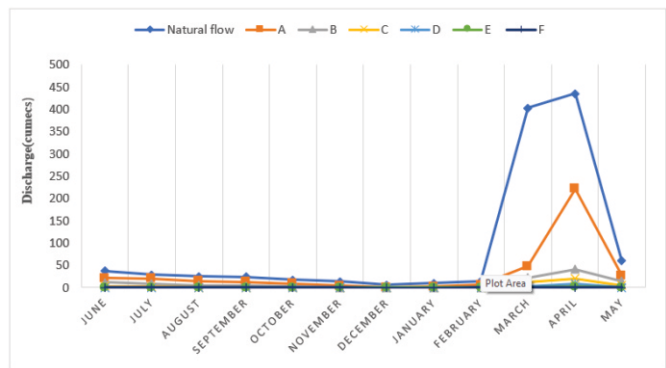


FIGURE 4 Estimated monthly environmental flows under different EMCs (A–F) using observed discharge data for the Sankh River

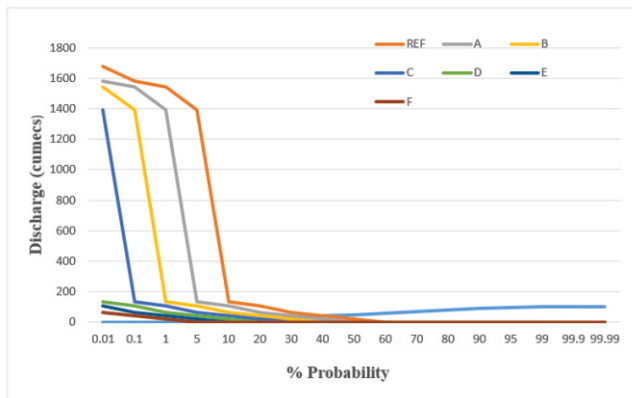


FIGURE 5 Flow Duration Curves (FDCs) for various EMCs based on SWAT-simulated discharge data for the Sankh River

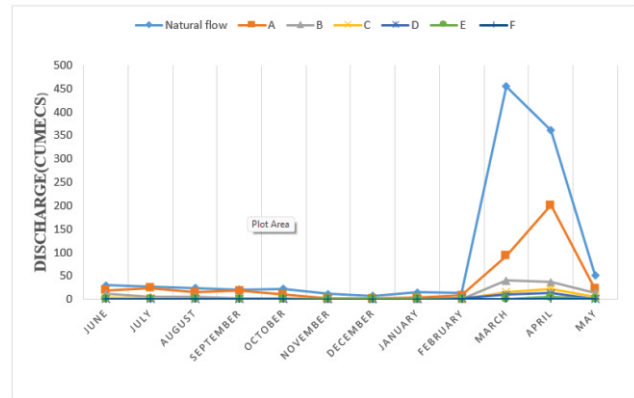


FIGURE 6 Estimated monthly environmental flows under different EMCs (A–F) using SWAT-simulated discharge data for the Sankh River

TABLE 7 Statistical comparison between observed and simulated environmental flows (January–December)

Statistical Parameter	Value
Root Mean Square Error (RMSE)	26.51 cumecs
Mean Absolute Error (MAE)	13.77 cumecs
Correlation Coefficient (R)	0.984 unitless

Establishing a scientifically grounded environmental flow regime is essential for ensuring the long-term health of river ecosystems. For the Sankh River, assessing environmental flows is vital to understanding its ecological dynamics. Environmental Management Classes (EMCs), which link ecological conditions to flow variability, serve as key indicators of ecosystem health (Sharma & Singh, 2024). In areas with limited ecological data, such as specific flow-depth needs or habitat thresholds for species, EMC categories "B" and "C" offer practical benchmarks to maintain ecological balance. Choosing these categories for

the Sankh River aims to balance ecological conservation with the basin's socio-economic needs. EMC "B" indicates a slightly altered ecology that supports biodiversity and near-natural functions, crucial during the monsoon and post-monsoon for the river's role as a habitat and migration route for aquatic species. Conversely, EMC "C" reflects a moderately modified state compatible with regulated river conditions and human activities like irrigation, reservoirs, and land use changes. This category preserves key ecosystem functions, although some sensitive species may be affected. Local observations and community accounts reveal native cyprinid species such as *Labeo rohita*, *Catla catla*, and *Bagarius bagarius*, which depend on seasonal hydrological cues for upstream migration and spawning. The IUCN Red List classifies *Bagarius bagarius* as Near Threatened, citing habitat fragmentation and declining river flows (IUCN, 2024). Reports from communities in Gumla and Simdega districts indicate that reduced dry-season flows over recent years have fragmented habitats, disrupting fish movement and aquatic diversity. EMC "B" maintains sufficient flow depths and velocities to support these migration and ecological processes, while EMC "C" provides a conservative flow range under current water use pressures. The states of Jharkhand and Odisha fall under identified regional conservation zones due to their high freshwater biodiversity and their inclusion in the Eastern Ghats–Chotanagpur dry deciduous ecoregion, which supports vulnerable and endemic species. EMCs "B" and "C" offer ecologically viable standards for maintaining ecosystem services while accommodating agricultural and domestic water needs. Their adoption aligns with India's environmental flow frameworks and policies, including the National Water Policy (2012), emphasizing maintaining flows in moderately impacted rivers. Thus, EMC "B" and "C" serve as ecological safeguards and practical flow management guidelines tailored to the Sankh River's hydrological and ecological setting.

Fig. 8 illustrates the recommended environmental flows for the Sankh River under EMC "B" and EMC "C," based on observed discharge data. The assessment shows seasonal variations, with flow minima in December (6.53 cumecs) and January (9.59 cumecs), likely due to less precipitation during winter. The highest flows occurred in March (403.06 cumecs) and April (435.04 cumecs), reflecting spring hydrological patterns. A minimum flow of 5.72 cumecs is recommended to protect the river's ecological functions, crucial for aquatic biodiversity, water quality, and ecosystem health. These e-flows align with India's 2012 National Water Policy, which emphasizes ecological flows in regulated rivers. They can be incorporated into operational schedules for major irrigation infrastructure like the Upper Sankh, Ramrekha, and Kansjore reservoirs, ensuring ecological releases in dry periods. They also support regulatory frameworks, assisting agencies such as MoEFCC and JSPCB in enforcing flow standards during environmental clearances or basin planning. Ecologically, this study provides a foundational benchmark for river health. The Sankh River sustains

migratory fish like *Labeo rohita*, *Catla catla*, and *Bagarius bagarius*, the latter listed as Near Threatened due to habitat fragmentation and flow changes. Community reports from Gumla and Simdega indicate declining dry-season flows have affected breeding and habitat connectivity. EMC "B" maintains the ecological depth and velocity needed for these species, while EMC "C" balances environmental needs with existing water withdrawals for agriculture and domestic use. These EMCs are suitable given the Sankh basin's location within the Eastern Ghats–Chotanagpur dry deciduous ecoregion, an area rich in freshwater biodiversity requiring conservation efforts. The chosen EMCs are based on ecological needs and regional water management realities. EMC "B" supports slightly altered river conditions, preserving dry-season flows critical for habitat, dissolved oxygen, and water quality during stressed months like December and January. It also sustains hydrological pulses that trigger migration and spawning for native fish, including *Labeo rohita*, *Catla catla*, and *Bagarius bagarius*. Maintaining natural flow variability is especially important for protecting habitats of Near Threatened species like *Bagarius bagarius*. EMC "C" offers a balanced level of protection by retaining core ecological functions while acknowledging existing abstractions and the presence of irrigation reservoirs such as Upper Sankh, Ramrekha, and Kansjore. This class allows for realistic implementation of environmental flows in a regulated river system while still ensuring minimum flow thresholds to maintain connectivity, support aquatic life, and avoid excessive habitat fragmentation.

Field interactions and local observations from communities in Gumla and Simdega districts also suggest that reduced dry-season flows have led to pool isolation, lower fish availability, and decreased water quality, highlighting the socio-ecological importance of maintaining adequate baseflows. The use of these classes aligns with India's National Water Policy (2012), which emphasizes ecological flow maintenance in regulated basins. This combined approach ensures that environmental flow targets are ecologically meaningful yet adaptable to on-ground hydrological and management constraints.

The study further endorses broader environmental governance efforts by providing a replicable scientific method for establishing e-flow regimes in other Indian rivers with similar regulatory and ecological environments. The validation PBIAS of −19.1% shows a tendency to systematically overestimate flows, potentially inflating GEFC-based e-flows, especially under low-flow EMCs, resulting in a more conservation-oriented approach. Nevertheless, the high NSE of 0.90, R^2 of 0.92, and the strong correlation between observed and simulated e-flows ($R = 0.984$), along with a non-significant mean difference (paired t-test $p = 0.702$, 95% CI −14.35 to 20.59 cumecs), support the overall reliability of the monthly e-flow patterns.

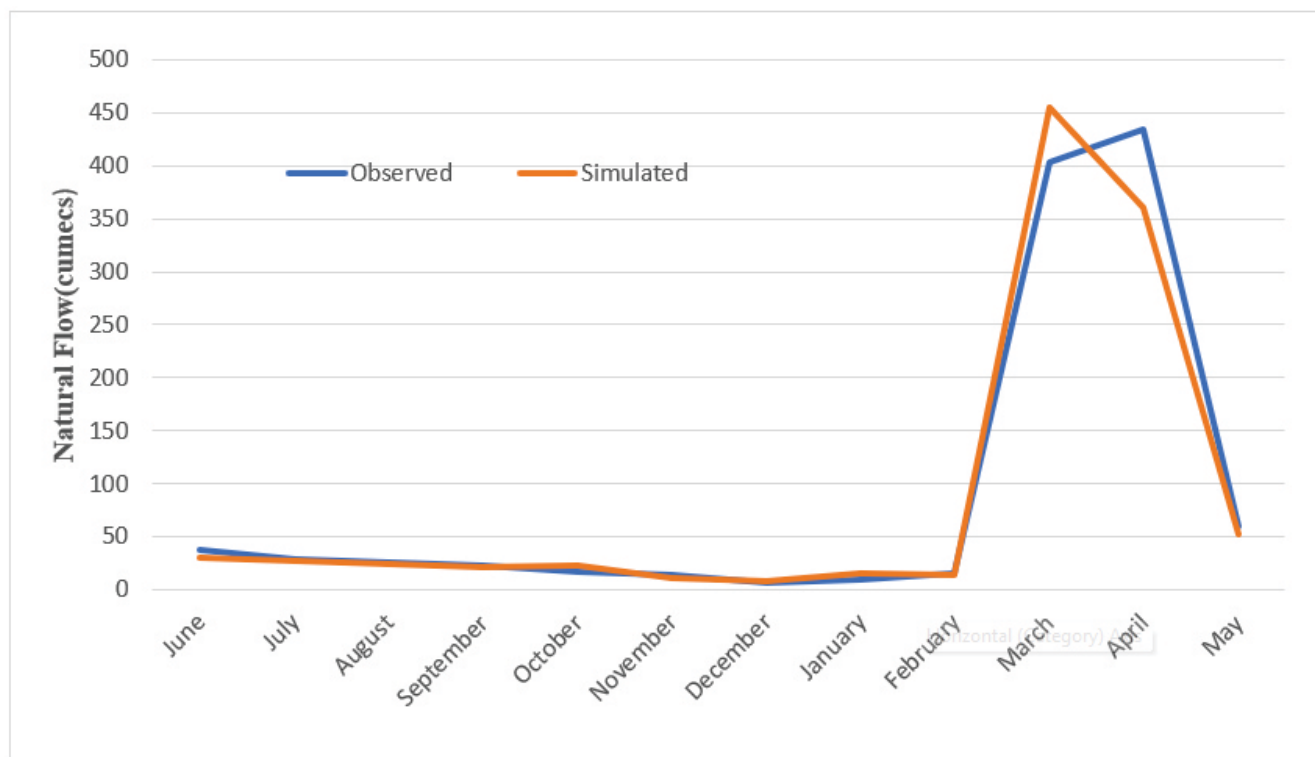


FIGURE 7 Comparison of natural flow regimes using observed discharge and SWAT-simulated discharge for the Sankh River

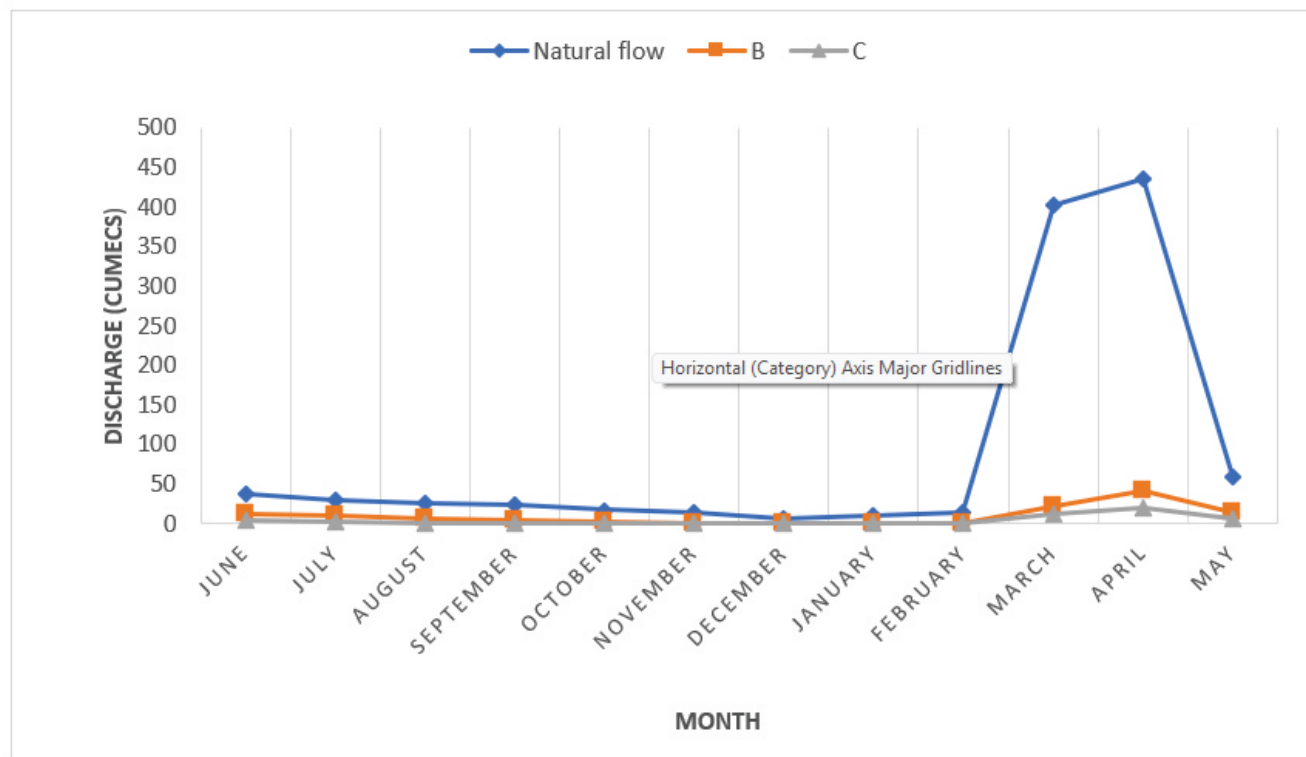


FIGURE 8 Environmental flows of Sankh river for EMC 'B' and EMC 'C'

4 | Limitations and Policy Recommendations

Despite the SWAT–GEFC framework's robustness, there are data and method limitations. NASA POWER meteorological data have uncertainty due to coarse resolution and potential bias in representing localized rainfall extremes, possibly underestimating high-intensity events affecting peak flows and sediment. Calibration with data from one station (Tilga) limits spatial representation and may mask local discrepancies, especially in heterogeneous catchments. Coarse-resolution DEM, soil, and land-use data can affect watershed features and hydrological process simulations at small scales. The environmental flow assessment relies mainly on hydrology without incorporating biological, ecological, or geomorphological data, and the lack of long-term ecological monitoring restricts validation of flow–ecology relationships and species-specific thresholds. Additionally, the model doesn't account for dynamic human activities like sand mining, reservoir rule changes, or groundwater use, which can influence low flows and ecological connectivity over time.

5 | CONCLUSIONS

An integrated SWAT–GEFC modeling framework for e-flow estimation in the Sankh River basin in Eastern India, a region that is both regulated and ecologically sensitive, was demonstrated through the successful application of this study. During both calibration and validation periods, the SWAT model showed high predictive performance with NSE and R² values exceeding 0.80. The statistical comparison of observed and simulated environmental flows indicated a strong correlation ($R = 0.984$), with low RMSE and MAE values. These results confirm the model's ability to simulate discharge and estimate e-flows in basins with limited data and human influences. The decline in Mean Annual Runoff (MAR) percentages from EMC 'A' to EMC 'F' was evident in both observed and simulated environmental flow estimates. The most ecologically sound condition (47.1% observed; 39.5% simulated) is EMC 'A', while critical degradation (1% observed; 0.9% simulated) corresponds to EMC 'F'. This study highlights December as the month with the lowest flow, suggesting that a minimum environmental flow of 5.72 cumecs is necessary to maintain ecological continuity. This threshold helps support aquatic species during dry seasons and sustains essential ecosystem functions such as nutrient cycling, fish migration, and water quality. The quantified e-flows under EMCs "B" and "C" are particularly important because they align with India's National Water Policy (2012), which emphasizes maintaining ecological flows in regulated rivers. In regions lacking continuous ecological or discharge data, the SWAT–GEFC approach provides a prototype for integrating hydrological simulation with policy development. Its applications extend beyond river ecology to reservoir operation, catchment restoration, and climate-resilient water planning. Future research on ecological indicators and climate variability will be crucial for refining environmental flow recommendations and promoting

sustainable water management amid anthropogenic and climate changes. These results affirm the model's robustness for discharge simulation in data-scarce basins, supporting its use in environmental flow estimation. Sustainable river management can be achieved by combining hydrological modeling with ecological considerations.

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CONFLICT OF INTEREST

Authors have no relevant financial interests or personal relationships to disclose.

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DATA AVAILABILITY STATEMENT

Data can be made available on request.

AUTHOR'S CONTRIBUTION

First author: Data collection, model set up and evaluation and analysis. Second author: Supervision, Drafting the manuscript.

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Frequency Analysis of Five Days Antecedent Rainfall for Different Seasons for Kohima (Nagaland)

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Continuous probability distribution function,
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5-day antecedent rainfall

ABSTRACT

In the present study, daily rainfall data recorded at Kohima for 26 years (1997-2022) were collected. Data were grouped by seasonal rainfall: monsoon, pre-monsoon, and post-monsoon. The 5-day total antecedent rainfall prior to the storm was calculated for three seasons and fitted to various probability distribution functions. The distribution with the lowest χ^2 value was declared the best fit function. Using the best fit probability distribution function, 05 days antecedent rainfall (mm) under different antecedent moisture conditions (AMCs) and seasons were calculated for different return periods. Only 15.56 % of the total number of 5 days of antecedent rainfall fall under AMC-II conditions. Therefore, of all recorded events, 60.05 per cent fall under AMC-I and 24.39 per cent under AMC-III, necessitating adjustment of the curve number from AMC-II to AMC-I or AMC-III, respectively, to reflect these proportions of cases. Results of the turning point test statistics fall within the 5% significance level for all seasons and AMC conditions, indicating that the data set could be considered random. Log normal and Normal probability distribution functions were found to be the best-fit probability distribution functions for AMC-I and AMC-III rainfall for the post-monsoon season, respectively. Extreme value-I probability distribution function was found to be the best fit for the pre-monsoon season rainfall of AMC-II and AMC-III, and the monsoon season rainfall of AMC-II. The log Pearson Type III probability distribution function was found to be the best fit for monsoon-season rainfall of AMC-I and for pre-monsoon-season rainfall of AMC-I. The gamma probability distribution function was found to be the best fit for post-monsoon season rainfall in AMC-II. Across all three seasons and AMCs, 5-day incident rainfall increased with increasing recurrence interval. The estimated values of 5-day antecedent rainfall (mm) under different AMCs and seasons at different recurrence intervals can be used to predict runoff in Kohima (Nagaland).

1 | INTRODUCTION

Abstractions such as interception, depression storage, and soil moisture decrease direct runoff from total storm rainfall. Due to their complexity and variability, many runoff models simplify these mechanisms (Dabral *et al.*, 2016). However, models often acknowledge that initial watershed moisture influences storm runoff, which is classified as Antecedent Moisture Conditions (AMC) based on recent rainfall. The AMC levels are: AMC I—dry soils with low runoff potential; AMC II—moderate moisture; AMC III—near saturation with high runoff potential. The AMC category is determined using 5-day antecedent rainfall totals. Specifically: for AMC I, the 5-day antecedent rainfall is less than 1.25 cm during the dormant season and less than 3.5 cm during the growing season; for AMC II, the 5-day antecedent rainfall ranges from 1.25–2.75 cm (dormant season) and 3.5–5.25 cm (growing season); for

AMC III, the 5-day antecedent rainfall exceeds 2.75 cm (dormant season) and 5.25 cm (growing season) (Murty & Jha, 2009).

When appropriate antecedent rainfall data are available, they can be used for runoff prediction. Hydrological frequency analysis estimates future antecedent rainfall using probability distributions. No single distribution is universally accepted; the best one accurately describes observed data. Estimating the probability of 5-day antecedent rainfall for each AMC class is crucial for runoff and hydrological models. Kumar and Kumar (1989) analyzed 26 years of rainfall data from Pant Nagar, finding only 10.96% in AMC-II, suggesting curve number adjustments to AMC-I (49.92%) or AMC-III (39.12%). Using various distributions, they estimated 5-day antecedent rainfall for AMC classes I, II, III across

recurrence intervals of 1.25, 2, 5, 10, 100 years. Kumar (1995) used 28 years of data from Pant Nagar for similar estimates. Sudhishri *et al.*, (1995) estimated averages across Odisha stations and created an ISO-AMC map. Tiwari *et al.*, (2006) showed antecedent moisture's impact on curve number and calculated AMCs. Dabral *et al.*, (2016) analyzed 26 years of rainfall at Doimukh, classifying events into AMC categories, with only 10.61% in AMC-II, using various distributions for 1- to 100-year return periods. Pandey *et al.*, (2019) employed a total of 55 single storm events selected between the years 1993 and 2012 for estimation. Antecedent moisture content (AMC) of the in Bhadokhar watershed, located in Gursarain block of Jhansi district, Uttar Pradesh by taking preceding five days rainfall for three conditions viz., AMC-I, AMC-II and AMC-III. It was observed that during the period, 33 rain storms were falling under AMC-I category.

Nagaland, a mountainous state in Northeast India, has Kohima as its capital, situated atop surrounding hills. The region receives about 1600 mm of annual rainfall from April to September. December is usually dry, while rainfall from January to March is minimal. However, no systematic study has been conducted on the frequency analysis of 5-day antecedent rainfall using probability distribution functions across different seasons and return periods for Kohima, Nagaland. Therefore, the present study aims to analyze 5-day antecedent rainfall and its statistical characteristics for the pre-monsoon, monsoon, and post-monsoon seasons, and to estimate 5-day antecedent rainfall for various return periods using suitable probability distribution functions for each season.

2 | MATERIALS AND METHODS

2.1 | Study Area and Data

For the present study, 26 years of daily rainfall data (1997–2022) recorded at Kohima (25°40'N, 94°07'E) (Fig. 1) were analyzed. The data were categorized into three seasons: pre-monsoon (March–May), monsoon (June–October), and post-monsoon (November–February). For each storm event, the 5-day total antecedent rainfall was calculated for all three seasons. In cases where one or two dry days occurred within the 5-day period, rainfall from the remaining four or three days was summed to estimate the 5-day antecedent rainfall. Monsoon and pre-monsoon seasons are the major growing seasons for crops, whereas post-monsoon includes winter, which is the dormant season in north-east India. Using the criteria given in Table 1, antecedent rainfall was classified into AMC-I, AMC-II, and AMC-III categories for the three seasons. The number of events falling under each AMC class for different seasons was also determined.

2.2 | Statistical Analysis of Data

Mean, standard deviation, coefficient of variation, and coefficient of skewness were calculated for the 5 days of antecedent rainfall for AMC-I, AMC-II and AMC-III conditions using the formulae below.

HIGHLIGHTS

- Study is focussed on frequency analysis of five days antecedent rainfall for different seasons for Kohima (Nagaland).
- Across all seasons and AMC classes, the estimated 5-day antecedent rainfall values increased with increasing recurrence intervals.
- These estimates of rainfall under various AMCs and seasons at different recurrence intervals can serve as important inputs for runoff prediction for Kohima (Nagaland).

2.2.1 | Mean

Mean represents measures of central tendency. The arithmetic mean is given by

$$\bar{X} = \frac{1}{N} \sum_{i=1}^N X_i \quad (1)$$

where, X = mean, X_i = variate and N = total number of observations

2.2.2 | Standard Deviation

This parameter, as a measure of variability, is most adaptable to statistical analysis.

It is computed by

$$S = \sqrt{\frac{\sum_{i=1}^N (X_i - \bar{X})^2}{(N-1)}} \quad (2)$$

Where, S = standard deviation

2.2.3 | Coefficient of Variation

This is a dimensionless dispersion parameter usually expressed as a percent. It is given by

$$CV = \frac{S}{\bar{X}} \quad (3)$$

Where, CV = coefficient of variation

2.2.4 | Coefficient of Skewness

The coefficient of skewness was determined for each set of data from the formula given below:

$$C_s = \frac{N \cdot M_3}{(N-1)(N-2) S^3} \quad (4)$$

Where, C_s = coefficient of Skewness

$$M_3 = \frac{1}{N} \sum_{i=1}^N (X_i - \bar{X})^3 \quad (5)$$

2.3 | Randomness Checking of the 5-Day Antecedent Rainfall Data

To assess the randomness of the 05-day antecedent rainfall data, the turning point test method was used. This test determines the number of turning points in the data. A turning point occurs when x_i is either greater than both the preceding and succeeding values or less than both. Therefore, any of the conditions for variate $x_{i-1} < x_i > x_{i+1}$ or

$x_{i-1} > x_i < x_{i+1}$ indicate a turning point. The procedure for the test is outlined as follows:

1. The data were arranged in order of their occurrence.
2. Either of the conditions $x_{i-1} < x_i > x_{i+1}$ or $x_{i-1} > x_i < x_{i+1}$ was applied to ascertain how many turning points were in the series.
3. Let the total number of turning points be p .
4. Expected number of turning points in the series is $E(p) = \frac{2(N-2)}{3}$, where N is the total number of data.
5. Variance of p is $Var(P) = \frac{(16N-29)}{90}$.
6. P can be expressed as a standard normal form $Z = \frac{(p-E(p))}{\sqrt{Var(p)}}$

If the calculated value of z is within the critical range of ± 1.96 for 5% level of significance, the hypothesis of randomness of data was accepted.

TABLE 1 Rainfall limits for estimating antecedent moisture condition (AMC)

AMC	5 days antecedent rainfall(mm)	
	Dormant Season	Growing Season
I	Less than 12.5	Less than 35
II	12.5 to 27.5	35 to 52.5
III	Over 27.5	Over 52.5

(Source: Murty and Jha,2009)

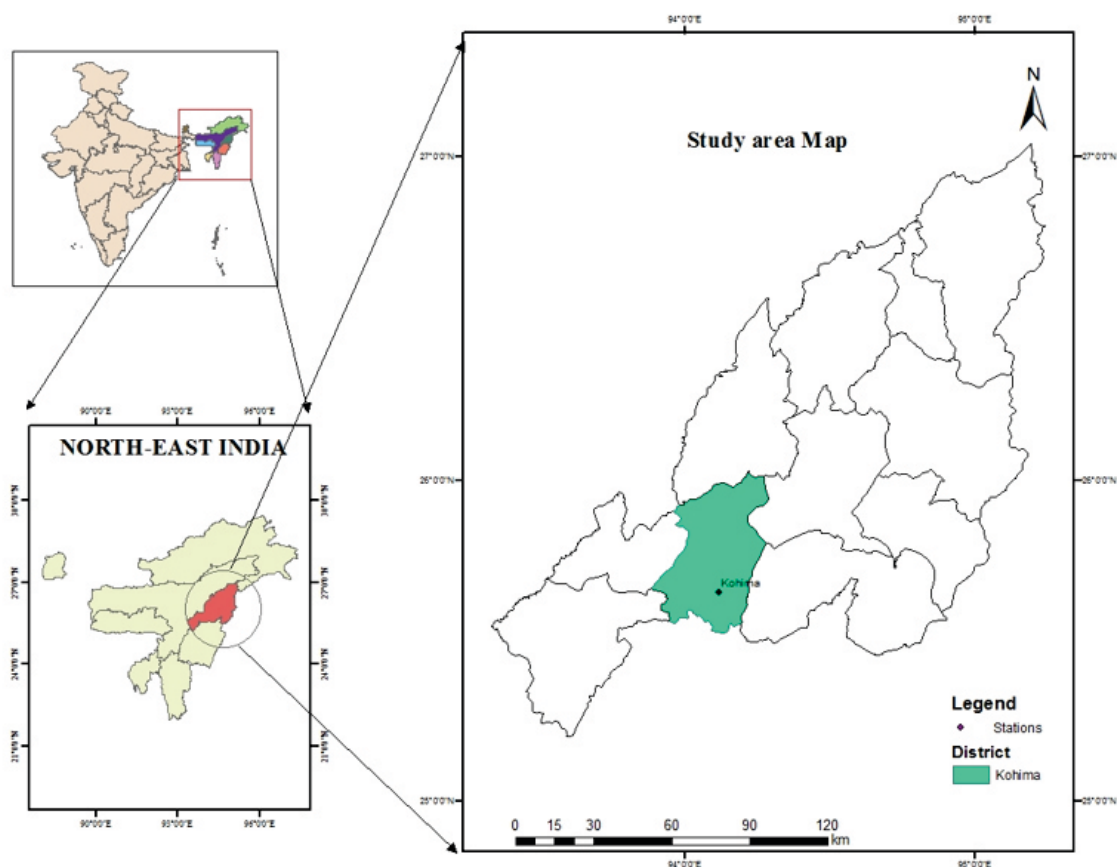


FIGURE 1 Location map of the Study area

2.4 | Fitting of Continuous Probability Distribution Functions

To evaluate the probabilistic behaviour of 5-day antecedent rainfall in Kohima, five continuous probability distribution functions were fitted and compared for their suitability. The distributions considered in this study were: i) Normal distribution (ND), ii) Log-Normal distribution (LND), iii) Gamma distribution (GD), iv) Log-Pearson Type III distribution (LPT-III), v) Extreme Value Type-I distribution (EVT-I). These distributions were selected based on their common application in hydrological frequency analysis.

The mathematical expressions and properties of each distribution are summarized in Dabral *et al.* (2016) and Dabral (2025).

2.5 | Goodness of Fit of the Probability Distribution Functions

To assess the goodness of fit of the selected probability distribution functions, a comparison between the theoretical and observed relative cumulative frequencies was conducted using the Chi-square (χ^2) test. The χ^2 distribution functions are tabulated in many statistics texts. In the χ^2 test

$v=m-p-1$, where m = number of intervals, p = number of parameters used in fitting the proposed distribution. The null hypothesis H_0 assumes that the chosen distribution adequately fits the observed data. The hypothesis is rejected if the calculated χ^2 exceeds the critical value χ^2 from the Chi-square distribution at the chosen significance level α . Otherwise, the fit is considered acceptable. A common confidence level used is 95% (i.e., $\alpha=0.05$).

2.6 | Frequency Analysis Using Frequency Factors

Chow (1951) has shown that many frequency analyses can be reduced to the following form:

$$X_T = \bar{X} (1 + CV \cdot K_T) \quad (6)$$

Where CV is the coefficient of variation, K_T is the frequency factor, $\bar{X}$ is the mean value of X , and X_T denotes magnitude of the event corresponding to a return period T .

For both ND and LND, the frequency factor can be expressed using the following equation (Chow, 1953):

$$K_T = \frac{(X_T - \mu)}{\sigma} \quad (7)$$

Where, X_T is the magnitude of the hydrological event, K_T is the frequency factor, μ is the sample mean of the sample, and σ is the sample standard deviation of the sample. This expression is equivalent to the standard normal variable z . The value of z corresponding to an exceedance probability p (where $p = 1/T$) can be obtained by first calculating an intermediate variable 'w':

where,

$$w = \left[\ln \left(\frac{1}{p^2} \right) \right]^{1/2} \quad (0 < p \leq 0.5) \quad (8)$$

Then, calculating z using the equation

$$z = w - \left[\frac{(2.515517 + 0.802853w + 0.010328w^2)}{(1 + 1.432788w + 0.189269w^2 + 0.001308w^3)} \right] \quad (9)$$

When $p > 0.5$, $1 - p$ is used in place of p in Equation (8), and the value of z is computed by Equation (9) is assigned a negative sign. For the EVT-I, Chow (1953) derived the corresponding expression:

$$K_T = -(\sqrt{6}) / \pi [0.5772 + \ln \{ \ln(\frac{T}{T-1}) \}] \quad (10)$$

Where T is the return period (in years).

For the Log-Pearson Type III distribution, the first step is to take the base-10 logarithms of the hydrological data. The mean, standard deviation, and coefficient of skewness are then computed from the logarithmic values. The frequency factor depends on the return period (T) and the coefficient of skewness, C_s . When $C_s = 0$, the frequency factor reduces to the standard normal variable z . However, when $C_s \neq 0$, K_T is approximated using the expression proposed by Kite (1977):

$$K_T = z + (z^2 - 1) k + \frac{1}{3} (z^3 - 6z) k^2 - (z^2 - 1) k^3 + z k^4 + \frac{1}{3} k^5 \quad (11)$$

For the Gamma probability distribution function, the λ parameters ($=$ mean (S.D.)⁻²) β , ($=$ (mean)² (S.D.)⁻²) and ν ($=2\lambda\beta$) were computed following the procedure suggested by Hann (1995). For a specified probability level, the value of χ^2 corresponding to the appropriate ν was obtained from

standard χ^2 tables. The expected rainfall at the given probability was calculated using the following relationship (Hann, 1995):

$$Xp = \chi^2 / (2 \times \lambda) \quad (12)$$

Frequency analysis was performed for the return periods listed in (Table 2).

T (Return Period, Years)	1.053	1.25	2	10	20	25	50	100
	95	80	50	10	5	4	2	1
P (Probability level in %)								

TABLE 2 Return period and probability level

3 | RESULTS AND DISCUSSION

3.1 | Five-Day Antecedent Rainfall Counts and Associated Statistical Parameters Across Seasons and Conditions

The distribution of 5-day antecedent rainfall under different conditions and seasons is presented in (Table 3). It is observed that only 15.56% of the total instances fall under AMC-II conditions. Consequently, of the total 5-day antecedent rainfall events, 60.05% fall under AMC-I and 24.39% fall under AMC-III. Since standard runoff estimation procedures are based on AMC-II, the curve number must be adjusted from AMC-II to AMC-I or AMC-III for these respective proportions of events. Standard conversion tables provide the necessary factors for this adjustment. Standard conversion tables are available to provide the necessary factors for adjusting the curve number from AMC-II to AMC-I and AMC-III.

TABLE 3 Numbers of 5-day antecedent rainfall under different conditions and seasons

Season	AMC-I	AMC-II	AMC-III	Total Numbers
Pre-monsoon	298	33	35	366 (28.62%)
Monsoon	347	137	263	747 (58.40%)
Post-Monsoon	123	29	14	166 (12.98%)
Total numbers	768 (60.05%)	199 (15.56%)	312 (24.39%)	1279

Dabral *et. al* (2016) analyzed 26 years (1988-2013) of daily rainfall data recorded at Doimukh (Itanagar), Arunachal Pradesh. They computed 5-day total antecedent rainfall preceding each storm for three different seasons and classified rainfall into AMC-I, AMC-II and AMC-III categories. Their analysis showed that only 10.61% of all 5 days antecedent rainfall values across the seasons fell within the AMC-II category.

3.2 | Statistical Parameters of 5-day Antecedent Rainfall Under Different Conditions and Seasons

Statistical parameters of 5 days of antecedent rainfall under different conditions and seasons are presented in (Table 4).

During the pre-monsoon season, the mean, standard deviation, coefficient of variation, and coefficient of skewness under AMC-I, II, and III ranged from 13.09 mm to 45.48 mm, 4.75 to 20.99, 10.44% to 74.71%, and -0.07 to 1.45, respectively. In the monsoon season, the mean, standard deviation, coefficient of variation, and coefficient of skewness for AMC-I, AMC-II, and AMC-III were observed to range from 16.94 mm to 83.22 mm, 9.87 to 29.63, 15.47% to 58.26%, and -2.37 to 2.07, respectively. During the post-monsoon season, the corresponding mean, standard deviation, coefficient of variation, and coefficient of skewness under AMC-I, II, and III were found to be between 4.14 mm and 54.09 mm, 3.29 mm and 18.9 mm, 22.32% to 79.49%, and 0.49 to 0.95, respectively.

TABLE 4 Statistical parameters of 5 days antecedent rainfall under different conditions

S.No	Parameter	Pre-monsoon			Monsoon			Post-monsoon		
		AMC-I	AMC-II	AMC-III	AMC-I	AMC-II	AMC-III	AMC-I	AMC-II	AMC-III
1	Mean (mm)	13.09	45.48	41.65	16.94	44.15	83.22	4.14	17.56	54.09
2	Standard deviation (mm)	9.78	4.75	20.99	9.87	6.83	29.36	3.29	3.92	18.90
3	Coefficient of variation (%)	74.71	10.44	50.40	58.26	15.47	35.28	79.49	22.32	34.94
4	Coefficient of skewness	0.54	-0.07	1.45	0.01	-2.37	2.07	0.95	0.68	0.49

3.3 | Turning Point Test for Assessing the Randomness of Data

The turning point test was applied to assess the dataset's randomness. A null hypothesis of randomness was formulated and examined using the corresponding test statistic, with the results presented in (Table 5). For all

seasons and AMC categories, the computed test statistics fell within the critical limits at the 5% significance level. Hence, the 5-day antecedent rainfall data under different AMC classes and seasonal conditions can be regarded as random.

TABLE 5 Result of turning point test

Season	AMC Class	P	N	E (P)	Var (P)	Z	Whether data is Random or not ?
Pre-Monsoon	AMC-I	198	298	197.33	52.65	0.09	Random
	AMC-II	23	33	20.66	5.54	0.99	Random
	AMC-III	23	35	22	5.90	0.41	Random
Monsoon	AMC-I	231	347	230	61.37	0.13	Random
	AMC-II	96	137	90	24.03	1.22	Random
	AMC-III	181	263	174	46.43	1.03	Random
Post-Monsoon	AMC-I	72	123	80.67	21.54	-1.87	Random
	AMC-II	21	29	18	4.83	1.36	Random
	AMC-III	9	14	8	2.17	0.68	Random

Note : P= number of turning points, N= total number of data, E(P)= Expected number of turning points in the series, Var(P)= Variance of P, Z= test statistics

3.4 | Fitting and Evaluation of Different Probability Distribution Functions

Five-day antecedent rainfall values (mm) for the pre-monsoon, monsoon, and post-monsoon seasons under AMC-I, AMC-II, and AMC-III were used in their original form and fitted to various probability distribution functions, namely the ND, LND, GD, LPT-III, and EVT-I. The computed χ^2 statistics for each fitted distribution were then compared with the corresponding tabulated χ^2 values at the 5% significance level.

For the pre-monsoon season, the rainfall data for AMC-II and AMC-III were found to be significantly fitted by all the probability distribution functions. Based on the minimum χ^2 value, the EVT-I distribution emerged as the best-fitting model for both AMC-II and AMC-III rainfall during the pre-monsoon season. For AMC-I rainfall, the LPT-III distribution provided a statistically significant fit (Table 6).

For monsoon season, for AMC-I and AMC-II, LPT-III and EVT-I probability distribution function significantly

fitted respectively. For AMC-III rainfall, LPT-III and EVT-I probability distribution function significantly fitted but EVT-I probability distribution function was the best fit based upon the lowest value of χ^2 (Table 6).

For Post Monsoon season, for the rainfall of AMC-I, II and III all selected probability distribution functions fitted significantly. The best fit functions for AMC-I, II and III rainfalls were found to be Log normal, Gamma and Normal probability distribution functions respectively based on lowest value of χ^2 (Table 6).

Dabral *et al.* (2016) conducted a frequency analysis of 5-day total antecedent rainfall for three seasons—pre-monsoon (March to May), monsoon (June to October), and post-monsoon (November to February) for Doimukh, Arunachal Pradesh, India. They fitted several probability distribution functions to the data and reported that all the selected distributions, namely ND, LND GD, LPT-III, and EVT-I, provided statistically significant fits for the 5-day antecedent rainfall across all three seasons.

TABLE 6 Chi-square value for different probability distribution functions

Season	AMC Class	Normal		Log Normal		Gamma		Log-Pearson III		Extreme Value-I		Class interval (m)
		Comp. χ^2	Tabu χ^2	Comp. χ^2	Tabu χ^2	Comp. χ^2	Tabu χ^2	Comp. χ^2	Tabu χ^2	Comp. χ^2	Tabu χ^2	
Pre-Monsoon	AMC-I	36.30	14.10	21.10	14.10	42.90	14.10	6.50*#	14.10	25.20	14.10	10
	AMC-II	2.00*	5.99	3.41*	5.99	2.11*	5.99	2.03*	5.99	1.73*#	5.99	5
	AMC-III	2.35*	5.99	3.83*	5.99	2.73*	5.99	3.20*	5.99	1.75*#	5.99	5
Monsoon	AMC-I	23.85	14.10	40.06	14.10	57.76	14.10	14.00*#	14.10	15.10	14.10	10
	AMC-II	17.62	14.10	15.9	14.10	17.20	14.10	17.60	14.10	13.34*#	14.10	10
	AMC-III	34.12	14.10	22.2	14.10	29.10	14.10	5.60*#	14.10	6.93*	14.10	10
Post-Monsoon	AMC-I	13.62*	12.6	3.90*#	12.6	14.00*	12.6	4.43*	12.6	12.14*	12.6	9
	AMC-II	2.66*	5.99	1.56*	5.99	0.96*#	5.99	5.50*	5.99	5.46*	5.99	5
	AMC-III	0.15*#	3.84	0.51*	3.84	0.35*	3.84	0.40*	3.84	0.25*	3.84	4

Best fit function, *Significant at 5 % level

3.5 | Estimation of 5 days Antecedent Rainfall (mm) Under Different AMC and Season at Different AMC Season at Different Recurrence Intervals

LND and ND were found to be best fit probability distribution function for AMC-I and III rainfall for post-monsoon season and (Table 7) presents the values KT for various return periods.

EVT-I probability distribution function was found the best fit for the Pre -monsoon season rainfall of AMC- II and AMC- III (Pre-monsoon season) and Monsoon season rainfall of AMC-II (section 3.4) and (Table 7) presents the values of K_T at various return periods.

LPT-III probability distribution function was found the best fit for monsoon season rainfall of AMC-I, III and Pre-monsoon season rainfall of AMC-I and (Table7) presents the values of K_T for various return periods.

Gamma probability distribution function was found best fit function for post- monsoon season rainfall of AMC-II and (Table 8) presents the value of χ^2 and other parameters at various return periods.

Using the equation 6, values of K_T and other parameter (χ^2) (Table7 and Table 8); 5 days antecedent rainfall (mm) under different AMC and seasons at different recurrence intervals were estimated and presented in (Table 9). It may be noted that for all three seasons and across all AMC classes, the estimated 5-day antecedent rainfall values increased consistently with an increase in the recurrence interval. These estimated antecedent rainfall values under different AMCs and seasons at various recurrence intervals can serve as useful inputs for runoff prediction for Kohima (Nagaland). The findings of the present study differ from those of Dabral *et al.* (2016), who conducted a similar study for Doimukh (Arunachal Pradesh).

TABLE 7 Values of K_r at various return periods for ND, LND and LPT-III

Return Period(T), years	Probability	K_r (Frequency Factor)				
		ND and LND	EVT - 1	LPT-III		
				Pre-Monsoon, AMC-I	Monsoon, AMC-I	Monsoon, AMC-III
1.053	0.95	-1.65	-1.04	-1.88	-2.84	-1.31
1.25	-0.84	-0.84	-0.82	-0.75	-0.60	-0.85
2	0.50	-0.0006	-0.16	0.17	0.25	-0.17
10	0.10	1.29	1.31	1.12	0.99	1.34
20	0.05	1.65	1.87	1.30	1.00	1.88
25	0.04	1.75	2.05	1.35	1.12	2.05
50	0.02	2.05	2.59	1.47	1.17	2.54
100	0.01	2.33	3.14	1.57	1.97	3.04

TABLE 8 Values of χ^2 ($v=40$) quantile for X_p estimation and other parameters at various return periods for Gamma probability distribution function (post-Monsoon season rainfall for AMC-II)

T (years)	1.053	1.25	2	10	20	25	50	100
p	0.95	0.8	0.5	0.1	0.05	0.04	0.02	0.01
$\chi^2(v=40)$ quantile	5.8	21	22	39	42	44	46	48

Mean=17.6, SD=3.92, $\lambda = 1.15$, $\beta = 20.16$ and $v = 40$

TABLE 9 Five days antecedent rainfall (mm) under different AMC and season at different recurrence intervals

Season	Condition	5 days antecedent rainfall(mm) at different recurrence interval (Years)							
		1.053	1.25	2	10	20	25	50	100
Pre-Monsoon	AMC-I	1.1	3.7	10.3	29.5	36.2	38.2	43.6	48.6
	AMC-II	40.6	41.6	44.7	51.7	54.3	55.2	57.8	60.4
	AMC-III	50.0	54.5	68.2	99.2	110.9	114.6	126.1	137.6
Monsoon	AMC-I	0.8	6.9	15.8	33.1	35.8	37.15	39.8	40.2
	AMC-II	65.6	38.55	43.04	53.11	56.91	58.13	61.87	65.62
	AMC-III	53.6	61.6	75.4	118.0	138.5	145.6	168.4	195.8
Post-Monsoon	AMC-I	0.6	1.27	2.82	9.50	13.35	14.77	19.45	25.35
	AMC-II	2.5	9.1	9.6	17.0	18.3	19.1	20.0	20.9
	AMC-III	23	38.2	54.1	78.4	85.2	85.6	92.8	98.9

4 | CONCLUSIONS

The predominance of AMC-I conditions (60.05%) over AMC-II (15.56%) at Kohima indicates that the watershed is dry for a substantial portion of the year, implying that direct application of standard AMC-II-based curve numbers would significantly overestimate runoff. Routine adjustment of curve numbers is therefore essential for reliable hydrological design in this region. The randomness of 5-day antecedent rainfall data across all seasons and AMC categories confirms the validity of applying classical frequency analysis techniques to this dataset, lending statistical credibility to the probability-based estimates derived in this study.

No single probability distribution function adequately describes antecedent rainfall behaviour across all seasons and moisture conditions at Kohima. This underscores the necessity of season- and AMC-specific distribution fitting

rather than adopting a uniform distribution for regional hydrological analysis. The season- and AMC-specific antecedent rainfall estimates at return periods up to 100 years fill a critical data gap for Kohima, Nagaland, and can be directly integrated into SCS curve number-based runoff models, watershed management plans, and hydraulic infrastructure design for the region.

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CONFLICT OF INTEREST

The contributing authors have driven the manuscript and the study in unison hence no conflict of interest exists.

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DATA AVAILABILITY STATEMENT

The authors confirm that data supporting the results of the study is available within the manuscript.

AUTHOR'S CONTRIBUTIONS

All authors equally contributed to preparing the manuscript and data analysis.

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Spatial Patterns of Soil Organic Carbon in South Delhi District: A Multi-Land Use Baseline Assessment

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ABSTRACT

Soil organic carbon (SOC) is a fundamental component of soil health and plays a critical role in climate regulation and ecosystem functioning. In rapidly urbanizing regions, spatial variation in SOC reflects complex land use patterns, yet spatially explicit assessments across diverse urban land uses remain limited. This study characterized the spatial distribution of SOC and associated soil physicochemical properties across five major land-use and land-cover (LULC) types in South Delhi District, India. Soil samples were collected from 98 locations representing agriculture, forest, scrub forest, built-up, and wasteland areas during 2021 and 2022. At each location, samples were obtained from three depth intervals (0–10, 10–20, and 20–30 cm) and analyzed for SOC, bulk density, moisture content, pH, electrical conductivity, water holding capacity, porosity, and particle density. Spatial patterns of SOC were assessed using Empirical Bayesian Kriging (EBK). SOC concentrations varied significantly across LULC types, with forest soils highest (0.62–0.66% at 0–10 cm) and wasteland soils lowest (0.15–0.17% at 0–10 cm, dropping to 0.06–0.08% at 20–30 cm). Built-up areas had similar low levels. SOC decreased with depth across all land uses, with 60–70% in the surface layer. SOC correlated strongly with bulk density, porosity, and water retention. EBK mapping revealed SOC-rich zones in forests and depleted zones in urban and degraded lands, with good validation. This study sets a baseline for SOC in South Delhi, highlighting hotspots and depleted areas for conservation. The spatial patterns suggest stability over two years. Limitations include uneven sampling, short duration, and lack of vegetation and land management data. Future work should include long-term monitoring, vegetation, soil texture, and SOC fractionation to better understand carbon dynamics.

1 | INTRODUCTION

Soils are a major terrestrial carbon reservoir, holding nearly twice as much carbon as the atmosphere and more than above-ground vegetation (Batjes, 1996; Onitl & Schulte, 2012). Soil organic carbon (SOC) is crucial for soil health, affecting structure, nutrients, water retention, and biological activity. Because SOC links closely to atmospheric carbon dioxide through biological and chemical processes, small changes in soil carbon stocks can influence the broader carbon cycle and climate (Lal, 2021). Land use and cover (LULC) changes significantly affect SOC (Singh *et al.*, 2019); converting natural vegetation to farmland or urban areas often leads to SOC loss from reduced organic inputs, soil disturbance, and increased decomposition. Globally, deforestation, agriculture, and urbanization have led to soil carbon loss (Lal, 2021), while vegetation cover and limited soil disturbance in forests and scrublands tend to preserve or boost SOC through litter and root inputs (Lupi *et al.*, 2021). Climate variability influences SOC by affecting decomposition and organic matter turnover, with rising temperatures and altered rainfall accelerating microbial

activity, especially in semi-arid regions (Wiesmeier *et al.*, 2019). Studies from India show land systems with perennial vegetation are more resilient to climate-driven SOC loss than intensive annual cropping (Paramesha *et al.*, 2025). Interactions between land use, climate, and soil make SOC dynamics complex in urban areas. To address this gap, the present study was guided to explore:

- How does soil organic carbon (SOC) vary across major land use/cover types and soil depths in South Delhi?
- What are the key relationships between SOC and soil physico-chemical properties such as bulk density, porosity, water holding capacity, pH, and electrical conductivity?
- What is the spatial distribution pattern of SOC across the study area, and which zones represent hotspots or depleted areas under different land use/cover types?

2 | MATERIALS AND METHODS

2.1 | Study Area

South Delhi District is one of the eleven administrative divisions of the National Capital Territory (NCT) of Delhi, India (Fig.1). Geographically, it lies between 28°22'N

and 28°45'N latitude and 77°00'E and 77°15'E longitude, occupying the southern segment of the city. The district spans approximately 247 square kilometres, accounting for about 16.65% of the total area of the NCT of Delhi (Government of NCT of Delhi, 2024). South Delhi presents a diverse mosaic of land uses, comprising planned residential colonies, urban villages, agricultural lands, forest patches, and major institutional zones.

Climatically, the district is in the semi-arid zone, with extreme seasonal changes: summer temperatures often go over 44°C and winter temperatures fall below 4°C. The

HIGHLIGHTS

- Significant spatial heterogeneity in SOC distribution across South Delhi (0.06–0.66%) was successfully captured using Empirical Bayesian Kriging with high accuracy.
- Land use type explained >80% of SOC variance, while soil depth accounted for an additional 12–13%.
- Forest soils maintained 2–4 times higher SOC than degraded land uses across all depth intervals.
- SOC showed consistent associations with soil properties (bulk density, porosity, pH, EC).

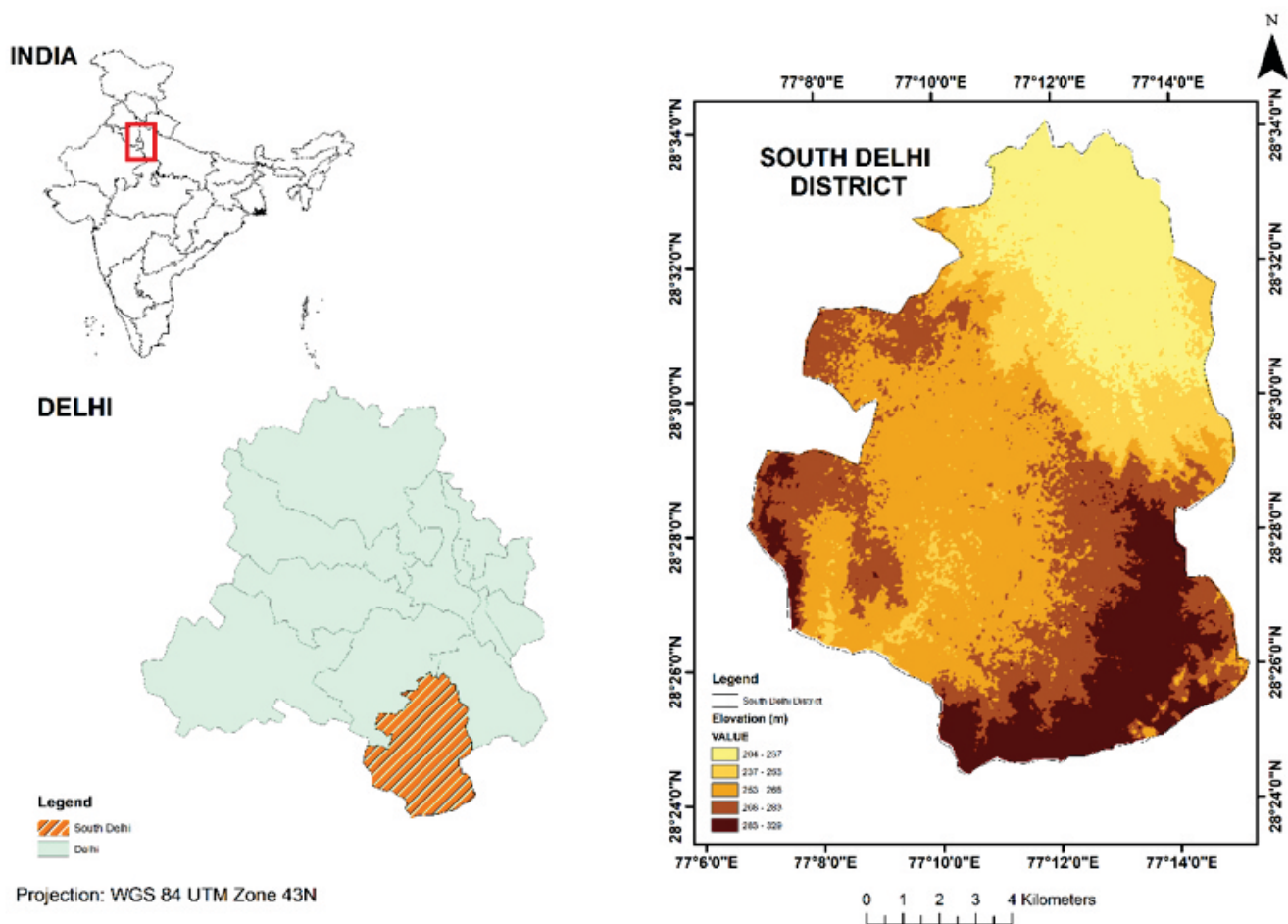


FIGURE 1 Location and topographic setting of South Delhi District showing its position within India and the National Capital Territory of Delhi

region gets about 790 mm of average annual rainfall, mostly during the monsoon season (IMD, 2023). Due to its complex LULC patterns and increasing environmental pressures, South Delhi becomes a key area for studying urban ecological dynamics, resource management issues, and ways to achieve sustainable development within the growing urban landscape.

2.2 | Soil Analysis

Soil sampling was conducted across five major land use/cover (LULC) types: agriculture, forest, scrub forest, built-up, and wasteland. A total of 98 sampling locations

were chosen using a stratified approach to ensure representation of each LULC category, while also considering accessibility constraints in forested and built-up areas. Forest and scrub forest sampling sites were limited to their fixed spatial extents, whereas agricultural sites were randomly selected from accessible fields. Wasteland and built-up locations were chosen based on field accessibility and land use characteristics. At each sampling site, a soil pit was dug, and samples were taken from three depth ranges: 0–10 cm, 10–20 cm, and 20–30 cm. Sampling occurred during similar periods in 2021 and 2022, with the same locations revisited using handheld GPS to ensure spatial

consistency. Visible plant residues, roots, and surface litter were removed before processing the samples. The samples were georeferenced, transported to the lab, and stored at 4 °C until analysis. They were air-dried, gently ground with a mortar and pestle, and passed through a 2 mm sieve for laboratory analysis. The spatial distribution of sampling locations is shown in (Fig. 2).

Physical and chemical soil properties were analyzed using standard protocols. Bulk density was determined by collecting undisturbed samples in metal cores and calculated with the core method (Blake & Hartge, 1986). Water holding capacity (WHC) was assessed gravimetrically after saturation and drainage procedures (Piper, 1945). Soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil-to-water suspension with a calibrated pH meter and EC meter, respectively (Estefan *et al.*, 2013). Particle density was determined via the pycnometer method (Bandyopadhyay, 2012), and porosity was calculated using bulk and particle density values (Estefan *et al.*, 2013). Soil moisture content was measured by oven-drying soil samples at 105°C until reaching a constant weight (Estefan *et al.*, 2013). Organic carbon was estimated using the Walkley-Black wet oxidation method, with appropriate blanks and standards to ensure data quality (Walkley & Black, 1934; Lal, 2021). All laboratory analyses were performed in triplicate to enhance accuracy.

2.3 | Statistical Analysis

Data were analyzed using descriptive statistics and inferential tests to evaluate differences in soil organic carbon (SOC) and related soil properties across land use/cover types and soil depths. One-way analysis of variance (ANOVA) tested differences among LULC categories and soil depths, followed by Tukey's HSD test for pairwise comparisons at $p < 0.05$. Before conducting ANOVA, the assumptions of normality and homogeneity of variances were checked using the Shapiro–Wilk test and Levene's test, respectively. Since these assumptions were mostly met, parametric ANOVA was deemed appropriate. Pearson's correlation analysis examined relationships between SOC and soil physicochemical properties, such as bulk density, porosity, water-holding capacity, electrical conductivity, and pH. All statistical analyses were performed using R software (version 4.5.1) and PAST (version 5.1).

2.4 | Spatial Analysis

Spatial analysis was carried out to study the distribution and variability of SOC across the South Delhi District. The geographic coordinates of all sampling sites were projected into the WGS 1984 UTM Zone 43N coordinate system to ensure spatial accuracy. Empirical Bayesian Kriging (EBK) was used in ArcGIS 10.4.1 to create continuous SOC prediction surfaces for 2021 and 2022. EBK was selected for its ability to handle uncertainty in semivariogram estimation through repeated simulations, which is well-suited for the heterogeneous urban landscape. The predicted SOC surfaces and the related prediction standard error maps

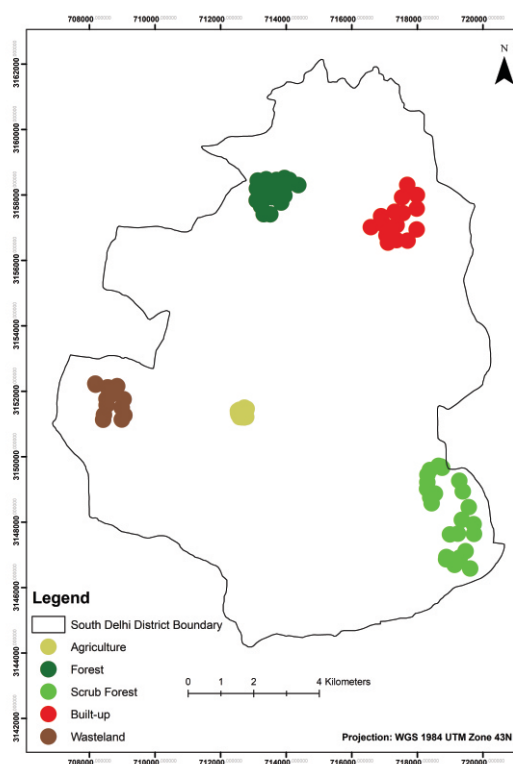


FIGURE 2 Spatial distribution of soil sampling locations across major LULC types in South Delhi District.

were clipped to the district boundary for visualization and analysis. Model performance was evaluated using cross-validation statistics, including mean error, root mean square error (RMSE), standardized RMSE, and regression slopes between observed and predicted values. The results showed that mean errors were nearly zero, regression slopes approached one, and standardized errors were close to one, indicating unbiased and reliable predictions of SOC spatial patterns.

3 | RESULTS AND DISCUSSION

3.1 | Soil Organic Carbon Distribution Across Land Use/Cover And Depths

Soil organic carbon (SOC) concentrations varied significantly across land use/cover (LULC) types and soil depths in both 2021 and 2022 (Tables 1 and 2). Forest soils consistently recorded the highest SOC values at all depths (0.62–0.66% at 0–10 cm), followed by scrub forest soils (0.54–0.58%). Agricultural soils showed moderate SOC concentrations (0.27–0.32%), whereas built-up (0.24–0.26%) and wasteland soils (0.15–0.17%) exhibited substantially lower values. Among all land uses, wasteland soils contained the lowest SOC across all depth intervals, with values declining to as low as 0.06–0.08% at 20–30 cm.

These patterns clearly demonstrate the dominant role of land use in regulating SOC distribution (Sharda *et al.*, 2019). Higher SOC in forest and scrub forest soils can be

attributed to continuous organic inputs from litter and roots, minimal disturbance, and relatively stable microclimatic conditions, which promote organic matter accumulation and stabilization. In contrast, built-up and wasteland soils showed pronounced SOC depletion, likely due to vegetation removal, soil sealing, compaction, and restricted

organic matter inputs associated with urbanization. Similar relationships between vegetation cover, disturbance, and SOC storage have been reported in earlier studies (Post & Kwon, 2000; Ontl & Schulte, 2012). Agricultural soils showed moderate SOC concentrations (0.27–0.32%),

TABLE 1 Soil physico-chemical properties (mean $\pm$ SD) across five land use/cover (LULC) types and three soil depths (0–10, 10–20, and 20–30 cm) in South Delhi District during 2021.

LULC Type (2021)	Depth (cm)	SOC (%)	Bulk Density (g cm^{-3})	pH	EC (dS m^{-1})	Moisture (%)	Particle Density (g cm^{-3})	Water Holding Capacity	Porosity (%)
Agriculture	0-10	0.27 $\pm$ 0.04	1.44 $\pm$ 0.04	6.67 $\pm$ 0.14	0.37 $\pm$ 0.06	18.5 $\pm$ 0.30	2.59 $\pm$ 0.02	26.92 $\pm$ 1.08	44.20 $\pm$ 1.46
	10-20	0.20 $\pm$ 0.02	1.52 $\pm$ 0.03	6.79 $\pm$ 0.31	0.35 $\pm$ 0.06	20.3 $\pm$ 4.03			
	20-30	0.15 $\pm$ 0.02	1.64 $\pm$ 0.03	7.18 $\pm$ 0.08	0.33 $\pm$ 0.05	22.2 $\pm$ 4.40			
Forest	0-10	0.62 $\pm$ 0.03	1.28 $\pm$ 0.05	6.50 $\pm$ 0.19	0.14 $\pm$ 0.02	9.7 $\pm$ 1.7	2.57 $\pm$ 0.04	30.06 $\pm$ 1.55	50.37 $\pm$ 2.01
	10-20	0.50 $\pm$ 0.02	1.37 $\pm$ 0.05	7.02 $\pm$ 0.21	0.13 $\pm$ 0.01	11.2 $\pm$ 2.0			
	20-30	0.41 $\pm$ 0.02	1.51 $\pm$ 0.05	7.52 $\pm$ 0.21	0.11 $\pm$ 0.01	12.1 $\pm$ 2.20			
Scrub Forest	0-10	0.54 $\pm$ 0.05	1.33 $\pm$ 0.04	6.25 $\pm$ 0.09	0.34 $\pm$ 0.05	4.1 $\pm$ 0.78	2.64 $\pm$ 0.02	25.20 $\pm$ 1.47	49.63 $\pm$ 1.63
	10-20	0.44 $\pm$ 0.04	1.41 $\pm$ 0.04	6.63 $\pm$ 0.23	0.30 $\pm$ 0.02	4.5 $\pm$ 0.86			
	20-30	0.36 $\pm$ 0.03	1.56 $\pm$ 0.04	7.05 $\pm$ 0.27	0.23 $\pm$ 0.02	4.9 $\pm$ 0.9			
Built-up	0-10	0.24 $\pm$ 0.05	1.48 $\pm$ 0.03	6.91 $\pm$ 0.29	0.51 $\pm$ 0.04	6.6 $\pm$ 3.2	2.66 $\pm$ 0.02	22.28 $\pm$ 0.66	44.17 $\pm$ 1.02
	10-20	0.15 $\pm$ 0.04	1.57 $\pm$ 0.03	7.51 $\pm$ 0.29	0.46 $\pm$ 0.02	7.4 $\pm$ 3.6			
	20-30	0.10 $\pm$ 0.02	1.72 $\pm$ 0.03	8.01 $\pm$ 0.29	0.39 $\pm$ 0.01	7.9 $\pm$ 3.94			
Wasteland	0-10	0.15 $\pm$ 0.02	1.51 $\pm$ 0.02	6.84 $\pm$ 0.40	1.51 $\pm$ 0.10	5.1 $\pm$ 1.87	2.67 $\pm$ 0.02	29.11 $\pm$ 0.61	43.30 $\pm$ 1.03
	10-20	0.09 $\pm$ 0.01	1.61 $\pm$ 0.03	7.31 $\pm$ 0.43	1.33 $\pm$ 0.05	5.8 $\pm$ 2.0			
	20-30	0.06 $\pm$ 0.01	1.74 $\pm$ 0.02	7.81 $\pm$ 0.43	1.19 $\pm$ 0.05	6.2 $\pm$ 2.248			

Note: Particle density, water holding capacity (WHC), and porosity were measured for surface soil (0–10 cm) only.

TABLE 2 Soil physico-chemical properties (mean $\pm$ SD) across five land use/cover (LULC) types and three soil depths (0–10, 10–20, and 20–30 cm) in South Delhi District during 2022.

LULC Type (2022)	Depth (cm)	SOC (%)	Bulk Density (g cm^{-3})	pH	EC (dS m^{-1})	Moisture (%)	Particle Density (g cm^{-3})	Water Holding Capacity	Porosity (%)
Agriculture	0-10	0.32 $\pm$ 0.04	1.46 $\pm$ 0.03	7.29 $\pm$ 0.30	0.38 $\pm$ 0.06	19.48 $\pm$ 3.5	2.59 $\pm$ 0.02	27.86 $\pm$ 1.13	43.96 $\pm$ 1.42
	10-20	0.24 $\pm$ 0.03	1.54 $\pm$ 0.03	7.40 $\pm$ 0.30	0.36 $\pm$ 0.06	21.2 $\pm$ 3.5			
	20-30	0.20 $\pm$ 0.02	1.64 $\pm$ 0.03	7.58 $\pm$ 0.30	0.34 $\pm$ 0.06	23.17 $\pm$ 3.6			
Forest	0-10	0.66 $\pm$ 0.03	1.30 $\pm$ 0.03	7.49 $\pm$ 0.25	0.15 $\pm$ 0.01	11.79 $\pm$ 2.0	2.57 $\pm$ 0.04	28.77 $\pm$ 0.98	49.58 $\pm$ 1.12
	10-20	0.54 $\pm$ 0.03	1.39 $\pm$ 0.03	7.59 $\pm$ 0.25	0.13 $\pm$ 0.01	13.49 $\pm$ 2.0			
	20-30	0.43 $\pm$ 0.03	1.50 $\pm$ 0.04	7.78 $\pm$ 0.25	0.12 $\pm$ 0.01	14.65 $\pm$ 1.9			
Scrub Forest	0-10	0.58 $\pm$ 0.05	1.38 $\pm$ 0.04	7.07 $\pm$ 0.27	0.32 $\pm$ 0.05	4.48 $\pm$ 0.8	2.64 $\pm$ 0.02	25.88 $\pm$ 1.25	47.71 $\pm$ 1.55
	10-20	0.47 $\pm$ 0.04	1.47 $\pm$ 0.04	7.17 $\pm$ 0.27	0.28 $\pm$ 0.02	5.98 $\pm$ 0.8			
	20-30	0.37 $\pm$ 0.03	1.59 $\pm$ 0.04	7.89 $\pm$ 0.38	0.23 $\pm$ 0.02	7.08 $\pm$ 0.90			
Built-up	0-10	0.26 $\pm$ 0.04	1.51 $\pm$ 0.04	7.99 $\pm$ 0.38	0.55 $\pm$ 0.05	6.51 $\pm$ 2.5	2.66 $\pm$ 0.02	23.68 $\pm$ 0.69	43.20 $\pm$ 1.56
	10-20	0.18 $\pm$ 0.03	1.61 $\pm$ 0.05	8.19 $\pm$ 0.38	0.47 $\pm$ 0.03	7.71 $\pm$ 2.5			
	20-30	0.13 $\pm$ 0.02	1.72 $\pm$ 0.04	7.80 $\pm$ 0.44	0.38 $\pm$ 0.02	8.01 $\pm$ 2.17			
Wasteland	0-10	0.17 $\pm$ 0.02	1.57 $\pm$ 0.05	7.90 $\pm$ 0.44	1.53 $\pm$ 0.11	5.3 $\pm$ 1.9	2.67 $\pm$ 0.02	28.77 $\pm$ 1.20	41.76 $\pm$ 1.93
	10-20	0.11 $\pm$ 0.01	1.66 $\pm$ 0.05	8.10 $\pm$ 0.44	1.35 $\pm$ 0.06	6.53 $\pm$ 1.9			
	20-30	0.08 $\pm$ 0.01	1.76 $\pm$ 0.04		1.19 $\pm$ 0.06	7.58 $\pm$ 1.6			

Note: Particle density, water holding capacity (WHC), and porosity were measured for surface soil (0–10 cm) only.

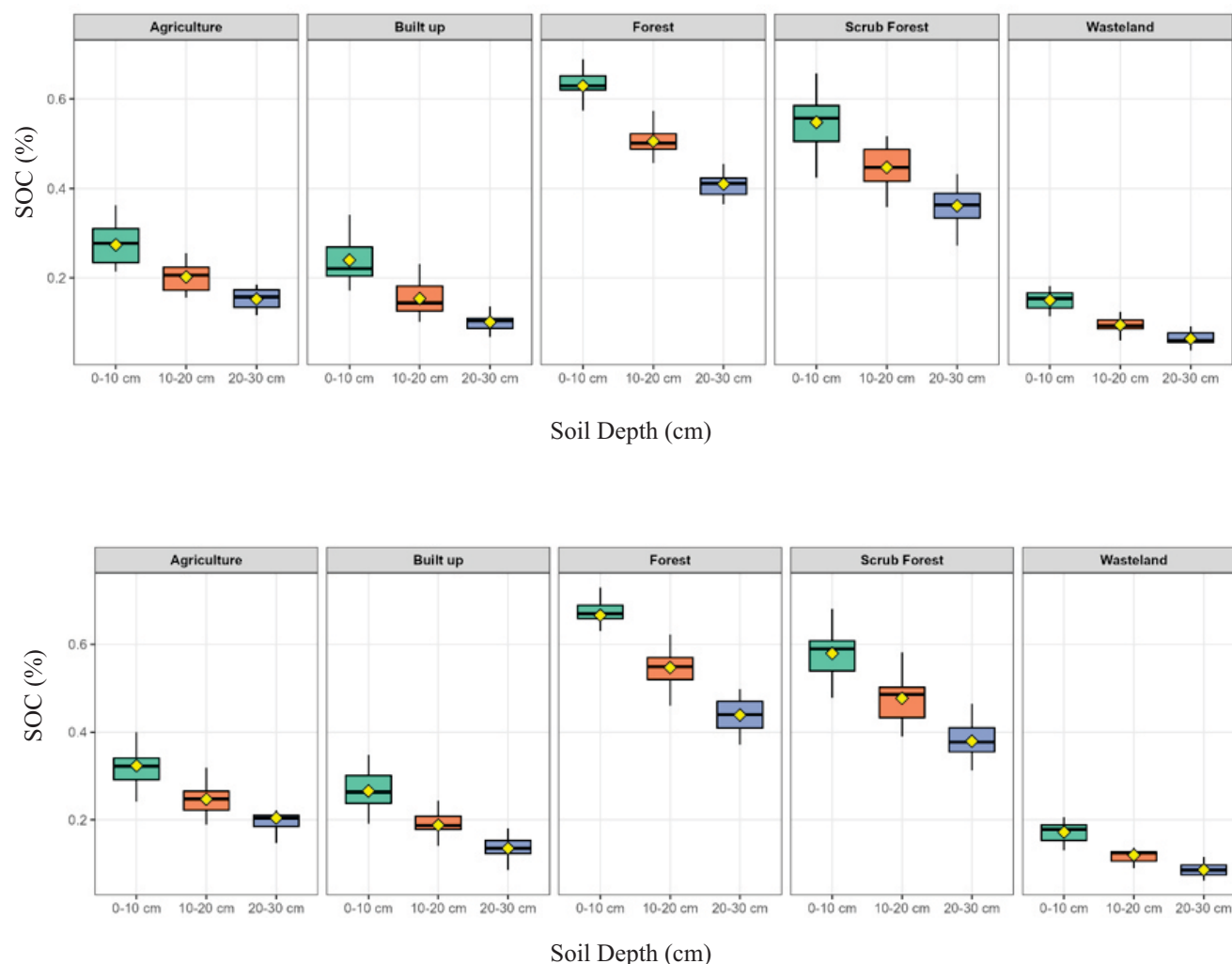


FIGURE 3 Boxplots showing the distribution of soil organic carbon (SOC %) across LULC types and soil depths (0–10 cm, 10–20 cm, 20–30 cm) in South Delhi during (A) 2021 and (B) 2022.

reflecting a balance between organic inputs from crop residues and carbon losses due to frequent tillage and limited organic amendments. Such intermediate SOC levels in agricultural systems have also been reported in semi-arid regions of India (Mandal *et al.*, 2019).

SOC decreased significantly with increasing soil depth across all LULC categories ($p < 0.001$), with approximately 60–75% of SOC concentrated in the surface layer (0–10 cm). Forest and scrub forest soils showed a more gradual reduction in SOC with depth, whereas agricultural, built-up, and wasteland soils exhibited a sharper decline. This vertical stratification reflects the concentration of organic inputs, root activity, and microbial processes near the soil surface, consistent with established soil carbon dynamics (Ontl & Schulte, 2012; Post & Kwon, 2000).

Boxplot analysis further illustrated a clear separation of SOC values across LULC types and soil depths (Fig. 3),

with minimal overlap between categories. Forest and scrub forest soils consistently showed higher median SOC values and narrower variability, whereas built-up and wasteland soils exhibited lower medians and greater spread. Similar distribution patterns were observed in both 2021 and 2022, indicating that the relative differences among land use types and depth-wise trends remained stable over time, reflecting short-term temporal consistency in SOC distribution.

3.2 | Statistical Significance of SOC Variation

One-way analysis of variance (ANOVA) confirmed statistically significant differences in SOC concentrations among land use/cover types and soil depths for both study years ($p < 0.001$; Table 3). Land use explained a substantial proportion of the observed variation in SOC (>80%), while soil depth accounted for an additional 12–13% of the variance. Interaction effects between land use and depth were comparatively weak, indicating that depth-related SOC declines were broadly consistent across different land uses.

Post hoc Tukey's HSD tests showed that forest and scrub forest soils contained significantly higher SOC compared to agricultural, built-up, and wasteland soils ($p < 0.05$). Similarly, the 0–10 cm soil layer differed

significantly from the 10–20 cm and 20–30 cm layers across all LULC categories, confirming the strong vertical stratification of SOC in the study area.

TABLE 3 Analysis of variance (ANOVA) results showing the effects of land use/cover (LULC) and soil depth on soil organic carbon (SOC) during 2021 and 2022.

Year	Factor	Source	df	SS	MS	F	p-value	ω^2
2021	LULC	Between groups	4	7.995	1.999	331.1	<0.001	0.82
2021		Within groups	289	1.745	0.006			
2021		Total	293	9.74				
2022		Between groups	4	8.013	2.008	311.5	<0.001	0.81
2022		Within groups	289	1.863	0.006			
2022		Total	293	9.894				
2021	Depth	Between groups	2	1.267	0.633	21.76	<0.001	0.12
2021		Within groups	291	8.473	0.029			
2021		Total	293	9.74				
2022		Between groups	2	1.327	0.663	22.53	<0.001	0.13
2022		Within groups	291	8.567	0.029			
2022		Total	293	9.894				

TABLE 4 Correlation matrix of soil organic carbon (SOC) with soil physico-chemical properties, 2021

Variable	SOC %	Moisture	EC (dS m ⁻¹)	pH	Bulk density (g cm ⁻³)	WHC	Porosity (%)	Particle density g cm ⁻³)
SOC %	1	-0.125	-0.721	-0.607	-0.919	0.302	0.879	-0.479
Moisture		1	-0.281	0.145	0.044	0.230	-0.169	-0.416
EC (dS m ⁻¹)			1	0.399	0.683	0.089	-0.592	0.563
pH				1	0.552	-0.085	-0.551	0.195
Bulk density (g cm ⁻³)					1	-0.383	-0.969	0.478
Water holding capacity						1	0.325	-0.367
porosity (%)							1	-0.247
Particle density g cm ⁻³								1

3.3 | Relationship Between SOC And Soil Properties

Correlation analysis showed strong, consistent relationships between SOC and key soil physico-chemical properties across both years (Tables 4 and 5). SOC exhibited a strong negative correlation with bulk density ($r = -0.92$ to -0.93 , $p < 0.001$), indicating reduced compaction in soils with higher organic carbon content. Moderate to strong negative correlations were also observed with pH ($r = -0.41$ to -0.61) and electrical conductivity ($r = -0.72$ to -0.77), while strong positive correlations were found with porosity ($r = 0.88$ – 0.91). Additionally, SOC showed a positive

relationship with water holding capacity ($r = 0.30$ – 0.37).

These relationships highlight the fundamental role of SOC in improving soil physical structure, enhancing porosity, and increasing moisture retention capacity. The negative association with electrical conductivity further suggests that higher organic matter content may contribute to improved soil chemical conditions. These findings are consistent with earlier studies demonstrating the role of SOC in enhancing soil quality and resilience (Gol, 2009; Singh & Sharma, 2017; Zhang & Shangguan, 2016).

TABLE 5 Correlation matrix of soil organic carbon (SOC) with soil physico-chemical properties, 2022

Variable	SOC %	Moisture	EC (dS m ⁻¹)	pH	Bulk density (g cm ⁻³)	WHC	Porosity (%)	Particle density g cm ⁻³)
SOC %	1	0.007	-0.766	-	-0.931	0.148	0.908	-0.479
Moisture		1	-0.330	-	-0.169	0.368	-0.044	-0.509
EC (dS m ⁻¹)			1	0.394	0.766	0.129	-0.699	0.568
pH				1	0.335	-	-0.325	0.165
Bulk density (g cm ⁻³)					1	0.018	-0.972	0.543
Water holding capacity porosity (%)						1	0.191	-0.294
Particle density g cm ⁻³							1	-0.332

3.4 | Spatial Distribution Patterns

Spatial interpolation using Empirical Bayesian Kriging (EBK) revealed pronounced heterogeneity in SOC distribution across South Delhi (Fig.4). High SOC concentrations were concentrated in forest and scrub forest patches, particularly in the northern and northeastern parts of the district associated with the Asola Bhatti Wildlife Sanctuary and ridge forest areas. These locations consistently appeared as SOC “hotspots,” attributable to dense vegetation cover and minimal disturbance.

Agricultural soils displayed moderate SOC levels, with higher values observed in areas where crop residues are likely retained, while intensively managed fields showed lower SOC. Built-up and wasteland soils appeared as distinct “coldspots,” reflecting vegetation removal, soil compaction, and sealing associated with urbanization.

The strong contrast between high-SOC forest zones and low-SOC urban/degraded zones demonstrates how land use transitions have reshaped soil carbon distribution across

the landscape. Similar spatial patterns have been reported in other regions, where natural vegetation patches function as important carbon reservoirs within human-dominated systems (Tomar & Baishya, 2019; Olorunfemi *et al.*, 2020; Mabicka *et al.*, 2021).

The persistence of high SOC in forest and scrub forest areas underscores the need to protect remnant green spaces and ridge ecosystems from further degradation, in line with broader soil and ecosystem conservation priorities (FAO & UNEP, 2020).

3.5 | Validation Of Spatial Predictions

Cross-validation statistics indicated good agreement between observed and predicted SOC values (Table 6). Mean prediction errors were close to zero, and root mean square error (RMSE) values remained low for both years. Regression slopes between observed and predicted SOC values ranged from 0.93 to 0.94, with coefficients of determination (R^2) exceeding 0.88. Standardized errors were close to unity, indicating unbiased predictions.

These results confirm that the EBK interpolation effectively captures spatial variability in SOC and produces

reliable prediction surfaces suitable for identifying SOC-rich and SOC-depleted areas within the study region.

TABLE 6 Cross-validation statistics for Empirical Bayesian Kriging (EBK) interpolation of soil organic carbon (SOC) in South Delhi during 2021 and 2022

Year	Mean Error	Root Mean Square Error (RMSE)	Root Mean Standardized Square Error	Regression Slope	R ²
2021	-0.0011	0.051	0.971	0.93	0.88
2022	-0.0011	0.048	1.01	0.94	0.90

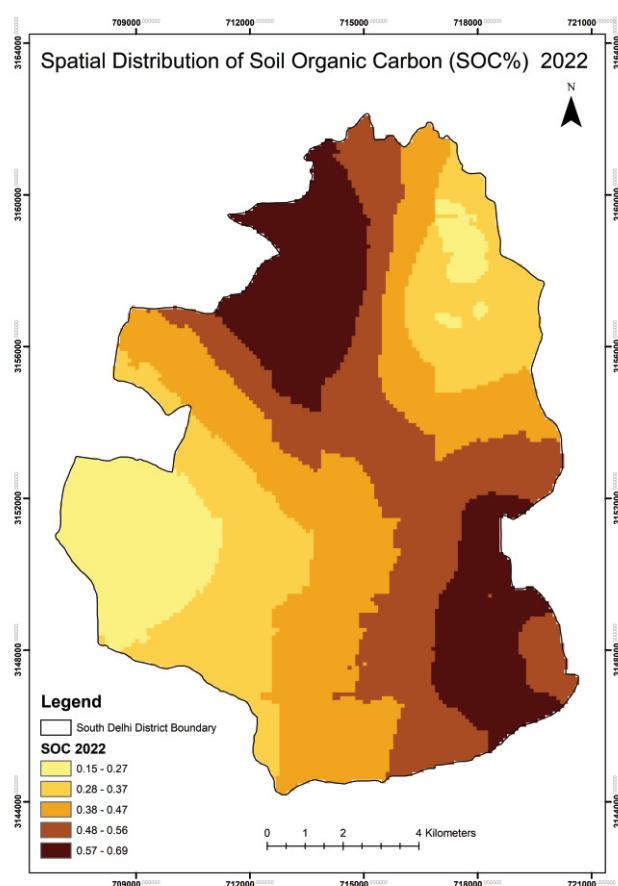
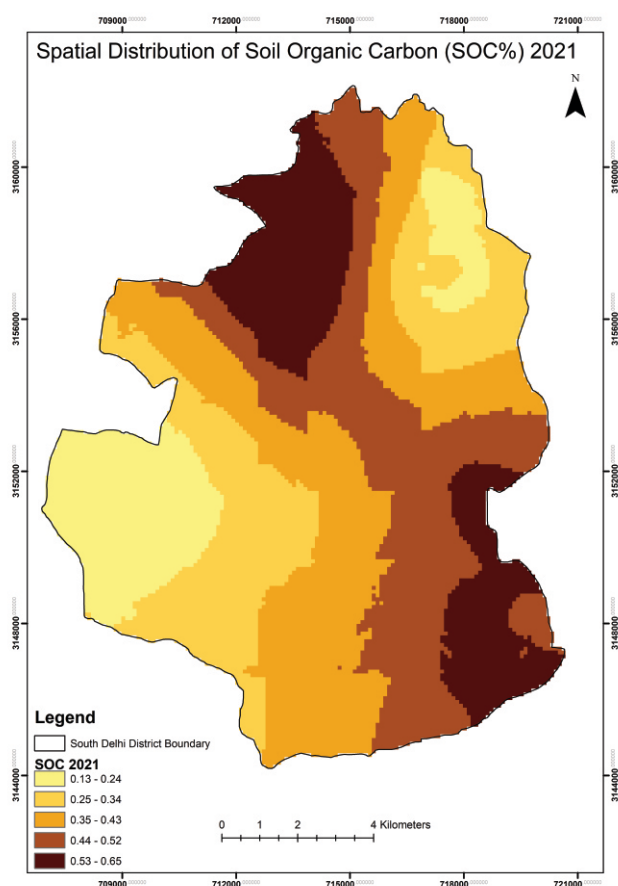


FIGURE 4 Spatial distribution of soil organic carbon (SOC, %) in South Delhi District, 2021 and 2022 (EBK interpolation)

3.6 | Key Findings

The study results show the following patterns:

1. Significant spatial variation across land uses: Forest and scrub forest soils contained the highest SOC concentrations (0.62–0.66% and 0.54–0.58% at 0–10 cm), approximately 2–4 times higher than built-up (0.24–0.26%) and wasteland soils (0.15–0.17%). Agricultural soils showed intermediate values (0.27–0.32%). These differences were highly significant ($p < 0.001$) and explained 81–82% of SOC variance.

2. Consistent depth stratification: SOC decreased significantly with soil depth across all land uses ($p < 0.001$), with 60–75% of organic carbon concentrated in the surface 0–10 cm layer. Forest and scrub forest soils showed more gradual depth-related declines (33–34%) compared to agricultural (44%), built-up (58%), and wasteland soils (60%).

3. Strong associations with soil properties: SOC exhibited strong negative correlations with bulk density ($r = -0.93$) and electrical conductivity ($r = -0.77$), and strong positive correlations with porosity ($r = +0.91$). These relationships were consistent across both study years, indicating stable associations between organic carbon and soil physical and chemical characteristics.

4. Distinct spatial patterns: Empirical Bayesian Kriging interpolation identified clear SOC hotspots in forest and scrub forest areas (particularly Asola Bhatti Wildlife Sanctuary and ridge forests) and depleted zones in built-up and wasteland areas. Cross-validation demonstrated good prediction accuracy ($R^2 > 0.88$, $RMSE < 0.051\%$), though prediction uncertainty was higher in under-sampled urban zones.

5. Spatial consistency across years: SOC distribution patterns were remarkably similar between 2021 and 2022, suggesting spatial stability in land use–SOC relationships over the short term, though the two-year period is insufficient for assessing temporal trends.

4 | LIMITATIONS AND FUTURE SCOPE OF THE STUDY

The current study has some limitations that should be recognized. Although soil samples were collected across major land use and cover types, the sampling density was uneven due to accessibility issues in developed and forested areas. Additionally, soil organic carbon was estimated using the Walkley–Black method, which might underestimate the total carbon content. The study also did not explicitly consider vegetation biomass, litter input, or land management history, which could help explain spatial differences in SOC. Future research should include SOC fractionation, microbial indicators, assessments of vegetation biomass, and long-term monitoring to better understand carbon stabilization in urban soils. Incorporating high-resolution remote sensing data and

climate projections would further improve the usefulness of SOC assessments for urban soil conservation and land use planning.

5 | CONCLUSIONS

This study offers a spatial baseline assessment of soil organic carbon (SOC) distribution across major land use and cover types in South Delhi District. Analysis of 98 locations sampled in 2021 and 2022 showed significant spatial variation in SOC concentrations, with clear differences among land uses and consistent vertical stratification with soil depth. Key findings include notable spatial variation across land uses, consistent depth stratification, and strong SOC relationships with soil properties. Forest and scrub forest soils had approximately 2–4 times higher SOC levels than built-up (0.24–0.26%) and wasteland soils. Agricultural soils exhibited intermediate values (0.27–0.32%). These differences were highly significant ($p < 0.001$) and accounted for 81–82% of SOC variance. SOC levels decreased significantly with soil depth across all land uses, with 60–75% of organic carbon found in the top 10 cm layer. Forest and scrub forest soils showed more gradual declines with depth (33–34%) compared to agricultural (44%), built-up (58%), and wasteland soils (60%). SOC had strong negative correlations with bulk density and electrical conductivity, and strong positive correlations with porosity. Empirical Bayesian Kriging interpolation identified clear SOC hotspots in forest and scrub forest areas (especially Asola Bhatti Wildlife Sanctuary and ridge forests) and depleted zones in built-up and wasteland areas. Cross-validation indicated good prediction accuracy ($R^2 > 0.88$, $RMSE < 0.051\%$), although uncertainty was higher in under-sampled urban zones. The SOC distribution patterns were remarkably similar between 2021 and 2022, suggesting spatial stability in land-use–SOC relationships over the short term, although the two-year period is insufficient to assess long-term trends.

These findings offer spatially explicit information for prioritizing soil conservation efforts in South Delhi. Forest and scrub forest areas represent existing SOC stores that require protection from further degradation or conversion. Agricultural lands exhibit intermediate SOC levels with potential for improvement through appropriate management, though specific practices warrant further investigation. Built-up and wasteland areas show significant SOC depletion and could benefit from restoration initiatives, although their feasibility and effectiveness require experimental evaluation. Spatial maps allow identification of priority zones for different management goals—either protecting hotspots or restoring depleted areas.

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CONFLICT OF INTEREST

The authors declare that there are no competing or conflicting interests.

DATA AVAILABILITY STATEMENT

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

AUTHOR'S CONTRIBUTION

TP conceived and designed the study, conducted all analyses, and wrote the first draft of the manuscript. PL and TS assisted with fieldwork and provided technical inputs. All authors reviewed and approved the final manuscript.

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Landform - Based Soil Variability and Water Regime Implications in the KRP Dam Catchment, Tamil Nadu, India

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ABSTRACT

Hydropedology studies soil and water processes across landscapes. This research characterized the soils in the Krishnagiri Reservoir Project (KRP) Dam catchment, Tamil Nadu, India, to identify pedological indicators of water regimes and the effects of land management. A (2020–2023) soil survey at a 1:10,000 scale provided data for the 12,483 ha catchment. Five soil series from various landforms were classified, and drainage classes were estimated based on soil features without direct hydrological monitoring. Soil properties varied by landform, from shallow (<50 cm) to deep (100–150 cm), with drainage from well to poorly drained. Colors ranged from dark reddish-brown to black; textures ranged from loamy sand to clay. Structure ranged from massive to subangular blocky; pH from neutral to moderately alkaline (6.74–9.19), electrical conductivity from non-saline to slightly saline (0.04–1.64 dS m⁻¹), organic carbon from low to high (0.15–2.17%), and cation exchange capacity from 4.43 to 54.0 cmol (p⁺) kg⁻¹. The soil exchange complex held Ca > Mg > K > Na. Soil classes included Alfisols (NGH & MLD series - uplands), Inceptisols (STP & SDK series - lowlands), and Entisols (KLV series - lowlands). Soils with periodic saturation (KLV, STP, SDK) had higher clay, CEC, and nutrients than well-drained uplands (NGH, MLD). Correlation analysis (n=45) showed strong positive relationships between clay, CEC, and exchangeable bases, with sand negatively correlating. Upland soils exhibited erosion and nutrient loss with low water-holding capacity (5.44–7.99%). Lowland soils had higher available water (11.89–22.39%) but signs of drainage issues and salt buildup. This study provides a baseline for soil features in the KRP Dam catchment. Water regime inferences need validation via direct hydrological monitoring, including water table, soil moisture, and hydraulic testing. Conservation strategies for uplands (erosion, organic matter) and lowlands (drainage, salinity) should be field-tested before implementation. This baseline supports future integrated research for sustainable crop management in dam-affected regions.

1 | INTRODUCTION

Hydropedology connects pedology, soil physics, and hydrology to bridge scales and convert soil survey data into soil hydraulic information (Kutilek & Nielsen, 2007). In this case, pedotransfer functions connect simpler soil characteristics, such as morphological features, to more intricate variables, such as soil hydraulic properties, which are difficult to measure (Lin *et al.*, 2006; Bouma, 2024). Determining the relationship between soil water regime and soil morphology thus requires an understanding of redox reactions in soil and their impact on the development of redoximorphic color patterns (Rabenhorst & Parikh, 2000). It is a helpful tool for monitoring and assessing climate change and for integrating soil and water data into land use systems (Daniel Filho & Barretto de Figueiredo, 2025). Additionally, hydropedology has a significant impact on formulating environmental policies from a global to a local

level (Bouma, 2006). Soil survey databases provide a wealth of information that can be utilized to predict the fate of water and contaminants in the landscape (Henry Lin, 2011). Wilding and Lin (2006) also assert that the focus of Pedology is transitioning from classification and inventory to the comprehension and quantification of spatial and temporal processes that are essential to the water cycle and ecosystem. Current knowledge deficits include the quantification of soil hydro morphology and modeling, predictions of soil and hydrological properties and processes, and data-bridging through pedotransfer functions (Lin *et al.*, 2006; Ma *et al.*, 2017; Kaur & Kumari, 2024). It is necessary to gain a better understanding of how water flow patterns affect soil processes and soil formation across the landscape. Quantification of soil variation, spatial and temporal, is essential for the effective modelling of hydraulic processes in the landscape (Zacharias *et al.*, 2009)

Before the construction of dams, the main land uses were betel vines and mango, which were based on a canal irrigation system that covered a small area. After the dam was built, the uplands were transformed into a paddy-based land-use system and coconut plantations (Srinivasan *et al.*, 2019; Srinivasan *et al.*, 2023). The transformation of well-drained soil into a layer saturated with water alters the soil systems hydro morphological and physical characteristics. Significant issues with soil physical and chemical deterioration, poor water management, monocropping systems, and their effects on inadequate ecosystem management (Srinivasan *et al.*, 2022). It is anticipated that hydopedology will increase our understanding of the environment, ecology, agriculture, and natural resources of the KRP Dam catchment. Mapping soil-water and soil-landscape at farm scales is made easier by measurements of soil hydro-morphology, soil structure, and their effects on water flow and movement across diverse landscapes, as well as their implications for crop management (Lin, 2003). These include nutrient cycling, precision agriculture, climate change, ecosystem functions, water and soil quality and landscape processes and management. Therefore, a case study was conducted in the KRP dam catchment to assess soil, water, and responses to crop and ecosystem management.

2 | MATERIALS AND METHODS

2.1 | Study Area

Krishnagiri Dam, known as Krishnagiri Reservoir Project (KRP) Dam, was built across the Thenpennai River fall in Dhuduganahalli village, Krishnagiri district. The study area, which is located between latitudes 21°29'37.44" N and longitudes 78°10'41.51" E, is part of the agroecological sub-region (AESR) of 8.2. It covers 12483 ha (Fig. 1), of which 8477 ha (67.94%) are majorly covering five soil series. The remaining area comprises minor soils and permanent features such as roads, waterbodies, and other features. This reservoir provides direct irrigation benefits to sixteen (16) villages. Successful cultural operations are guaranteed by a water supply from the reservoir for ten (10) months of the year. During the 150–180-day growing period, the northeast monsoon (October–December) receives 60–70% of the mean annual rainfall, which ranges from 750 to 900 mm (LGP). During the summer, the average high temperature is 37°C, while the average low temperature is 25.5°C. The soil temperature class is hyperthermic. It is a hot, semi-arid ecoregion with mixed red loamy soils and the "ustic" moisture regime. There are a significant number of forests at the top of the mountains and hillocks. The primary crop grown in the dam catchment is paddy, but there are also significant amounts of coconut, jasmine, ragi, mango, and legumes. Site characteristics are given in (Table 1).

2.2 | Field Studies

The base map was prepared using geological data, a survey of India Toposheet (1:50,000 scale), and remote sensing data from IRS-P6 LISS IV (5.8 m of resolution). Different

HIGHLIGHTS

- Detailed soil survey (1:10,000 scale) characterized five major soil series across landforms in a dam catchment in semi-arid tropical India.
- Upland Alfisols showed well-drained characteristics with erosion evidence, while lowland Inceptisols and Entisols exhibited morphological features suggesting periodic saturation.
- Strong correlations between clay content, cation exchange capacity, and nutrient retention demonstrate texture's role in soil fertility management.
- Soils with morphological indicators of seasonal saturation had higher clay content (42-58%), available water capacity (11-22%), and nutrient availability than well-drained upland soils.

physiographic regions, landscapes, landforms, and land use/land cover were identified by visually interpreting the satellite image based on tone/color, texture, pattern, and shape, among other factors. In the KRP dam catchment, a thorough soil study at a 1:10,000 scale was carried out between 2020 and 2023. Satellite image interpretation, ground-truth observation (soil survey fieldwork), laboratory analysis, and GIS mapping comprise the four tiers of the detailed soil survey methodology. Given the variability, random observations were made throughout the slope, encompassing all landform units. Soil profiles (vertical cuts and arrangements of soil layers/horizons) excavated to a depth of 1.5 to 2 m, or until they reached rock or hard substratum/parent materials, were used to study soil morphological properties (Soil Survey Staff, 2003). A portable global positioning system (GPS) was used to record the latitude, longitude, and elevation at each sampling location. In the KRP dam catchment, ninety-two (92) soil profiles were examined. The KRP dam catchment was divided into ten (10) soil series (homogeneous units with similar responses for level management) based on the soil characteristics. Of these, five major soil series were used to assess the hydopedology in the area: Kalveli (KLV), Santhapuram (STP), and Sundekuppam (SDK) are lowland, and Nagojanahalli (NGH) and Malayandahalli (MLD) are upland (Table 2). The soil profiles from each landform were comprehensively analyzed to characterize morphological attributes and assess key soil parameters, including slope, depth, and physicochemical properties (Soil Survey Staff, 2003). Topography-soil-hydrology sequences in the KRP Dam catchment are given in (Fig. 2).

2.3 | Soil Analysis

Major soil parameters were analyzed by systematically collecting horizon-wise soil samples, air-drying, processing, and sieving them through a 2 mm mesh. Particle-size distribution was determined using the international pipette method (Day, 1965). Soil pH and electrical conductivity (EC) were measured according to the standard procedures described by Page *et al.* (1982). Soil organic carbon content was estimated by the moist oxidation method of Walkley & Black (1934). To determine

soil moisture-retention characteristics, disturbed soil samples were saturated for 48 hours, followed by pressure application at 0.03, 0.05, 0.1, and 1.5 MPa in a pressure plate extractor until drainage ceased. The samples were then oven-dried at 105°C for 24 hours, and the difference in water retained between 0.03 and 1.5 MPa suctions was used to compute the available water capacity (AWC) (Klute, 1986). Cation exchange capacity (CEC) was determined using neutral normal ammonium acetate at pH 7.0, and base saturation was calculated as the percentage ratio of the sum of exchangeable bases to CEC. Exchangeable calcium (Ca) and magnesium (Mg) were extracted with the same solution and quantified using an atomic absorption spectrophotometer (AAS) (Jackson, 1973). Available

phosphorus was estimated via the ascorbic acid reduction method (Bray & Kurtz, 1945), while available potassium was extracted using neutral normal ammonium acetate (pH 7.0) and determined by flame photometry. Accessible sulfur was extracted with 0.15% CaCl₂, and sulfate concentration was measured by the turbidimetric method (Jackson, 1973). Available boron was quantified using the Azomethine-H reagent (Jackson, 1973). Micronutrient availability (Fe, Mn, Cu, and Zn) was assessed through DTPA extraction followed by analysis with an atomic absorption spectrophotometer (Lindsay & Norvell, 1978). Finally, soil classification was performed in accordance with the criteria outlined in Keys to Soil Taxonomy (Soil Survey Staff, 2014).

TABLE 1 Site characteristics of the study area

S.No	Landform	Series	Elevation MSL (m)	Slope %	Erosion	Major crops	Management
P1	Gently sloping Upland	Nagojanahalli (NGH)	615	1-3	Moderate	Mango, Sorghum	Moderate
P2	Gently sloping Upland	Malayandahalli (MLD)	479	1-3	Moderate	Mango, Pulses, Groundnut	Moderate
P3	Nearly level Lowland	Kalveli (KLV)	450	0-1	Very slight	Paddy, Coconut	Moderate
P4	Nearly level Lowland	Santhapuram (STP)	426	0-1	Slight	Paddy, Coconut	Good
P5	Nearly level Lowland	Sundekuppam (SDK)	418	0-1	Very slight	Paddy, Jasmine, Coconut	Good

TABLE 2 Soil characteristics and classification in the KRP Dam catchment

Landforms	Soil Series	Soil landform relationship	Area (ha) % of TGA	
Upland	Nagojanahalli (NGH)	Moderately deep, well-drained, dark reddish-brown to reddish-brown, sandy clay loam texture in series control section (37-90 cm) on very gently sloping (1-3%) upland with loamy sand surface texture and moderate erosion. (<i>Fine-loamy, mixed, isohyperthermic, Typic Haplustalfs</i>)	1334.3	10.69
	Malayandahalli (MLD)	Deep, well-drained, dark reddish-brown to dark red, sandy clay to sandy clay loam texture in series control section (23-109 cm) on very gently sloping (1-3%) upland with sandy loam surface texture and moderate erosion. (<i>Fine-loamy, mixed, isohyperthermic, Rhodic Palustalfs</i>)	481.0	3.85
	Kalveli (KLV)	Deep, moderately well-drained, dark gray to brown, sandy clay loam to sandy loam texture in series control section (14-137 cm) on nearly level sloping (0-1%) low land with sandy clay loam surface texture and very slight erosion. (<i>Sandy, mixed, isohyperthermic (Calcarious), Typic Ustifluvents</i>)	1639.2	13.14
Lowland	Santhapuram (STP)	Shallow, moderately well-drained, dark yellowish-brown to brown, sandy clay loam texture in series control section (21-48 cm) on nearly level sloping (0-1%) lowland land with sandy loam surface texture and slight erosion. (<i>Fine-loamy, mixed, isohyperthermic (Cal), Typic Haplustepts</i>)	4035.0	32.35
	Sundekuppam (SDK)	Deep, somewhat poorly drained, dark brown to dark grayish brown, sandy clay to sandy clay loam texture in series control section (20-150 cm) on nearly level sloping (0-1%) lowland land with sandy clay surface texture and very slight erosion. (<i>Fine-loamy, mixed, isohyperthermic, Fluevntic Haplustepts</i>)	987.6	7.91
Total			8477	67.94

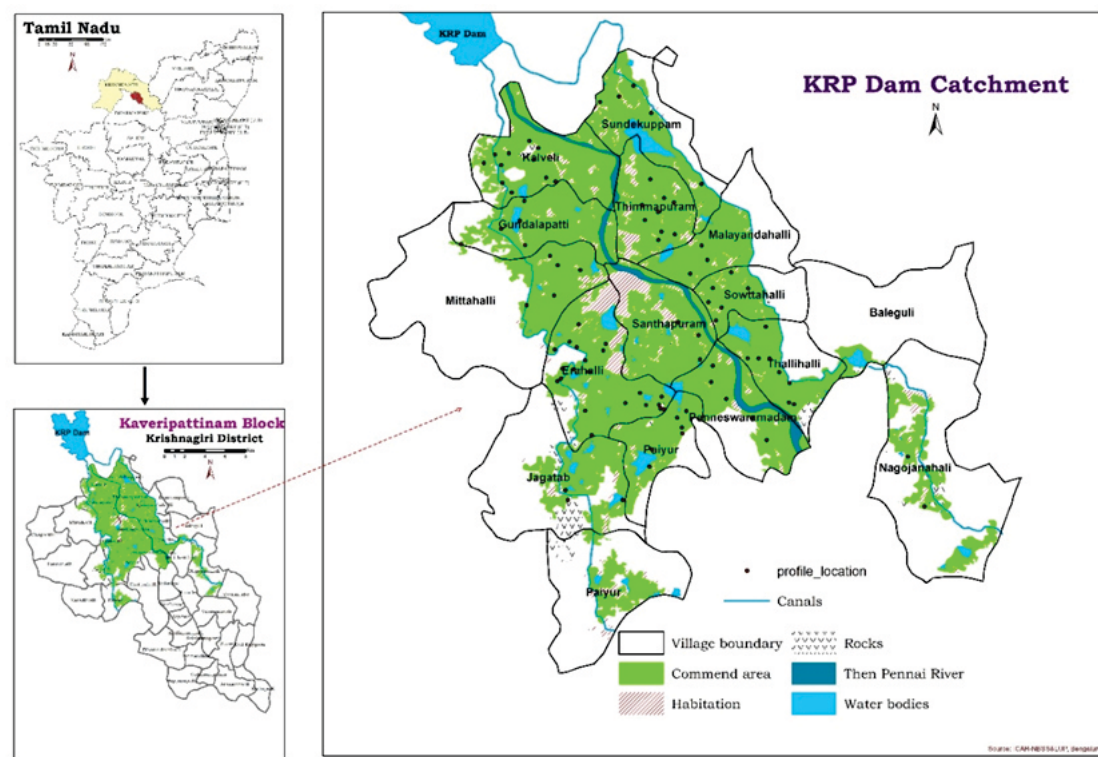


FIGURE 1 Location map of the Study area

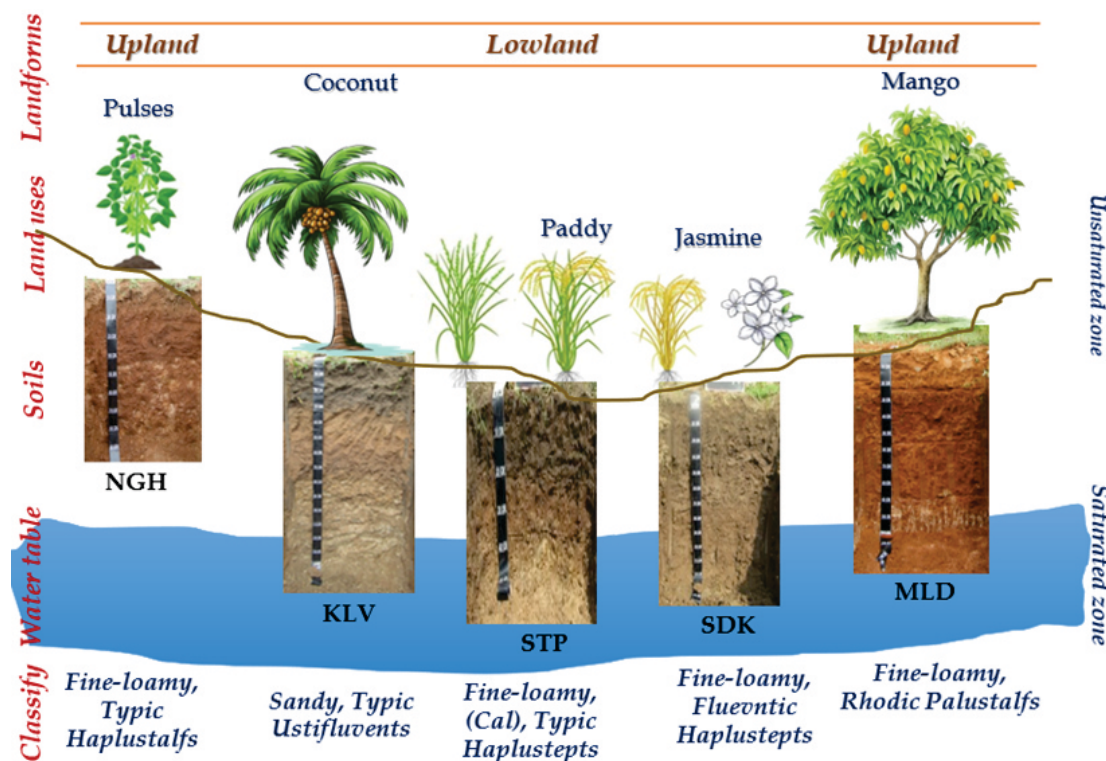


FIGURE 2 Topography-soil-hydrology sequences in KRP Dam catchment (*"Water table positions inferred from soil morphology; direct measurements not available". Include scale and clearer labels)

2.4 | Statistical Analysis

The correlation coefficient was evaluated for various soil characteristics in the KRP Dam catchment to determine the influence on soil and water. A network map visualization was carried out using R software, and the Q graph package involves plotting nodes (variables or items) and edges (relationships, usually correlations or partial correlations) for interpretations.

2.5 | Study Limitations and Scope

This study details soil characteristics for the KRP Dam catchment, but faces limitations. Soil drainage was assigned based on morphological criteria without hydrological validation. Hydraulic properties were limited to available water capacity; other parameters were not measured. Soil sampling was conducted only once during (2020-2023), without seasonal monitoring. Water quality analysis was absent, impeding the assessment of water's influence on soil chemistry. These findings are preliminary and need further hydrological validation.

3 | RESULTS AND DISCUSSION

3.1 | Morphological Characteristics and Inferred Drainage Classes

(Table 3) shows brief morphological features of the pedons. Soil depth ranged from shallow (<50 cm) to deep (100-150 cm). Upland soils (NGH, MLD series) were moderately deep to deep (90-109 cm), while lowland soils varied from shallow (STP: 48 cm) to deep (KLV: 137 cm; SDK: 150 cm). Drainage classes were assigned based on soil color, structure, landscape, and land use, following standard procedures (Soil Survey Staff, 2003). Upland soils were well drained and aerobic, while lowland soils showed moderately well to poorly drained conditions, suggesting periodic saturation. These classifications are based on morphological criteria; direct water table or seasonal soil moisture data were not collected.

3.1.1 | Soil Color Patterns

Surface soil colors in upland areas ranged from dark reddish brown (5YR 3/3 in NGH) to dark reddish brown (2.5YR 3/4 in MLD). Subsurface horizons exhibited colors from dark reddish brown (2.5YR 3/3) to reddish brown (2.5YR 4/4). The consistent reddish hues (2.5YR to 5YR) throughout upland profiles, with no gray tones or strong mottling, indicate well-oxidized soils and align with well-drained conditions. Lowland soils showed darker shades: surface horizons varied from very dark gray (10YR 3/1 in STP and SDK) to dark gray (10YR 4/1 in KLV), while subsurface horizons ranged from brown (7.5YR 4/2-4/3) to black (10YR 2/1). These darker colors in lowland soils may stem from several factors, including: (a) organic matter buildup during saturation periods under anaerobic conditions; (b) formation of reduced iron compounds (ferrous iron) producing gray to black shades; or (c) accumulation of organic-rich sediments from upslope erosion. Oxidation-reduction (redox) processes influence soil color development, especially in soils with alternating aerobic

and anaerobic conditions (Tiruneh *et al.*, 2024). However, this survey did not systematically document redoximorphic features (iron/manganese concentrations and depletions), limiting precise assessment of saturation duration and timing.

3.1.2 | Soil Texture

The gravel content varied across soil series and with depth. The NGH series had 15-40% coarse fragments, reaching a maximum of 40% in the surface horizon. MLD and STP series mainly accumulated gravel in lower horizons (30-60%), while KLV and SDK series were mostly free of gravel throughout. The presence of coarse fragments in upland soils can limit rooting depth, reduce water retention, and impact tillage. Surface textures ranged from loamy sand in NGH to clay in SDK. Upland soils had loamy sand to sandy loam surfaces (NGH: loamy sand; MLD: sandy loam), while lowland soils ranged from sandy loam (STP) to sandy clay loam (KLV) and clay (SDK). Subsurface textures generally contained more clay: sandy loam to sandy clay in uplands and sandy clay loam to clay in lowlands. The increasing clay content with depth in upland Alfisols aligns with translocation processes (illuviation) that create argillic horizons. In lowland soils, higher clay levels may result from: (a) depositional processes moving fine particles from upslope areas; (b) in-situ weathering under different moisture conditions; and (c) textural stratification in alluvial parent materials (Srinivasan *et al.*, 2024).

3.1.3 | Soil Structure

The soil structure ranged from massive to subangular blocky forms. Upland soils consistently showed fine to medium, weak to moderate, subangular blocky structures throughout the profile. In contrast, lowland soils exhibited notable structural differences: the surface horizons of the STP and SDK series were massive, a result of repeated puddling during paddy cultivation. Puddling—wet tillage under saturated conditions—disrupts natural soil aggregates, leading to particle rearrangement and destruction of structural units in the topsoil. This process creates a compacted plough pan in the subsoil that can hinder water percolation and root penetration (Ye *et al.*, 2024). Beneath the puddled zone, the lowland soils displayed fine to medium, weak to moderate, subangular blocky structures.

3.1.4 | Consistency

Dry consistency ranged from loose (NGH, MLD surface horizons) to slightly hard (KLV) to hard (MLD subsurface). Moist consistency varied from very friable to friable across most horizons. Wet consistency showed clear differences between soil series: upland soils ranged from non-sticky/non-plastic to moderately sticky/moderately plastic, while lowland clay-rich soils (particularly SDK) exhibited very sticky/very plastic consistency, affecting workability and tillage timing.

3.1.5 | Morphological Indicators of Water Regime

While drainage classes were assigned based on

morphological features, observations suggest contrasting soil-water regimes warrant further investigation. Upland soils (NGH, MLD) showed uniform reddish colors, no gray mottling, reduction features, or horizon-specific color changes, indicating fluctuating water tables. Their structure and friability suggest aerobic, well-drained conditions, though confirmation requires water-table depth and hydraulic-conductivity tests. Lowland soils (KLV, STP, SDK) exhibited features such as darker colors, massive puddled surfaces, a sticky consistency when wet, and low-lying landscape positions, suggesting periodic saturation. However, the lack of gray mottling or iron/manganese concretions, common in poorly drained soils, indicates only brief or surface saturation from irrigation or flooding. Black colors in SDK horizons might show reduced iron or organic matter in young deposits. Massive structures may be anthropogenic. These ambiguities highlight the need for hydrological monitoring—installing water table wells, soil moisture sensors, and redox potential measurements—to validate drainage classifications.

3.2 | Physical Characteristics

Detailed physical properties are in (Table 3 and Table 4). Particle size varied by landform position and depth. Upland soils: In the NGH series, sand dominated (67.01%-85.95%), with clay (8.13%-20.62%) and low silt (5.92%-12.37%). The MLD series had lower sand (52.66%-76.88%) and higher clay (14.64%-38.33%), especially in the Bt2 horizon, indicating argillic horizon development. Silt ranged from 7.50 to 9.87%. The KLV series showed variable texture, with sand (58.76%-78.95%), clay (9.31%-22.98%), and silt (11.31%-20.98%), reflecting stratified alluvial parent material with lithological discontinuities (Zhang *et al.*, 2025). The STP series had a sandy loam surface (sand 76.4%, clay 12.2%) over sandy clay subsurface (sand 55.4%-60.3%, clay 37.3%-39.2%). The SDK series had the highest clay (42.15% surface to 58.26% in the deepest layer), decreasing sand with depth. Silt ranged from 25.0-29.18%, higher than in other series. Increasing clay with depth suggests clay illuviation forming argillic horizons in Alfisols, with clay translocated via percolating water over long profile development. Lowland soils exhibit more complex clay distributions due to depositional sorting, differential weathering, stratification, and limited pedogenic translocation. Silt patterns may indicate lithological discontinuities or variable parent material composition (Zhang *et al.*, 2025).

Most soils are dominated by sand (>50%) due to granite-gneiss weathering into quartz-rich sand. Available water capacity (AWC), calculated as the difference between gravimetric water at field capacity and permanent wilting point, ranged from 5.44% to 22.39% across horizons. The NGH series had the lowest AWC (5.44-6.77%), indicating minimal water storage, while the MLD series was slightly higher (5.91-7.99%). Low AWC in upland soils is due to coarser textures, coarse fragments (15-40% NGH, up to 30% MLD lower horizons), and lower organic carbon (0.15-0.41%) compared to lowlands. The KLV series had

intermediate AWC (8.09-13.34%), the highest in surface horizons. STP series showed AWC of 9.52-11.89%. The SDK series had the highest AWC (7.84-22.39%), with maximum water retention (22.39%) at 110-150 cm depth, associated with clay content (58.26%). Higher AWC in lowlands relates to more clay and silt, higher organic carbon (1.49-2.17%), and finer pore sizes that retain water. AWC offers a potential water storage index, but factors like effective rooting depth (soil depth, restrictive layers, gravel, barriers) influence the water accessible to plants. Drainage and water table dynamics affect actual water availability, with capillary rise or waterlogging either supplementing or reducing accessible water. Hydraulic conductivity impacts water infiltration, percolation, and redistribution, yet it was not measured here. Water retention measurements at only two points provide rough estimates; full profiles would offer better insights. Additionally, crop water use depends on atmospheric demand, crop stage, and management, making AWC one of many influencing factors.

The correlation analysis (Section 3.6, Fig. 3) shows expected links between particle sizes and water retention. Clay content strongly correlates positively with AWC, silt moderately, while sand strongly negatively correlates (see Figure 3 and Supplementary Table S1 for details). These relationships highlight texture's role in water capacity and underscore the importance of managing soil texture (preventing erosion of fine particles, maintaining organic matter). The AWC range (5.44-22.39%) across the catchment suggests different irrigation strategies. Upland soils with AWC <8% need: (a) frequent, light irrigations; (b) mulching; (c) organic matter to boost water retention. Lowland soils with higher AWC (11-22%) can: (a) be irrigated less often with larger depths; (b) buffer drought stress; but (c) need drainage management to avoid waterlogging. All implications remain hypothetical until validated by field trials, moisture monitoring, and crop performance assessments.

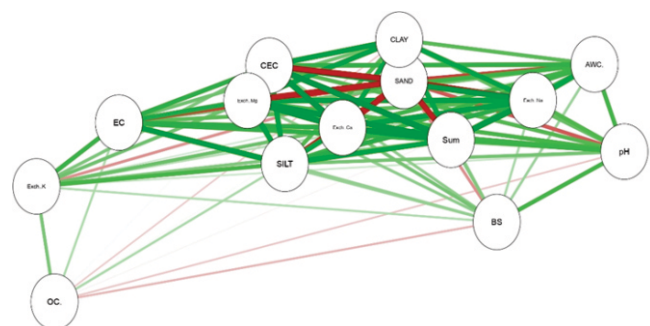


FIGURE 3 Pearson's correlation coefficients between different soil properties ($n = 45$) Only statistically significant correlations ($p < 0.05$) are displayed. Line color indicates direction (green=positive, red=negative), and thickness represents correlation strength.

TABLE 3 Morphological and physical characteristics of the KRP Dam soils

Depth (cm)	Horizon	Colour (moist)	Sand	Silt (%)	Clay	Texture	Coarse fragments (%)	Structure	Consistence		
									D	M	W
P1: Nagojanahalli (NGH) series											
0-16	Ap	5YR 3/3	85.95	5.92	8.13	ls	40	f 1 sbk	l	vfr	so/po
16-37	Bt1	2.5YR 3/4	71.84	7.63	20.53	scl	15	m 2 sbk	-	vfr	ms/mp
37-90	BC	2.5YR 4/3	67.01	12.37	20.62	scl	25	m 2 sbk	-	vfr	ms/mp
P2: Malayandahalli (MLD) series											
0-23	Ap	2.5YR 3/4	76.88	8.48	14.64	sl	-	m 2 sbk	h	fr	ss/sp
23-53	Bt1	2.5YR 4/4	52.66	9.48	37.86	sc	-	m 2 sbk	-	fr	ms/mp
53-88	Bt2	2.5YR 3/6	54.17	7.50	38.33	sc	-	m 2 sbkm	-	fr	ms/mp
88-109	BC	2.5YR 3/3	58.55	9.87	31.58	scl	30	m 1 sbk	-	fr	ms/mp
P3: Kalveli (KLV) series											
0-14	Ap	10YR 4/1	59.24	20.22	20.54	scl	-	m 2 sbk	sh	fr	ms/mp
14-28	A2	10YR 4/1	58.76	20.98	20.26	scl	-	m 2 sbk	-	fr	ms/mp
28-54	A3	7.5YR 4/3	78.95	11.74	9.31	sl	-	f 1 sbk	-	fr	ss/sp
54-78	A4	7.5YR 4/2	71.03	11.31	17.66	sl	-	f 2 sbk	-	fr	ss/sp
78-137	AC	10YR 5/3	64.24	12.78	22.98	scl	-	m 1 sbk	-	fr	ms/mp
P4: Santhapuram (STP) series											
0-21	Ap	10YR 3/1	76.4	11.4	12.2	sl	-	Puddled	-	fr	ss/sp
21-38	Bw1	10YR 4/4	55.4	5.40	39.2	sc	-	m 2 sbk	-	fi	ms/mp
38-48	BC	10YR 4/3	60.3	2.31	37.3	sc	60	m 1 sbk	-	fr	ms/mp
P5: Sundekuppam (SDK) series											
0-19	Ap	10YR 3/1	28.67	29.18	42.15	c	-	Puddled	l	l	vs/vp
19-49	Bw1	10YR 3/1	27.98	25.24	46.78	c	-	f 2 sbk	-	vfr	vs/vp
49-75	Bw2	10YR 3/1	24.21	26.47	49.32	c	-	f 2 sbk	-	vfr	vs/vp
75-110	Bw3	10YR 2/1	17.57	25.25	57.18	c	-	f 2 sbk	-	vfr	vs/vp
110-150	Bw4	10YR 2/1	16.74	25.00	58.26	c	-	f 2 sbk	-	vfr	vs/vp

Texture: ls - loamy sandy, sl - sandy loam, scl - sandy clay loam; sc - sandy clay; c - clay

Structure: Size (S) - vf - very fine, f - fine, m - medium, c - coarse; Grade (G) - 0 - structure less, 1 - weak, 2 - moderate, 3 - strong;

Type (T) cr - crumb, sg - single grain, abk - angular blocky, sbk - sub-angular blocky; *Consistence:* Dry: s - soft, l - loose, sh - slightly hard, h - hard Moist: l - loose, vfr - very friable, fr - friable, fi - firm, vfi - very firm; Wet: so - non-sticky, ss - slightly sticky, ms - moderately sticky; vs - very sticky; po - non-plastic, sp - slightly plastic, mp - moderately plastic; vp - very plastic

3.3 | Physico-Chemical Characteristics

Soil reaction in the lowland soils of the Dam catchment ranges from neutral to moderately alkaline, with pH values between 6.74 and 9.19 (Table 4). These soils exhibit slight to moderate alkalinity, attributed to regular water movement that enriches salt content. Electrical conductivity (EC) values range from 0.04 to 1.64 dS m⁻¹, indicating a generally non-saline condition; however, SDK soils show comparatively higher salt concentrations. The low EC values may result from the undulating terrain, which facilitates percolation and drainage, thereby leaching soil salts after rainfall (Nachshon, 2018). Organic carbon (OC) content varies from low to high, ranging from 0.36 to 2.17% in surface soils and 0.15 to 0.80% in sub-surface soils. Land use and management practices influence OC levels, with upland soils exhibiting lower content (~0.50%) compared to medium to high levels in lowland paddy soils. The generally low organic matter content is likely due to the predominance

of tropical climates, which accelerate organic matter decomposition and reduce vegetation cover (Srinivasan *et al.*, 2020). A variety of intricate connections between hydrogeology and soil biogeochemistry, frequently involving the temporal and geographic variation in water, nutrients, and carbon are varied in landform structure and vegetation (Ma *et al.*, 2017). Base saturation (BS) and cation exchange capacity (CEC) range from 80 to 100% and 4.43 to 54.0 cmol (p⁺) kg⁻¹, respectively, reflecting variations in clay content, organic carbon, and clay mineralogy across soil strata. Exchangeable bases in all pedons follow the order Ca²⁺ > Mg²⁺ > Na⁺ > K⁺ on the soil exchange complex. Elevated exchangeable calcium in surface soils may result from its redistribution by plant activities and water movement (Yang *et al.*, 2024). This increased Ca²⁺ occupancy on colloidal exchange sites likely accounts for the enhanced base saturation observed in all the soil series. The degree of leaching was assessed by variations in base saturation (Vasu *et al.*, 2016).

3.4 | Soil Nutrient Contents

Soil fertility indicates nutrient levels and contributes to plant growth and productivity (Table 5). The N estimation was avoided since the available N content was often low. The amount of nitrogen in Indian soils is minimal. This widespread deficit, which stunts plant growth and reduces crop yields, is partly due to low organic matter content, considerable leaching, and runoff losses (Dey & Sekhon, 2016). Tight cycling and minimal mineral N loss result from biotic processes that focus on competition for mineral N between microbes and plants (Kaye & Hart, 1997). The available P varied from 1.0 to 71 kg ha⁻¹ in different soils in the Dam catchment. Very low level in upland soils, Overall P rated as low and surface soils of lowlands are rated medium to high (23- 57 Kg ha⁻¹). On the other hand, lower soil horizons showed decreasing order and the surface horizons showed the maximum accessible P concentration. In poor land conditions, the application of complex fertilizers and phosphate to paddy and jasmine crops is increasing the availability of P (Srinivasan *et al.*, 2019). The greatest amount of soil P mobility and availability is determined by crop residue and water movement (Misal *et al.*, 2022). Due to the fixation of released P by clay minerals and iron and aluminum oxides, subsurface horizons have a lower P concentration than surface horizons. Soil's available K content ranged from 44 to 638 kg ha⁻¹. K fertilizer application, upstream K translocation from deeper depths, and groundwater capillary rise in a paddy environment all usually demonstrated a falling tendency with depth, with the highest accessible K content found in the surface and subsoils of the Dam catchment (Das *et al.*, 2022). Except for MLD soils, which had less organic matter in the intermediate and lower layers, the accessible S in soils ranged from 4.16 to 106.3 mg kg⁻¹ and was generally evaluated as high (>20 ppm). In soils, available B ranged from 0.04 to 0.56 mg kg⁻¹, which is considered poor. The distribution of clay and organic carbon over several strata is correlated with available S and B. The soil's DTPA-extractable zinc content varied from 0.02 to 3.30 mg kg⁻¹. There was little deep variation in the vertical distribution of zinc. The threshold level for accessible zinc in these soils was 0.60 mg kg⁻¹, with the exception of the KLV soils' surface layer (Lindsay & Norvell, 1978). High soil pH levels may have contributed to the restricted amount of zinc available by forming insoluble calcium zincate or Zn complexes in poorly drained low land condition (Rahman *et al.*, 2022).

Each Pedon had a sufficient amount of available Cu (0.34 to 2.70 mg kg⁻¹), and each value was far greater than the critical limit of 0.20 mg kg⁻¹ in soils. The DTPA-extractable Fe concentration of the soils varied from 0.76 to 74.50 mg kg⁻¹. The critical limit of 4.5 mg kg⁻¹ shows that there was sufficient accessible Iron (Fe) in the surface layers but not in the subsoils. The distribution of available Fe across all pedons showed no obvious pattern, yet it abruptly decreased. The buildup of organic carbon in the surface horizons could be the cause of the availability. Because of

the increased organic C, surface horizons showed higher quantities of DTPA-extractable Fe. The soil's accessible Mn content ranged from 0.36 to 11.30 mg kg⁻¹. The crucial limit of 1.0 mg kg⁻¹ for accessible Mn was met by the soils, and it almost decreased with depth. This could have been due to increased biological activity and organic C in the surface strata. The chelation of organic compounds created during the breakdown of organic sources provides the basis for micronutrient availability. Micronutrient availability is based on the chelation of organic compounds produced during the decomposition of organic matter (Dhaliwal *et al.*, 2019). By considering the relationships between soil structure, flow pathways, and hydrology, hydropedology may integrate ecological and hydrologic perspectives on nutrient cycle and biogeochemistry when assessing various nutrient transport and transformation (Castellano *et al.*, 2012).

3.5 | Soil Classification

Based on morphological characteristics, analytical properties, and moisture regime inference, the five major soil series were classified to the subgroup level according to USDA Keys to Soil Taxonomy (Soil Survey Staff, 2014). The classification, family designations, and area extent are presented in (Table 2 and Fig. 2).

3.5.1 | Upland Alfisols

Two soil series were identified: Nagojanahalli (NGH), classified as Typic Haplustalfs (Fine-loamy, mixed, isohyperthermic), characterized by an argillic horizon, ochric epipedon, ustic moisture regime, and isohyperthermic temperature, with minimal horizon development. The Malayandahalli (MLD), classified as Rhodic Palustalfs (Fine-loamy, mixed, isohyperthermic), features darker red coloration, presence of argillic horizons with clay accumulation, well-drained, and more developed profile features, placing these soils in the Alfisol order, typical of subhumid to semi-arid regions with seasonal moisture deficits.

3.5.2 | Lowland Inceptisols

The Santhapuram series (STP) is a Typic Haplustepts (Fine-loamy, mixed, isohyperthermic, calcareous) based on a Cambic horizon (Bw1, BC) with alteration but no clay accumulation, too shallow (48 cm) for Alfisol or Mollisol, with ustic moisture, throughout profile calcareous, and indicating simple profile development; the Sundekuppam series (SDK) is a Fluvaquentic Haplustepts (Fine-loamy, mixed, isohyperthermic) with Cambic horizons (Bw1-Bw4), features of fluvial parent material, periodic saturation near aquic conditions, a deep profile (150 cm), and isohyperthermic temperature. "Fluvaquentic" suggests occasional saturation, with dark colors indicating possible saturation or organic matter; future monitoring may lead to reclassification. Inclusion of the drainage class warrants re-evaluation if hydrological data contradict observed morphology. Inceptisols are young, minimally developed soils in recently saturated or periodically saturated materials.

TABLE 4 Physico-chemical characteristics of the KRP Dam soils

Depth (cm)	pH (1:2.5) H ₂ O	EC (dS m ⁻¹)	OC (%)	AWC (%)	Exchangeable cations				Sum of cations	CEC	BS (%)
					Ca	Mg	Na	K			
					(1 N NH ₄ OAc, pH 7.0) cmol (p ⁺) kg ⁻¹						
P1: Nagojanahalli (NGH) series											
0-16	6.76	0.116	0.36	5.44	3.24	0.68	0.04	0.15	4.11	4.43	93
16-37	6.92	0.049	0.17	6.77	8.95	1.43	0.05	0.16	10.59	11.54	92
37-90	7.42	0.091	0.15	6.48	11.3	3.78	0.08	0.15	15.31	14.42	100
P2: Malayandahalli (MLD) series											
0-23	7.34	0.075	0.41	5.91	3.60	1.95	0.03	0.12	5.70	7.09	80
23-53	7.53	0.080	0.41	7.99	6.44	3.95	0.65	0.07	11.12	11.99	93
53-88	7.62	0.078	0.20	6.66	6.89	3.74	0.61	0.06	11.30	11.77	96
88-109	7.88	0.074	0.24	6.75	9.29	3.56	0.71	0.06	13.62	13.95	98
P3: Kalveli (KLV) series											
0.14	7.75	1.140	0.43	13.34	9.12	4.85	1.65	0.28	15.90	15.97	100
14-28	8.18	0.649	0.58	12.61	9.85	4.23	1.36	0.35	15.78	15.45	100
28-54	8.62	0.226	0.54	9.66	8.00	3.20	0.43	0.15	18.43	7.21	100
54-78	8.70	0.245	0.80	8.09	10.2	3.40	0.78	0.30	14.68	13.18	100
78-98	8.76	0.260	0.60	12.36	11.3	4.21	0.78	0.25	16.54	14.52	100
P4: Santhapuram (STP) series											
0-21	6.74	0.499	2.17	11.89	5.73	3.44	0.92	0.42	10.50	12.15	86
21-38	8.17	0.336	0.21	9.52	9.23	5.21	1.01	0.46	15.91	15.39	100
38-48	8.30	0.335	0.16	10.41	11.3	5.29	1.18	0.47	18.29	17.74	100
P5: Sundekuppam (SDK) series											
0-19	8.01	1.640	1.49	7.84	23.5	12.32	6.74	0.93	43.53	43.12	100
19-49	8.36	1.100	0.41	11.44	24.0	14.20	7.02	0.60	45.82	43.22	100
49-75	8.87	1.040	0.35	9.92	25.0	15.45	10.72	0.34	51.51	49.20	100
75-110	9.10	1.340	0.29	18.33	24.0	14.00	14.27	0.24	52.51	51.55	100
110-150	9.19	0.528	0.29	22.39	25.0	13.20	18.07	0.28	56.55	54.00	100

TABLE 5 Nutrient's status of the KRP Dam soils

Depth (cm)	Macronutrients		Secondary and Macronutrients					
	P	K	S	B	Fe	Mn	Cu	Zn
	← (Kg ha ⁻¹) →		← (mg kg ⁻¹) →					
P1: Nagojanahalli (NGH) series								
0-16	9	174	12.13	0.15	4.64	5.68	0.34	0.12
16-37	7	189	13.64	0.17	2.90	5.42	0.62	0.04
37-90	6	187	8.34	0.26	1.86	2.82	0.56	0.04
P2: Malayandahalli (MLD) series								
0-23	5	104	4.16	0.47	8.22	3.06	0.68	0.16
23-53	3	58	6.66	0.56	6.18	11.3	0.66	0.08
53-88	4	44	5.83	0.26	4.40	8.36	0.50	0.14
88-109	3	49	5.00	0.35	4.02	6.94	0.36	0.10

continued on next page

Table 5 continued

Depth (cm)	Macronutrients		Secondary and Macronutrients					
	P	K	S	B	Fe	Mn	Cu	Zn
	← (Kg ha ⁻¹) →		← (mg kg ⁻¹) →					
P3: Kalveli (KLV) series								
0-14	71	323	106.3	0.23	7.78	1.38	2.04	1.76
14-28	52	360	56.34	0.15	5.32	1.46	1.94	0.80
28-54	16	210	16.66	0.07	2.86	1.08	0.56	0.14
54-78	14	363	13.49	0.24	1.38	1.26	1.08	0.04
78-137	18	316	15.87	0.16	1.24	1.10	0.48	0.02
P4: Santhapuram (STP) series								
0-21	64	359	59.16	0.36	74.5	2.18	2.70	3.30
21-38	3	349	20.83	0.04	3.70	0.46	1.76	0.12
38-48	8	367	19.16	0.15	2.04	0.36	1.28	0.18
P5: Sundekuppam (SDK) series								
0-19	57	638	58.33	0.12	6.70	3.40	2.16	1.06
19-49	5	384	36.66	0.12	2.04	1.70	1.44	0.20
49-75	1	248	17.50	0.09	1.32	1.02	0.68	0.14
75-110	3	203	21.66	0.27	1.20	1.20	0.90	0.18
110-150	1	207	45.00	0.12	0.76	1.92	1.18	0.10

3.5.3 | Lowland Entisols

Kalveli series (KLV) is classified as Typic Ustifluvents (Sandy, mixed, isohyperthermic, calcareous). It lacks diagnostic horizons, has fluvial parent material with stratification, shows a decrease in organic carbon with depth, and has a calcareous, sandy texture. Entisols are recent deposits, and the KLV series reflects alluvial deposition with limited horizon development. Soil-forming factors like drainage, moisture, landform, age, human activities, and parent material influence soil types. Well-drained uplands have more developed soils, while lowlands with saturation or recent deposition have less developed soils. Human activities like tillage disrupt horizons, complicating classification. Landscape position affects weathering, impacting classification, which can be uncertain based on climate and morphology. Hydrological conditions influence soil properties, but were not measured here.

Soils from five major Dam catchments were classified by the USDA based on their morphological traits and soil properties, influenced by climate, topography, and vegetation. Upland soils are mainly Alfisols (NGH: Typic Haplustalfs, MLD: Rhodic Palustalfs) due to argillic horizons and an ochric epipedon. STP and SDK soils are Inceptisols (STP: Typic Haplustepts, SDK: Fluvisol Haplustepts) with cambic epipedons. Lowland Kalveli soil (KLV) is an Entisol, despite lacking epipedon and endopedon. Water fluctuations cause poor oxidation and biological activity, limiting development. Upland soils drain well, leading to rapid leaching and accumulation in lower layers.

3.6 | Correlation Analysis

The correlation between the different soil parameters is depicted on the network map; green lines indicate positive correlation, red lines indicate negative correlation, and the thickness of the line indicates the degree of the association (Fig. 3). Exchangeable Ca, Mg, Clay, and sum cations exhibit significant positive associations with CEC. Silt appears to have a positive correlation with both CEC and AWC (available water content), while AWC has a positive correlation with both CEC and clay. Results show that sandy soils have reduced nutrient retention and water-holding ability, and exhibit substantial negative associations with clay, CEC, and AWC. A few variables, such as BS and the sum of the bases, have negative associations with organic carbon (OC). The sum of the cations, exchangeable calcium, and pH all have a positive correlation with base saturation (BS). A similar outcome was also verified by Lalitha *et al.*, (2023). There are no measurable relationships between soil hydraulic functions and morphological features of soil structure. There is a strong correlation between the qualitative evaluations of micro-morphological features and unsaturated conductivity, which is linked to soil fluxes to macro-morphological elements (Vervoort & Cattle, 2003).

3.7 | Soil Management

Major soil variability in the KRP Dam catchment, based on the landforms, water movement, and their resources and management are given in Figure 4. Mango, ragi, pulses, and oilseed crops are grown on moderately to severely degraded upland soils (NGH and MLD). The soil's color ranges from dark reddish brown to dark red, depending on the well-drained, excess leaching of base cations (Ca, Mg, Na, and K), and the presence of iron and aluminum ions (Srinivasan *et al.*, 2021). Soils are shallow to fairly deep. The texture of

the soil ranges from sandy loam to sandy clay, which is classified as having a medium amount of clay content and a low capacity to retain water. Adopting soil-based land use methods, applying organic manures to promote soil fertility, and using carbon-enhancing techniques to increase sequestration are all ways to manage upland soils (Li *et al.*, 2025). Various soil and water conservation techniques are used to manage soil erosion issues (Raj *et al.*, 2024). In the KRP Dam basin, paddy, coconut, and jasmine are mostly supported by lowland soils (KLV, STP, and SDK). The soils have a high clay concentration, are deep, poorly drained, and have a high AWC. Excess calcium and sodium salts make the soil unsuitable for various cropping systems, and

inadequate drainage results in poor water quality and workability. Management of lowland paddy soils where need to be adopt suitable drainage systems, and excess salt content in water and soils needs to be evaluated and recommended suitable reclamation techniques to improve crop performances and productivity (Kumar *et al.*, 2022). To increase the contribution of hydropedology to the hydrology with respect to land use in KRP catchments by measuring crop yield and soil water regime. Hydropedologists might be able to make a substantial contribution with similar work on other land-use and climate change issues (Vepraskas *et al.*, 2009)

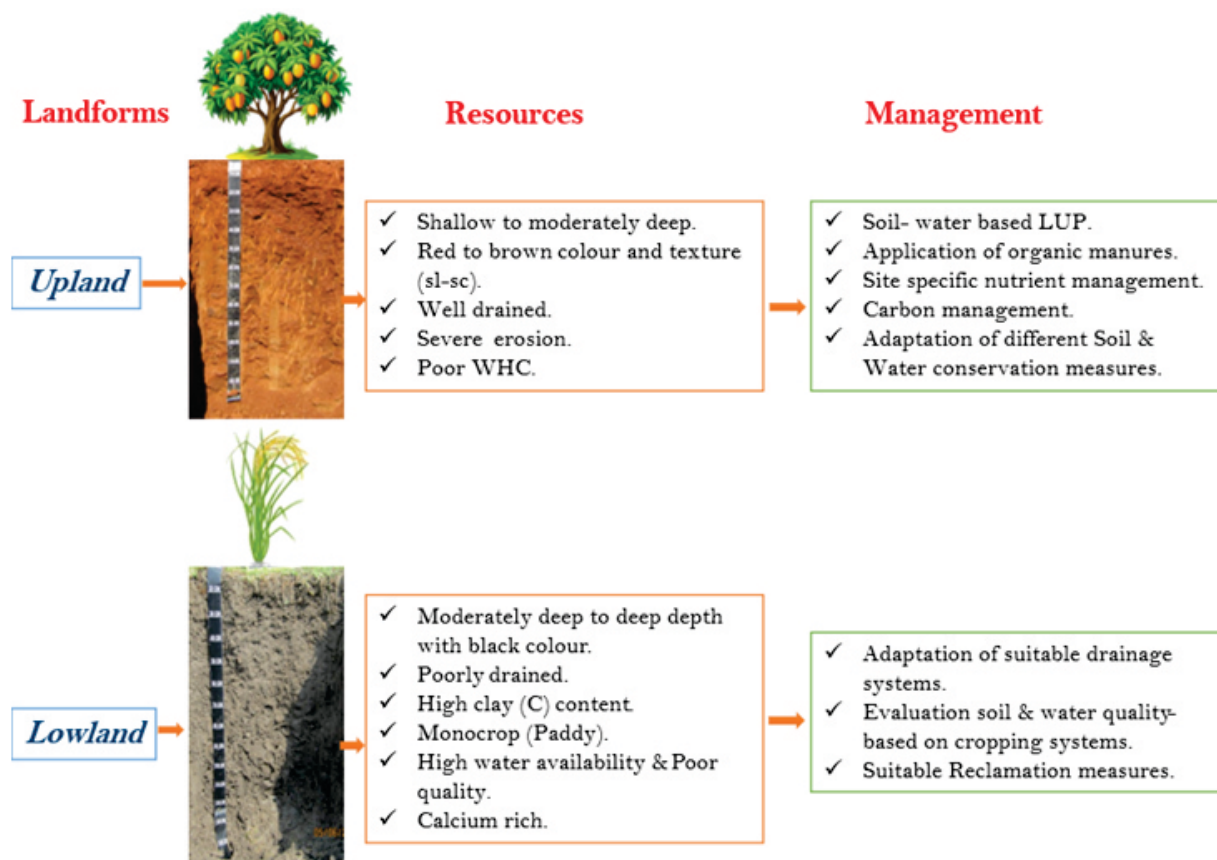


FIGURE 4 Conceptual framework for soil and water management based on identified soil limitations (*Proposed interventions require field validation)

4 | CONCLUSIONS

A detailed soil survey of the KRP Dam catchment at a 1:10,000 scale identified five major soil series with distinct properties linked to landform position. Variations in soil characteristics support topography's influence on pedogenesis. Upland soils (Nagojanahalli and Malayandahalli, classified as Alfisols) are moderately deep (90-109 cm), well-drained, dark reddish-brown to reddish-brown, with sandy loam to sandy clay textures and argillic horizons. These soils show moderate to severe erosion, low organic carbon (0.15-0.41%), limited water holding capacity (5.44-7.99%), and nutrient depletion

(P: 3-9 kg ha⁻¹), requiring soil conservation, organic matter, and fertility management. Coarse fragments (15-40%) further reduce agricultural potential. Lowland soils (Kalveli, Santhapuram, and Sundekuppam, classified as Entisols and Inceptisols) exhibit features of periodic saturation: dark gray to black colors, massive, puddled surface horizons, and higher clay content (37-58%). They have higher water capacity (11.89-22.39%), better nutrients (available P: 23-71 kg ha⁻¹), and greater cation exchange capacity (43-54 cmol [p⁺] kg⁻¹). Yet, they also show elevated electrical conductivity (up to 1.64 dS m⁻¹), alkaline pH (8.01-9.19), and zinc deficiency (<0.60 mg kg⁻¹),

indicating potential issues with drainage, salinity, and micronutrient availability. Correlation analysis revealed strong positive relationships between clay, cation exchange capacity, silt, and exchangeable bases, and negative correlations with sand. These findings highlight the importance of soil texture in nutrient retention and water holding capacity, supporting texture-based management zoning.

Several limitations must be acknowledged. First, drainage class assignments relied solely on morphological indicators like soil color, structure, and landscape position, without direct water table measurements or hydrological monitoring. The classification of soils as "periodically saturated" or "poorly drained" is inference, not measured hydrology. Second, while the study identifies areas with contrasting pedological features, soil-water dynamics such as seasonal water table fluctuations, hydraulic conductivity, and moisture patterns remain unquantified. Third, proposed management interventions for upland soils (contour bunding, organic amendments, water conservation structures) and lowland soils (subsurface drainage, gypsum, zinc) are conceptual and require validation through controlled experiments with replication and farmer participation. Future research should include: (i) installing piezometric networks for water table monitoring; (ii) using soil moisture sensors; (iii) measuring hydraulic conductivity; (iv) assessing irrigation water quality; (v) setting up long-term experimental plots to test management options with economic analysis; and (vi) integrating soil and hydrological data to develop quantitative models. Despite limitations, this study contributes by: (a) providing the first detailed soil map of the KRP Dam catchment at 1:10,000 scale, creating a baseline for future monitoring; (b) characterizing soil variability across 8,477 ha (67.94%) with 92 profiles; (c) identifying soil-landscape relations to guide precision agriculture; (d) documenting soils supporting current cropping systems; and (e) establishing a framework for future hydropedological research. In conclusion, the data offers an essential baseline for land use and agriculture planning. Soils indicating water regimes offer initial management guidance, but hydropedological understanding needs integration with hydrological monitoring. The proposed framework is a research agenda needing field validation, not ready-to-implement recommendations. This study lays the pedological groundwork for future soil-hydrology research to develop site-specific strategies for sustainable agriculture and ecosystem management in dam-affected areas.

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CONFLICT OF INTEREST

There is no conflict of interest in the study.

DATA AVAILABILITY STATEMENT

Data is available with the corresponding author and will be provided if it's required.

AUTHOR CONTRIBUTION

SR: Concept planning, Field survey and data preparation, Methodology and drafting manuscripts.

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Short-Term Effects of Solid Piggery Sludge Application on Soil Properties and Metal Accumulation In Rice and Maize under Humid Lowland Tropical Conditions in Papua New Guinea

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ABSTRACT

The livestock industry in humid tropical regions is generating increasing amounts of piggery waste, necessitating sustainable solutions. Agricultural land application offers waste-to-resource potential, but concerns about heavy metal contamination and crop safety necessitate evaluation. This study examined short-term effects of solid piggery sludge (SPS) on soil properties and metal accumulation in rice and maize in Papua New Guinea over six months, with four SPS rates (0, 2.5, 5, and 10 t ha⁻¹) and five replicates. Soil samples were analyzed for physical, chemical, macronutrients, and heavy metals; plant tissues for metal content and bioaccumulation; and growth parameters were measured pre-reproduction. Data showed SPS increased soil organic carbon (121-185% in control vs. 1,021-1,316% at 10 t ha⁻¹), organic matter, and water holding capacity; nitrogen rose from 1,200-1,450 to 2,100-2,300 mg kg⁻¹; macro- and micronutrient levels increased dose-dependently. Heavy metals like lead, cadmium, and chromium exceeded FAO limits at higher rates. Maize benefited from SPS, with height and dry matter up by 69-83% and 55-140%, respectively; rice showed growth inhibition at higher rates despite more tillers. Tissue metal levels were higher in rice; bioaccumulation factors often below 1.0, except for Co, Zn, and Mn at higher doses. Low SPS (≤ 2.5 t ha⁻¹) improved soil fertility while keeping metal levels near background; higher rates risk metal accumulation. Maize tolerated metals better than rice. Plants were harvested before grains fully matured, so actual grain safety is unknown. Six months limit long-term assessment of metal buildup and system sustainability. Results suggest 2.5 t ha⁻¹ as a tentative safe maximum, but multi-year studies are needed before commercial use.

1 | INTRODUCTION

The rice (*Oryza sativa*) and maize (*Zea mays*) industries are essential to livestock for feed and to humans as food (e.g., Li, 2017; Yu *et al.*, 2019; Soto-Gómez & Pérez-Rodríguez, 2022; Ding *et al.*, 2023) in the humid tropics. However, production of the two crops is limited to specific farms on a small scale only, and production is always low (e.g., Wu *et al.*, 2024) due to the need for more investment, awareness, research, and development (Li & Zhang, 2023; Michael, 2023). The production of these grain crops on a large scale is expensive, requiring heavy investment and intensive production practices, one of which is the need for large quantities of inorganic (chemical) fertilizers (Xue *et al.*, 2024). The supply of inorganic fertilizers is limited to certain areas, and availability and affordability are issues for most farmers, especially smallholders (Fillippo, 2022). The problems related to the supply and affordability of inorganic fertilizers allow local farmers to use piggery sludge (or other livestock wastes) as an alternative soil nutrient source (Levario *et al.*, 2025). Still, its wider use is yet to be realized

(Zhang *et al.*, 2011) in the wider humid tropical areas.

The livestock industry has grown, there is a demand for the need to manage waste (Zhao *et al.*, 2023), and a need to know how this can be done sustainably. Not only that, the rising need to manage soil fertility in grain (rice and maize) production, using piggery sludge (livestock wastes) as an example, has broader implications (e.g., Yuan *et al.*, 2021; Bertici *et al.*, 2022). Piggery waste management and its associated environmental impacts are significant global issues as the livestock industry expands (e.g., Loyon, 2018; Park *et al.*, 2018; Thakur *et al.*, 2025). Hence, the need to manage, handle, and utilize agricultural waste to meet the increasing demand for food and resource recovery has become paramount (Zhang & Jahng, 2010; Ferreira *et al.*, 2023). The drive toward sustainable waste management is to understand the different types of waste and how best to manage them to protect the environment and benefit from them (Cao *et al.*, 2021; Koul *et al.*, 2022; Hao *et al.*, 2024).

On the other hand, land use has increased, and soil nutrient availability has declined, thereby undermining sustainable agriculture (Topas & Michel, 2023); (Chakraborty *et al.*, 2024). The increased production of livestock waste and the decline in soil fertility, coupled with the high prices of chemical fertilizers (Bertici *et al.*, 2022), warrant thorough, systematic research on the agricultural use of livestock waste (Khan *et al.*, 2024). The background review of the literature showed that the use of piggery wastes on farms has been well-documented (e.g., Iregbu *et al.*, 2014; Roba, 2018; Machete & Chabo, 2020; Doreswamy *et al.*, 2021; Kodani, 2023; Zhao *et al.*, 2025). Still, the results are variable and cannot be extrapolated due to differences in environmental conditions and the feeding systems. There is a need to establish the sustainable use of solid piggery sludge in agriculture to assess the changes in soil chemistry induced when applied as a soil amendment from an agricultural and environmental perspective under humid lowland tropical agroclimatic conditions. Further, the need to investigate the different rates (quantities) that can be applied and the resultant impact on the performance of crops important to the livestock industry is not clearly established.

2 | MATERIALS AND METHODS

2.1 | Description of Study Site

The study was conducted at PNGUoT Agriculture Farm (6°41" S, 146°98" E) in Lae, Morobe Province, PNG, at 65 m elevation, described in many publications (e.g., Michael, 2019a; b; 2020a; b; c; d). The climate has 3800 mm annual rainfall, evenly spread, with mean temps of 26.3°C, min 22.9°C, max 29.7°C. Evaporation is 2139 mm annually, with rainfall exceeding evaporation each month. Climate is Af (Koppen), a tropical rainy climate with >60 mm driest month. The soil is well-drained, sandy, alluvial, classified as Typic Tropofluents or Eutric Fluvisol (2006), with soil parameters shown in (Table 1).

2.2 | Collection and Preparation of Piggery Sludge

Solid treated piggery sludge was collected from a stockpile from a commercial piggery farm outside of Lae City and brought to the farm for use. The samples were dried on canvas under direct sunlight for a week and weighed using an electric scale. The dried sludge samples were packed into 1000 g, 500 g, and 250 g polyester bags and kept dry before field applications. A sample was sent to an analytical laboratory for mineral analysis.

2.3 | Sourcing of Planting Materials

Rice (*O. sativa*) and maize (*Z. mays*) were chosen as grain crops. The plants chosen are essential for various industries as raw materials for feed production for livestock as well as food for human consumption in PNG. The planting materials were sourced as seeds from local supplies within Lae City, Morobe Province, PNG.

2.4 | Land Preparation and Setting of Experiment

A piece of land (17 m x 13 m) on the farm was ploughed and harrowed using a tractor (Messy Ferguson, Germany). A total of 96 experimental plots (1 m x 1 m) were prepared.

HIGHLIGHTS

- Solid piggery sludge addition improved soil physical and chemical properties.
- Solid piggery sludge addition improved soil nutrient availability to maize and rice.
- Changes in soil chemistry and nutrient availability to maize and rice were dose-dependent.
- Tissue accumulation of metals was dose and crop dependent, maize being more tolerant than rice.

The plots were separated by a 0.5 m spacing within and between plots. There were four treatments: control (0), 2.5 (lowest), 5 (high), and 10 (highest) t ha⁻¹ of dry piggery sludge. The treatments were arranged in a completely randomized block design with five replications. Dry sludge was applied to the soil surface and manually incorporated into the top 30 cm using handheld shovels.

2.5 | Planting and Production Management

Based on germination test results, fifteen seeds of rice and five seeds of maize were sown. Throughout the four months of running the study, watering, weeding, and pest and disease control were carried out in accordance with the farm's general practice. The maize plants were thinned to two tillers per treatment plot, and no thinning was done to the rice plants.

2.6 | Field Sampling and Preparations

2.6.1 | Sampling

All biomass (above- and below-ground) was sampled from all treatment plots. Soil and root samples were collected from the top 30 cm rhizosphere or a 10 cm radius of the pots. Each plant was gently uprooted with minimum root disturbance using a handheld shovel. The soil with intact roots was carefully shaken onto a canvas and homogenized by mixing before collecting 3 kg of soil subsample per replicate (12 kg per treatment) and bagging it into pre-labelled paper bags. The shoot and root biomasses were chopped into 1-2 cm long pieces using a gardener's clipper and bagged in pre-labelled plastic bags. The same amount of soil was collected from the other treatments; no amendment was made (control), and an amendment was made but not planted. All the samples were transported to the laboratory for further processing (cleaning, washing, and oven-drying).

2.6.2 | Sample Preparations

In the laboratory, the roots were gently washed under tap water to remove excess soil, and their fresh weight was recorded. Then the samples were air-dried at room temperature for 24 hours, and all the leaves, stems, and roots were chopped into 1-2 cm long pieces using kitchen knives, packed into paper bags, and oven-dried at 65 °C for three days to determine dry matter (yields). The dry samples were then ground using a food blender, packed into resealable bags, and kept dry for mineral analysis. The soil samples from the field were transferred to aluminium trays, air-dried

at room temperature for 7 days, and then sieved to 2.0 mm, 0.5 mm, and 0.05 mm for different measurements and

analyses at the PNGUoT Analytica Laboratory.

TABLE 1 Soil parameters of the farm soil, SPS and expected range in the amended soils.

Soil parameters	Composition of parameters of the farm soil and the SPS		
	Farm (Study site)	SPS	Range
Soil organic matter (SOM, %)	2.59±0.1	22.17±0.1	3-22
Soil organic carbon (SOC, %)	1.50±0.0	12.76±0.8	2-13
pH	6.50±0.1	6.80±0.6	6-7
Cation exchange capacity (meq/100 g)	7.23	-	-
Base saturation (BS, %)	65.30±0.5	11.76±0.2	6.5-12
Electrical conductivity (EC, mS m ⁻¹)	0.03±0.1	1.92±1.2	0-2
Water holding capacity (WHC, %)	54.25±1.0	53.71±0.6	54-54
Bulk density (BD, g cm ⁻³)	1.12±0.0	0.60±0.1	0.6-1
Total porosity (TP, %)	52.02±0.6	56.02±1.2	52-56
Particle composition (SPC, %)			
(a) Sand	89.98±2.0	83.13±0.0	83-90
(b) Silt	0.45±0.0	4.01±0.1	0.5-4
(c) Clay	9.63±0.0	12.83±0.0	10-13
N (mg kg ⁻¹)	1500.12±0.2	17,600.45±20.3	15,000-18,000
P (mg kg ⁻¹)	10.62±0.3	49.62±1.1	11-50
K (mg kg ⁻¹)	20.73±0.3	145.94±4.9	21-146
Mg (mg kg ⁻¹)	131.28±5.7	666.02±10.6	131-670
Ca (mg kg ⁻¹)	732.11±5.6	2,643.27±54.5	732-2,640
S (mg kg ⁻¹)	6.52±0.7	144.24±0.8	7-144
Na (mg kg ⁻¹)	14.32±0.5	62.72±2.3	14-63
Fe (mg kg ⁻¹)	507.38±0.2	72.89±0.50.2	73-507
B (mg kg ⁻¹)	8.82±0.8	18.01±0.9	9-18
Mn (mg kg ⁻¹)	46.30±0.6	191.17±0.5	46-191
Al (mg kg ⁻¹)	270.67±1.1	9.23±1.3	9-271
Cd (mg kg ⁻¹)	6.62±0.2*	12.67±0.3*	7-13
Ni (mg kg ⁻¹)	70.61±0.8*	43.73±0.7	44-71
Pb (mg kg ⁻¹)	730.56±1.3*	4.43±0.2	4-731
Zn (mg kg ⁻¹)	89.56±1.1	439.14±1.5	90-439
Cr (mg kg ⁻¹)	96.08±0.1	21.19±0.7	21-96
Co (mg kg ⁻¹)	<5.12±0.0	<5.21±0.0	<5
Cu (mg kg ⁻¹)	257.82±2.3*	65.09±0.2	65-258

The values are means of four replicate samples ± standard error. Note, range is the expected change in the amended soils. An asterisk shows concentrations higher than FAO permissible limits of agricultural soil.

Important soil physical and chemical properties that influence soil fertility, mineral, and nutrient availability were determined according to Michael (2020a; b; c; d). Ground biomasses were analysed using laboratory analytical equipment, and the standard equations (Eqns. 1 to 10) were used to assess them. Total nitrogen was analysed by the Kjeldahl method (Buchi K436 speed digester and Buchi K-350 Kjeldahl distillation unit). A sample of one-gram (<2 mm) air-dried soil was digested using 15 ml of concentrated sulfuric acid at 300 – 400 °C (H₂SO₄ reduces nitrogen as ammonium sulphate (NH₄)₂SO₄). The sample solution was distilled using 60% sodium hydroxide (NaOH), where ammonium (NH₄⁺) was converted to ammonia (NH₃) gas, which was collected using 25 ml of 2% boric acid with three drops of mixed indicator. It was then back-titrated with 0.01 M HCl. The available nitrogen (NO₃⁻ N) was determined using the salicylic acid method with UV light after extraction with 0.027 M Ca(OH)₂. Available

phosphorus (P) was determined by the Olsen method using a spectrophotometer (UV1800, Shimadzu Corporation, Japan) with 0.5 M sodium bicarbonate (NaHCO₃) after adjusting the pH to 8.5 with NaOH. Extraction was for 30 minutes using a 200-rpm shaker at a soil-to-extraction solution ratio of 1:20 (w/v).

All the other nutrients (K, Mg, Na, Ca, S, Mn, Zn, B, Cu, Fe, and Al) were extracted with a Melich 3 extraction solution (0.2 M CH₃COOH + 0.25 M NH₄NO₃ + 0.015 M NH₄F + 0.13 M HNO₃ + 0.001 M EDTA) in 1:10 (soil: extractant ratio) and analysed using an ICP OES. The data was calculated as per Melich3 18F1 standard as follows:

$$N = ((C - B) \times (V_e \div W_s)) \quad (1)$$

V_e is effective volume used in the extraction calculation (1:20 soil is to solution),

Where N is nutrient, e.g., K, C is concentration, B is blank ((mg element/dm³), and W_s is the weight of the sample. The

data in milli-equivalent (mEq./100 g soil) were converted to milligrams (mg) as follows:

$$\text{mg} = [(\text{mEq} \times \text{Aw}) \div \text{V}] \quad (2)$$

Where Aw is the atomic weight of an element (e.g., nitrogen) and V is valence, respectively.

Cation exchange capacity (CEC) was estimated based on the nutrient data. Soil moisture content was determined by oven-drying samples at 105 °C for 24 hours, and the final weight was estimated after 2 hours of cooling by subtracting the dry weight from the initial fresh weight.

The pH was measured using a standard dilution (1:5 soil: water w/v) method (Michael, 2019b). Electrical conductivity was measured using a Direct Soil EC meter (Spectrum Technologies Inc., 12360S Industrial Dr., East Plainfield, IL 60585, USA) with the same solutions (Michael, 2020a-d).

The bulk density (g cm^{-3}) was calculated by oven-drying the cores at 105 °C for 48 hours, followed by weighing again (Michael, 2020a-d). The oven-dry weights were divided by the core volume and estimated as follows:

$$\text{BD} = (\text{Odw} \div \pi r^2 h) \quad (3)$$

Where BD is bulk density (g cm^{-3}), Odw is oven dry weight, and the formula for estimation of the volume of the core.

The soil organic carbon (SOC) content was analyzed using the weight-loss-on-ignition method (Schulte & Hopkins, 1996). A five-gram sample was weighed into a crucible and heated in a muffle furnace for 12 hours at 105 °C (Wf). The weights were recorded after 2 hours of cooling, further combusted at 375 °C for 17 hours (Fw), cooled for 2 hours, and weighed (Michael, 2019a). The SOC content was estimated by multiplying the carbon value by a conversion factor (1.72) and expressed as a percentage:

$$\text{SOC} (\%) = [((\text{Wf} - \text{Fw}) \div \text{Wf}) \div 1.724] 100 \quad (4)$$

The conversion factor was used to convert soil organic matter content to organic C, assuming 58% C in the organic matter. The size of the C stock in each profile was calculated as the sum of the individual C fractions (%) $\times$ BD (g cm^{-3}) $\times$ profile depth (SP, cm) $\times$ Cf and expressed as a percentage as per Michael (2020) as follows:

$$\text{SOC}_{\text{stock}} (\%) = [((\text{SOC}/100) \times \text{BD} \times \text{SP}) \times \text{Cf}] \quad (5)$$

SOC was determined using Eqn. 4, and the Cf was obtained as $100 \div 58$. The soil organic matter (SOM) contents were estimated using the SOC content and the conversion factor as follows:

$$\text{SOM} (\%) = [(\text{SOC}) \times \text{Cf}] \quad (6)$$

The water holding capacity (WHC) was estimated by soaking soil samples in water (100% WHC) and draining them through filter paper overnight (e.g., Michael, 2019a). These were weighed for the wet weight (W_w), dried in an oven at 105 °C for 24 hours, and reweighed to obtain the oven-dry weight (OD_w). The WHC was estimated as follows:

$$\text{WHC} (\%) = [((W_w - OD_w) \div OD_w) 100] \quad (7)$$

The total porosity was determined as follows:

$$P = \left[\left(1 - \frac{\text{BD}}{d} \right) 100 \right] \quad (8)$$

Where P is total porosity (%), BD was defined and d is particle density of 2.65 g cm^{-3} .

The weight of the SOM to a given depth and area was estimated as follows:

$$\text{SOM (tons)} = [(\text{SOC} \times \text{BD} \times \text{SP} \times \text{ha}) 1.72] \quad (9)$$

Where SOC is in %, BD is in g cm^{-3} , SP is in m and ha is hectare ($10\,000 \text{ m}^2$).

Bioaccumulation factors (BiF) were calculated as:

$$\text{BiF} = [\text{Metal}]_{\text{plant tissue}} / [\text{Metal}]_{\text{soil}} \quad (10)$$

Values >1 indicate metal accumulation, while values <1 suggest limited uptake or exclusion mechanisms.

2.7 | Statistical Analysis

Data from four replicates were used for analysis. The fifth replicate served as a backup and was excluded from statistical analysis to maintain a consistent sample size across parameters. Treatment means and standard errors were calculated for all parameters. For each response variable, assumptions of normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test) were tested. Data were log-transformed where necessary to meet assumptions. To test for main effects and interactions, two-way ANOVA with crop type and amendment rate as fixed factors was performed. When a significant interaction was detected ($p < 0.05$), one-way ANOVA for each crop species was performed. For one-way ANOVAs with significant treatment effects, Tukey's HSD post hoc test for pairwise comparisons was used. Significance level was set at $\alpha = 0.05$ for all tests. All analyses were conducted using JMP Pro 16 (SAS Institute Inc., Cary, NC, USA).

3 | RESULTS AND DISCUSSION

3.1 | Changes in Soil Properties

The changes in soil properties measured under rice are shown in Table 2. Generally, an increase in sludge improved all the soil properties except electrical conductivity, pH, and particle composition. The measured changes in soil properties were as follows: organic carbon was 1.65 – 96.69%, organic matter was 18.84 – 138.45%, base saturation was 4.62 – 10.77%, and moisture and water-holding capacity in the soil amendment with the highest amount were 50% and 76.47%, respectively. All three rates significantly improved water-holding capacity and total porosity, except for bulk density. The highest sludge-only rate significantly increased this.

The changes in soil properties under maize production were similar to those under rice production (Table 2), except for some notable differences. All the different rates

significantly increased soil organic carbon and organic matter contents, the highest being recorded in the soil amended with the highest amount of sludge. Base saturation, moisture level, and water holding capacity were highest at higher rates. Soil electrical conductivity, pH, bulk

density, and soil texture remained nearly unchanged under maize. The different rates significantly increased total porosity, while the bulk density remained unchanged (Table 2).

TABLE 2 Changes in Soil Properties Following Six Months of Piggery Sludge Amendment

Parameter	Crop	Control (0)	Low (2.5 t ha ⁻¹)	Medium (5 t ha ⁻¹)	High (10 t ha ⁻¹)	Effect Size ¹
Organic Carbon (%)	Rice	1.21±0.04 ^a	3.23±0.02 ^b	6.75±0.03 ^c	10.38±0.02 ^d	856%
	Maize	1.85±0.02 ^a	3.05±0.02 ^b	7.09±0.03 ^c	13.16±0.02 ^d	711%
Organic Matter (%)	Rice	2.09±0.10 ^a	2.55±0.03 ^b	3.15±0.02 ^c	4.91±0.20 ^d	235%
	Maize	3.19±0.03 ^a	2.79±0.02 ^b	3.81±0.02 ^c	5.09±0.03 ^d	160%
pH	Rice	6.50±0.10 ^a	6.60±0.10 ^a	6.50±0.10 ^a	6.70±0.03 ^a	NS
	Maize	6.42±0.10 ^a	6.62±0.10 ^a	6.54±0.10 ^a	6.52±0.10 ^a	NS
Moisture (%)	Rice	6.10±0.04 ^a	6.90±0.30 ^b	6.72±0.50 ^b	8.70±0.10 ^c	143%
	Maize	6.42±0.10 ^a	8.13±0.30 ^b	10.42±0.20 ^c	17.32±0.10 ^d	270%
WHC (%)	Rice	33.70±0.50 ^a	45.65±0.70 ^b	50.35±0.70 ^c	59.61±0.50 ^d	177%
	Maize	56.34±0.50 ^a	54.63±0.60 ^a	61.04±0.70 ^b	65.65±0.70 ^c	117%
Base Saturation (%)	Rice	64.50±0.50 ^a	67.57±0.50 ^b	67.37±0.80 ^b	71.77±0.80 ^c	111%
	Maize	64.41±0.60 ^a	66.77±0.80 ^{ab}	69.27±0.70 ^{bc}	74.63±0.70 ^c	116%
EC (mS m ⁻¹)	Rice	120.02±0.20 ^a	130.03±0.10 ^b	145.73±0.30 ^c	240.56±0.20 ^d	200%
	Maize	130.23±0.10 ^a	145.24±0.10 ^b	158.14±0.20 ^c	185.44±0.20 ^d	142%
Bulk Density (g cm ⁻³)	Rice	1.16±0.10 ^{ab}	1.20±0.02 ^a	0.56±0.10 ^b	0.29±0.10 ^c	25%
	Maize	1.11±0.04 ^a	1.24±0.10 ^a	1.25±0.10 ^a	1.17±0.04 ^a	NS
Porosity (%)	Rice	48.12±0.40 ^a	56.22±1.20 ^b	64.21±1.10 ^c	72.24±1.30 ^d	150%
	Maize	50.12±0.40 ^a	44.22±1.10 ^b	44.21±1.10 ^b	46.23±1.30 ^{ab}	NS

Notes: ¹Effect size = (High treatment / Control) × 100%, ²Decrease from control, WHC = Water Holding Capacity; EC = Electrical Conductivity. The different letters within a row indicate statistical differences at p<0.05.

The farm soil and sludge served as good sources of organic matter, with the sludge enhancing water-holding capacity. The particle composition showed a high proportion of clay (Table 1). When sludge was added to the soil, it significantly increased organic matter, thereby positively affecting organic carbon content. This boost in organic matter further improved soil moisture, water-holding capacity, and pH under rice and maize cultivation. Soil electrical conductivity indicates the soluble salt content (salinity) and is an important marker of soil mineral content, influencing whether salt ions could limit crop growth. This parameter was very low, ranging from 0.03 to 0.05 mSm⁻¹, similar to the normal pH range, suggesting the soil was suitable for crop growth. Bulk density improved notably after sludge amendment, as reflected by increased soil porosity observed under each crop. This increase in porosity was partly due to the high sand content in the sludge. Particle composition remained fairly stable, showing little impact from sludge on this property. In a long-term study spanning 2004–2020, Ferreira *et al.*, (2022) examined the effects of piggery sludge and litter, finding that adding a unit increased soil C content and raised soil pH. Over a 17-year period, Tavares *et al.*, (2019) applied various rates of piggery sludge and measured changes in soil carbon balance, organic matter mineralization, humic substance formation, and soil aggregation. In a shorter 10-year study, the addition of liquid swine manure improved soil porosity, organic matter content, and exchange cations in soybean production (Antoneli *et al.*, 2019). Our findings, based on a

shorter timeframe, generally agree that applying piggery wastes in slurry, liquid, or solid form enhances overall soil properties, regardless of application timing, duration, or agroecological conditions.

3.2 | Changes in Soil Mineral and Metal Compositions

Table 3 shows the changes in soil mineral content. The most notable increase was in soil nitrogen, which was also significantly higher than P and K, the other main macronutrients. Among secondary macronutrients, Ca, Mg, and Na showed significant increases, while sulfur decreased, especially in soils amended with the highest sludge amount. For micronutrients, higher sludge rates raised their levels, and even the lowest rate caused significant increases in Zn, Mn, Pb, and Cr. Cu, Co, and Al showed no significant change except at the highest application rate. Compared to pre-amendment levels, the overall changes in soil nutrients, especially nitrogen, B, and Cu were relatively smaller.

Increasing soil amendment rates elevated all primary and secondary macronutrients in maize and enhanced nearly all other mineral levels, except cadmium and cobalt (Table 4). For every mineral, the lowest amendment rate had no significant effect on P, K, Ca, S, B, Ni, Pb, Cr, and Co concentrations. Comparing the two grain crops revealed notable differences—for instance, with aluminum. Soil aluminum was markedly higher under rice at elevated

amendment rates. In maize, soil aluminum levels rose across all soil types. Conversely, sulfur decreased in rice but

increased under maize. Additionally, soil boron content remained low for both crops.

TABLE 3 Changes in soil mineral and metal compositions under rice production

Element (mg kg ⁻¹)	The different rates of the amendment (t ha ⁻¹)			
	0	2.50	5.00	10.00
N	1200±0.0	1400±0.0*	2000±0.0*	2100±0.0*
P	8.21±0.5	9.43±0.4	12.77±0.7*	16.46±0.5*
K	15.74±0.8	32.66±0.9*	34.48±0.4*	44.84±0.8*
Ca	515.65±0.9	1068.71±0.9*	1168.71±0.6*	1349.26±0.8*
Mg	112.04±0.8	175.00±0.9*	190.43±0.9*	240.58±0.9*
Na	11.29±0.8	30.41±0.8*	68.83±0.8*	97.68±0.6*
S	5.77±0.3	15.71±0.3*	33.87±0.2*	43.79±0.4
B	6.11±0.7	11.43±0.9*	18.51±0.9	22.30±0.6
Fe	394.55±0.9	597.26±0.9	650.52±0.9*	773.44±0.9*
Cu	192.73±0.9	177.47±0.5	275.85±0.8	307.83±0.9*
Zn	84.95±0.9	105.79±0.2*	216.63±0.8*	311.3±0.8*
Mn	33.69±0.8	64.53±0.6*	79.40±0.8*	114.07±0.8*
Cd	4.70±0.3	6.45±0.8	10.01±0.0*	17.01±0.0*
Ni	55.65±0.8	64.22±0.6*	76.30±0.9	94.23±0.2*
Pb	407.47±0.1	539.86±0.9*	692.15±0.6*	723.02±0.9*
Cr	88.29±0.9	92.77±0.8*	106.27±0.7*	115.38±0.9*
Co	0.06±0.0	0.10±0.0	0.17±0.0	0.95±0.0*
Al	135.17±0.9	143.08±0.7*	196.42±0.8*	210.80±1.0*

The values are mean ± standard error of four replicates (n=4). An asterisk indicates a significant difference (p<0.05) between the control and the treatment.

TABLE 4 Changes in soil mineral and metal compositions under maize production.

Element (mg kg ⁻¹)	The different rates of the amendment (t ha ⁻¹)			
	0	2.50	5.00	10.00
N	1450.00±0.0	1670.00±0.0*	2100.00±0.0*	2300.00±0.08*
P	8.63±0.3	10.53±0.2	13.37±0.2*	21.36±0.1*
K	17.81±0.9	21.68±0.9	23.39±0.8*	36.61±0.8*
Ca	645.66±0.9	754.34±0.7	836.32±0.6*	915.63±0.7*
Mg	124.75±0.9	145.82±0.6*	156.42±0.5*	215.44±0.5*
Na	9.63±0.6	30.99±0.9*	47.50±0.8*	63.13±0.5*
S	3.83±0.2	10.97±0.2	24.50±0.2*	64.70±0.1*
B	5.57±0.5	10.23±0.2	14.96±0.5	21.38±0.1*
Fe	415.21±0.6	443.56±0.8*	458.93±0.9*	473.53±0.8*
Cu	156.54±0.9	168.09±1.0*	175.59±1.0*	208.30±0.8*
Zn	66.38±0.8	109.17±0.8*	145.93±1.0	226.06±0.6*
Mn	35.34±1.0	57.56±0.6	73.40±0.9*	108.77±0.8*
Al	152.17±0.8	166.85±0.9*	223.52±0.9*	261.07±0.6*
Cd	5.06±0.7	8.72±0.1	12.50±0.3	16.36±0.3
Ni	64.47±0.9	69.89±0.9	76.06±0.8*	101.09±0.9*
Pb	516.65±0.8	562.89±0.9*	672.85±0.9*	722.88±0.9
Cr	83.37±0.5	93.00±0.7*	98.87±0.9*	112.78±0.9*
Co	0.05±0.0	0.07±0.0	0.18±0.0	0.25±0.0

The values are mean ± standard error of four replicates (n=4). An asterisk indicates a significant difference (p<0.05) between the control and the treatment.

The sludge's mineral and metal contents were high for all the primary and secondary macronutrients and for Cd and Zn, and the farm soil was high in Al, Ni, Pb, and Cu, agreeing with the results of previous studies. When fermented piggery sludge was applied to pasture land, Bertici et al. (2022) noted a positive influence on total nitrogen and available P and K, with a lesser influence on Cu and Zn. All the primary and secondary macronutrients were improved when sludge was added under the two-grain crops. Under the highest amendment rate, N, P, and S were low under rice, whereas the rest of the primary and secondary nutrient contents were higher than those of maize. These nutrient differences could mean different affinities for the two-grain crops. Under the same amendment rate, Fe, B, Mn, Ni, Pb, Cr, and Al were higher under rice than in the soils planted with maize. The low concentrations measured under maize could mean crop uses of these soil minerals. Still, tissue concentrations of Al and other metals raise concerns about bioavailability to livestock and humans, especially when above the minimal standard limits (FAO, 2025). This could mean establishing the most effective application rate under agricultural conditions, especially when increases in soil mineral content, including heavy metals, were measured under each crop. The Cd, Cr, and Pb contents (0.86, 22, and 400 mg kg⁻¹) were outside, whereas Zn, Cu, and Ni were within the FAO permissible limits, which could be a concern for the environment. The estimated bioaccumulation factors for all metals were less than 1, except for Co, Zn, and Mn, which suggests that the bioavailability of these metals may be a concern. Under glasshouse conditions, Seo et al., (2011) added swine slurry continuously for five years at 50%, 100% and 200%, and planted tomato (*Lycopersicon esculentum*) and cucumber (*Cucumis sativus*). The results showed no positive influence on phosphate and trace elements, but high K and Na. The effect on yield was not much of that of the chemical fertilizer treatment. The disparity between our study results and those reported by Tavares et al., (2019), Antoneli et al., (2019), and Ferreira et al., (2022) indicates that piggery wastes

positively influence soil mineral and metal compositions and are largely influenced by prevailing agroecological conditions.

3.3| Metal Concentrations in Biomass

Table 5 shows the metal compositions in forage tissues. In plants grown on unamended soil, high levels of Pb, Al, Fe, and Cu were observed, with maize showing higher Cu levels than rice. Applying 2.5 t ha⁻¹ of sludge raised the tissue concentrations of Zn, Pb, Mn, Cu, Fe, and Al in both forages by at least 50 mg kg⁻¹. Metals like Cd and Co remained below 5 t ha⁻¹, with levels under 20 mg kg⁻¹. Increasing the amendment to 5 t ha⁻¹ reduced Al, Cu, Fe, and Pb in rice tissues, while other metals increased, except Al and Pb in maize, which decreased. The highest tissue concentration increases above 5 t ha⁻¹ were observed for Zn, Mn, Pb, Al, and Cu, especially in rice. At 10 t ha⁻¹ amendment, metal levels declined overall, except for Cu. Despite this, Mn, Zn, and Al remained high in rice, and Cu, Fe, Zn, and Mn remained elevated in maize (Table 5).

The bioaccumulation factor (BiF), an indicator of the crop's capacity to accumulate the metals, was determined as the ratio of the concentrations in the crops' biomass. Generally, the BiF were less than 1 except for Zn and Mn at 5 and 10 t ha⁻¹, respectively. The bioaccumulation patterns revealed three distinct groups:

Group 1 - Limited Uptake (BiF < 0.5): Al, Cr, Cu, Fe, and Ni showed restricted translocation to above-ground tissues in both crops, suggesting active exclusion mechanisms or low phytoavailability. These metals remained predominantly in root tissues or were sequestered in soil.

Group 2 - Moderate Accumulation (BiF 0.5-1.0): Cd and Pb showed intermediate uptake efficiency. The BiF values <1 indicate that soil-to-plant transfer was limited, but tissue concentrations still approached or exceeded safe consumption limits (FAO, 1996), particularly at higher amendment rates.

TABLE 5 Metal concentrations in biomass of rice and maize following different rates of sludge amendment

Metals (mg kg ⁻¹)	Amendment rates (t ha ⁻¹) and crops							
	0 Rice	Maize	2.50 Rice	Maize	5.00 Rice	Maize	10.00 Rice	Maize
Al	125±0.2	115.22±0.3	130.54±0.1*	109.22±0.4*	73.42±0.4*	50.11±0.2*	60.13±0.2*	15.52±0.8*
Cd	1.54±0.2	1.45±0.3	12.51±0.4*	7.13±0.2*	8.20±0.2	5.11±0.4*2	2.64±0.4*	3.22±0.5*
Co	4.52±0.4	4.14±0.3	7.11±0.1*	8.12±0.6*	8.64±0.6*	8.82±0.4*	8.89±0.4*	9.65±0.3*
Cr	7.23±0.1	11.10±0.3	22.99±0.2*	19.26±0.2*	10.11±0.4*	16.45±0.3*	1.24±0.6*	3.12±0.5*
Cu	61.33±0.1	95.18±0.4	135.06±0.4*	153.34±0.6*	46.14±0.4*	140.22±0.2*	14.64±0.5*	114.06±0.2*
Fe	109.44±0.5	81.55±0.3	80.55±0.3*	130.27±0.2*	27.12±0.3*	119.33±0.4*	6.27±0.6*	103.11±0.9*
Ni	12.22±0.3	5.55±0.4	39.03±0.6*	32.22±0.5*	25.65±0.4*	26.89±0.5*	10.23±0.7*	3.65±0.5*
Pb	221.26±0.2	211.19±0.4	185.24±0.6*	162.15±0.4*	115.22±0.4*	95.60±0.5*	36.55±0.2*	39.33±0.5*
Zn	4.23±0.5	3.09±0.3	419.64±0.3*	410.62±0.2*	299.31±0.4*	381.54±0.2*	212.44±0.3*	295.55±0.6*
Mn	10.55±0.4	8.65±0.4	165.55±0.4*	176.22±0.3*	149.55±0.2*	160.35±0.5*	119.44±0.4*	125.21±0.2*

The values are mean ± standard error of four replicates (n=4). An asterisk indicates a significant difference (p<0.05) between the control and the treatment.

Group 3 - Enhanced Accumulation ($\text{BiF} > 1.0$): Co, Zn, and Mn at rates $\geq 5 \text{ t ha}^{-1}$ showed bioaccumulation factors exceeding unity, indicating these elements were actively concentrated in plant tissues relative to soil content. This pattern is consistent with their roles as essential micronutrients with active uptake mechanisms. The declining BiF values at 10 t ha^{-1} for most metals (except Co) suggest toxicity-induced reduction in root function or activation of metal tolerance mechanisms at high soil concentrations.

Rice produced an increasing number of tillers and leaves, shorter plants, and fewer roots with an increasing sludge concentration. In other words, higher amounts of the amendment retarded the growth and development of the rice plants. The tiller number (only two were maintained), plant height, and root length of maize were not affected, except that leaf number decreased as the amendment rate increased. The dry matter of the two-grain crops was significantly higher across all three rates, particularly at 10 t ha^{-1} of sludge. These results show that rice is sensitive to high concentrations of heavy metals and Al toxicity. Santos *et al.*, (2018) showed that piggery sludge application favours pasture biomass production (Santos *et al.*, 2018), but did not consider an actual rate. Fahad *et al.*, (2019) reported that soil accumulation of Cd, Pb, Cu, and Ni decreased rice seedling emergence and growth, consistent with the findings in this study, which indicate that heavy metal accumulation affected the roots. The higher tiller and leaf number produced by the shorter plants could be an adaptive response to metal and Al in the soil.

On the other hand, maize seems to have a certain degree of tolerance and tissue accumulation (Atta *et al.*, 2023). This ascertainment is based on the fact that the concentration of heavy metals and Al was lower in all the amended soils, and the effects of these metals on the roots needed to be more evident. The fewer leaves produced by the maize plants could mean more tissue accumulation in the leaves. These results agree with those of Ruiz-Huerta *et al.* (2022), who found that high levels of heavy metal accumulation significantly reduced maize growth when planted in mine-contaminated soil. Overall, the tissue concentrations of Cd,

Co, Pb, and Zn were outside the FAO (1996) permissible limits of heavy metals in soil and plants. These results could hinder the potential agricultural use of piggery sludge, which is increasingly produced in PNG, and highlight the need for more research to determine how much and how to apply it to avoid crop loss and minimize environmental, livestock, and human toxicity concerns. Piggery sludge application under field conditions improved pea (*Pisum sativum*) yield without affecting soil pH (Hlisnikovský *et al.*, 2022), further indicating the bioresource's broader applications.

3.4 | Plant Biomass Production

The plant growth characteristics for the assessed crops are shown in (Table 6). Sludge amendment increased the number of tillers in rice at all rates, except for maize, which was thinned to just two plants and kept throughout. The rice plants became stunted—as seen by a decrease in height—as sludge rates increased, while the opposite trend was observed in maize plants. Higher sludge rates resulted in much taller maize plants. Root biomass decreased in rice but increased in maize. As the amendment rate was high, both plants produced more leaves, and their dry matter reflected in the biomass produced. Yield data are not shown because plants were harvested at the tillering stage (rice) and tasseling stage (maize).

This study provides preliminary evidence for short-term soil chemical changes following piggery sludge application, but has several important limitations. The six-month duration captured initial soil responses but cannot assess: (i) long-term metal accumulation trajectories, (ii) organic matter stabilization and mineralization dynamics, (iii) multi-season cumulative effects, or (iv) chronic toxicity impacts on soil biota. Plants were harvested at vegetative stages (rice at tillering, maize at tasseling) to assess early growth responses and metal uptake patterns. Consequently, grain yield data—critical for evaluating practical agricultural value—were not obtained. The vegetative dry matter results indicate growth potential but cannot be extrapolated to predict grain production. Results from a single location under humid lowland tropical conditions may not apply to other soil types, climatic zones, or piggery

TABLE 6 Biomass production by rice and maize at different rates of sludge amendment

Plant growth parameters	The different rates of amendment (t ha^{-1}) and crops							
	0 Rice	Maize	2.50 Rice	Maize	5.00 Rice	Maize	10.00 Rice	Maize
Tillers (number)	64.67±0.2	2.00±0.6	100.33±0.5*	2.00±0.4	114.32±0.5*	2.00±0.6	121.67±0.4*	2.00±0.9
Plant height (cm)	91.67±0.1	146.67±0.3	81.30±0.7	248.33±0.5*	54.32±0.4*	271.67±0.4*	42.45±0.6*	268.67±0.7*
Root length (cm)	32.33±0.0	10.33±0.1	32.28±0.3	40.21±0.2*	27.35±0.3*	48.23±0.8*	24.33±0.7*	60.25±0.6*
Leaf (number)	152.32±0.5	35.22±0.2	175.62±0.8*	27.32±0.4*	203.20±0.2*	19.24±0.9*	230.36±0.9*	11.67±0.8*
Dry matter (g)	129.28±0.4	119.11±0.4	164.23±0.4*	184.24±0.6*	175.37±0.4*	232.03±0.5*	181.92±0.8*	286.33±0.4*

The values are mean ± standard error of four replicates ($n=4$). An asterisk indicates a significant difference ($p<0.05$) between the control and the treatment.

Note that dry weight is the difference between the fresh weight and moisture content.

operations with different feeding regimes and waste characteristics. Several metals (Pb, Cd, Cr) exceeded FAO permissible limits, raising concerns about food safety. However, without grain analysis, we cannot assess actual human or livestock exposure risks through feed/food consumption. Nevertheless, based on these preliminary findings, we offer cautious recommendations: (i) application rates $\leq 2.5 \text{ t ha}^{-1}$ appear relatively safe for soil properties improvement while minimizing metal accumulation concerns, (ii) pre-application sludge analysis is essential to characterize metal content, (iii) crops intended for direct human consumption should be avoided until grain metal concentrations are verified, and (iv) further research is needed with multi-year field trials with complete grain harvest and yield analysis, economic viability assessment comparing sludge application to conventional, fertilization, food safety evaluation with grain metal analysis against international standards, and investigation of metal remediation strategies (phytoremediation species, and also soil amendments to reduce bioavailability).

4 | CONCLUSIONS

This six-month trial offers initial evidence on soil chemical responses to solid piggery sludge in humid tropical lowlands. Key findings: i) sludge consistently improved soil organic carbon (up to 10x), water holding capacity (77%), and base saturation across crops, quickly (within six months) and dose-dependently; ii) macronutrients (N, P, K) and secondary nutrients (Ca, Mg, Na) increased significantly with amendment rate, with the highest rate (10 t ha^{-1}) providing about $21,000 \text{ kg N ha}^{-1}$, surpassing crop needs; iii) soil Pb, Cd, and Cr exceeded FAO limits at multiple rates, with metal levels strongly linked to sludge rate; iv) maize tolerated metal stress, maintaining growth, while rice showed growth inhibition at $\geq 5 \text{ t ha}^{-1}$, indicating species sensitivity; v) metals mostly had bioaccumulation factors < 1 , showing limited soil-to-plant transfer, except Co, Zn, and Mn at higher rates, requiring monitoring for feed use. Based on initial findings, applying rates $\leq 2.5 \text{ t ha}^{-1}$ improves soil quality and maintains metal levels near their natural baseline. Maize is more appropriate than rice for systems amended with sludge. - Rice grown on sludge soils should be limited to $\leq 2.5 \text{ t ha}^{-1}$. The six-month window captures initial reactions but doesn't reveal long-term sustainability, cumulative metal effects, or seasonal variation. Since harvest occurs before reproductive stages, it can't assess grain yield, quality, or the actual nutritional value of the grain. Conducted at a single site with specific soil and climate, limiting broader application. Total metal content measurement doesn't reflect plant-available fractions, so toxicity risks may differ. The study lacks a cost-benefit analysis comparing this method to traditional fertilization or waste management. For piggery sludge as a sustainable soil amendment, future research should focus on: 1. Completing crop cycles and evaluating yields. 2. Monitoring over 3-5 years for long-term effects. 3. Analyzing grain quality for metals, nutrition, and safety. 4.

Comparing costs, labor, and returns of sludge versus fertilizers. 5. Multi-site trials across different soils and climates in PNG and tropical regions. 6. Studying metal speciation for bioavailability and risks. 7. Investigating soil microbiology's impact on beneficial organisms and decomposition. 8. Developing metal contamination remediation strategies like phytoremediation or amendments. 9. Exploring treatments like composting or biochar to reduce metal availability. 10. Setting policies for safe application, monitoring, and farmer training. While initial evidence suggests piggery sludge can boost soil and fertility crop yields at low rates, long-term data on this aspect of sustainable soil management is needed.

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CONFLICT OF INTEREST

The authors declare that there are no competing financial or personal interests that may appear to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

All the data are included in the manuscript.

AUTHOR'S CONTRIBUTION

Conceptualization, Methodology, Supervision, and Writing draft and editing: PM; Formal analysis, Data collection, analysis, and investigation: LK. All authors read and approved the final manuscript.

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Combined Application of Biochar and Nitrogenous Fertilizers Influences Growth and Productivity of Rainy and Spring Seasons Maize

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ABSTRACT

The use of biochar and other organic amendments not only reduces fertilizer dosage but also improves crop growth and water productivity. A field study was conducted in rainy or *kharif* season maize (2019) and spring maize (2020) with main-plots having BN₁ (biochar @ 7.5 t ha⁻¹ + N @ 75 kg ha⁻¹), BN₂ (biochar @ 7.5 t ha⁻¹ + N @ 150 kg ha⁻¹), FN₁ (farmyard manure @ 20 t ha⁻¹ + N @ 75 kg ha⁻¹), FN₂ (farmyard manure @ 20 t ha⁻¹ + N @ 150 kg ha⁻¹), N₁ (N @ 75 kg ha⁻¹) and N₂ (N @ 150 kg ha⁻¹) and sub-plots with two irrigations, viz., I_{0.6} (IW/CPE: 0.6) and I_{0.9} (IW/CPE: 0.9). Higher plant height (2.96 m), SPAD value (58.55), stover yield (23.89 t ha⁻¹), cob yield (8.14 t ha⁻¹) and grain yield (5.78 t ha⁻¹) were obtained under BN₂ treatment compared to other treatments. BN₂ increased grain yield by 22.7% and 28.5%, and water productivity by 21.6% and 27.6% in rainy season and spring season compared to N₂. The I_{0.6} treatment resulted in higher water productivity by 5.5% compared to I_{0.9} during the spring season, but grain yield was significantly higher under the I_{0.9} treatment. Therefore, BN₂ with I_{0.9} is a viable practice for achieving higher crop productivity.

1 | INTRODUCTION

In the Indo-Gangetic Plains (IGP), diversification from puddled transplanted rice to maize is increasingly promoted due to maize's lower water requirement, higher water-use efficiency (WUE), and adaptability to both rainy (*kharif*) and spring seasons. Compared to the rainy season, spring maize benefits from higher solar radiation and reduced disease pressure, and often exhibits superior yield stability and WUE due to controlled irrigation and reduced biotic stress. Primary challenges of crop production in the subtropical region encompass insufficient soil fertility and water scarcity. Addressing these concerns demands research aimed at refining soil's physical and chemical attributes while enhancing water retention and crop water-use efficiency (WUE). Among all approaches, one promising strategy is soil amendment with biochar (Katterer *et al.*, 2019).

Biochar, a carbon-rich by-product of the thermal decomposition of crop biomass, offers the potential to transform agricultural residues from environmental burdens into valuable resources. Biochar is considered more effective than farmyard manure (FYM) or other organic amendments due to its greater stability, porosity, and long residence time in soil. Unlike FYM and compost, which decompose rapidly under the hot semi-arid climate of the IGP, biochar persists for years, improving soil aggregation, increasing water-holding capacity, and reducing evaporative losses. Its superior surface area and porosity enable it to retain nutrients and water, fostering the

growth of beneficial microorganisms (Warnock *et al.*, 2007) and thereby affecting porosity, water retention, and hydraulic conductivity, thereby influencing plant growth and yield (Ajayi *et al.*, 2016). Biochar can retain more irrigation water and reduce irrigation frequency, effectively optimizing the limited water available for crops. Farmyard manure (FYM), a traditional method, is commonly used by farmers in maize cultivation in the IGP, as FYM decomposes rapidly under the hot, semi-arid climate. FYM improves soil fertility, provides balanced nutrition for plants, and significantly enhances the soil's physical, chemical, and biological properties. Higher FYM levels correlate with increased root and shoot growth, plant height, and nutrient uptake in maize (Dass *et al.*, 2008; Bandyopadhyay *et al.*, 2010; Dass *et al.*, 2013; Masood *et al.*, 2014). Similarly, several studies indicate that adding organic material in the field significantly improves soil physical properties and water conservation (Manna *et al.*, 2016; Sahoo *et al.*, 2017). Another important agricultural input is irrigation, which helps achieve optimal productivity. Maize requires 600–700 mm of water for its optimum growth (Reddy, 2006). Water deficiency at any growth stage hampers maize growth, reducing leaf area and plant height due to impaired cell division and leaf expansion (Soler *et al.*, 2007).

Innovative strategies to enhance water and crop productivity of maize involve optimum irrigation (IW/CPE: 0.6 or 0.9; Agbna *et al.*, 2017) and fertilization. This approach sustains productivity through improving soil

water extraction by plant roots. Integrated approaches combining biochar and fertilizers are gaining traction to address water and fertility issues (Uzoma *et al.*, 2011; Akhtar *et al.*, 2014). The study was conducted with the hypothesis that combined application of biochar or FYM with nitrogenous fertilizer under different irrigation treatments would enhance maize grain yield, crop and water productivity. The objective was to study the interactive effect of biochar, nitrogen, farmyard manure and irrigation on maize and water productivity, and to optimize the irrigation and nitrogen levels under biochar and farmyard manure application in maize.

2 | MATERIALS AND METHODS

2.1 | Geographical Location and Microclimate of the Experimental Site

The field experiment was conducted during the rainy (kharif) season of 2019 and the spring season of 2020 on sandy loam soil at the research farm of the Department of Soil Science, Punjab Agricultural University, Ludhiana, Punjab, India. The soil of the experimental site was sandy loam, non-calcareous, with moderate organic carbon content and a neutral pH. Detailed soil characteristics for the experimental site are presented in (Table 1).

Regarding the region's agroclimatic conditions, Ludhiana experiences a sub-tropical, semi-arid climate with hot and dry summers from April to June, followed by a humid, sultry climate from July to September, and chilly winters from November to January. The meteorological data were collected from the Department of Agrometeorology observatory at Punjab Agricultural University, Ludhiana, and are provided in (Table 2).

2.2 | Experimental Treatment Details

The biochar used in the experiment was procured from the Department of Soil Science, Punjab Agricultural University, Ludhiana. The biochar was produced from rice residues via slow pyrolysis. The field experiment was laid out in a split-plot design with three replications; experimental details are given in Table 3. The treatments consisted of six different soil amendments, denoted as BN₁ (biochar @ 7.5 t ha⁻¹ + N @ 75 kg ha⁻¹), BN₂ (biochar @ 7.5 t ha⁻¹ + N @ 150 kg ha⁻¹), FN₁ (farmyard manure @ 20 t ha⁻¹ + N @ 75 kg ha⁻¹), FN₂ (farmyard manure @ 20 t ha⁻¹ + N @ 150 kg ha⁻¹), N₁ (N @ 75 kg ha⁻¹) and N₂ (N @ 150 kg ha⁻¹) in main-plots and two regimes of irrigation i.e. IW/CPE: 0.6 and IW/CPE: 0.9 as I_{0.6} and I_{0.9}, respectively, in sub-plots.

It is important to acknowledge that the organic amendments used in this study contributed additional macro- and micronutrients beyond nitrogen. Rice residue-derived biochar applied at 7.5 t ha⁻¹ typically contributes approximately 68 kg N ha⁻¹, 118 kg P₂O₅ ha⁻¹, and 233 kg K₂O ha⁻¹, though exact values depend on pyrolysis conditions and feedstock composition. Similarly, farmyard manure applied at 20 t ha⁻¹ contributes substantial quantities of N, P, and K in addition to the inorganic nitrogen supplied by the treatment. Phosphorus was applied uniformly as

HIGHLIGHTS

- Biochar @ 7.5 t ha⁻¹ combined with 150 kg N ha⁻¹ (BN₂) increased maize grain yield by 22.7% and 28.5% in rainy and spring seasons, respectively, over nitrogen alone (N₂).
- BN₂ improved water productivity by 21.6% (rainy season) and 27.6% (spring season) relative to N₂, demonstrating superior resource-use efficiency.
- Where biochar is unavailable, farmyard manure @ 20 t ha⁻¹ with 150 kg N ha⁻¹ (FN₂) yields similar to BN₂, providing a cost-effective option for resource-limited farmers.
- The IW/CPE 0.9 irrigation regime maximized grain yield, while IW/CPE 0.6 increased water productivity by 5.5%; BN₂ with IW/CPE 0.9 is recommended for northwest India.

TABLE 1 Soil characteristics of experimental site

Depth (cm)	pH	EC (dS m ⁻¹)	OC (%)	Sand (%)	Silt (%)	Clay (%)	FC (%)	PWP (%)
0-15	7.4	0.21	0.52	67.6	18.2	14.1	23.8	13.7
15-30	7.3	0.20	0.45	66.8	17.3	16.0	24.2	12.1
30-60	7.2	0.17	0.26	62.3	19.4	18.2	24.1	11.9
60-90	7.6	0.18	0.16	58.9	20.1	20.9	25.4	12.8
90-120	7.7	0.16	0.12	58.6	20.6	20.7	25.0	14.5

TABLE 2 Climatic data of the crop growing periods

Month	Max. temp (°C)	Min. temp (°C)	Evaporation (mm)	Rainfall (mm)	Month	Max. temp (°C)	Min. temp (°C)	Evaporation (mm)	Rainfall (mm)
Rainy Season					Spring Season				
June	40.4	25.8	291.4	29.9	Feb	21.5	8.5	57.8	15.0
July	34.0	26.7	174.1	218.4	Mar	24.5	12.9	79.4	69.0
August	33.8	26.1	131.4	331.4	Apr	32.8	17.7	138.3	13.2
September	33.1	25.5	101.1	264.8	May	36.9		213.0	49.6
October	30.6	18.4	76.7	0.0	June	37.6	26.5	220.4	9.6
Total	-	-	774.7	844.5	Total	-	-	708.9	156.4

single super phosphate, and potassium as muriate of potash, as basal doses across all treatments in spring maize. However, because P and K contributions from biochar and FYM were not separately quantified and deducted from basal fertilizer applications, the total P and K supply was not strictly balanced across amendment treatments. Readers should therefore interpret treatment comparisons with the awareness that biochar and FYM treatments received additional P and K relative to the N-only control treatments. This nutrient confounding is acknowledged as a limitation and is discussed further in Section 4. Both biochar and farmyard manure were reapplied to the soil during land preparation in both *kharif* maize and *spring* maize crops. This was done deliberately to evaluate the agronomic response to annual application of amendments rather than residual carry-over effects, and to assess whether the benefits observed in the first year were reproducible and potentially cumulative under repeated inputs.

2.3 | Details of Cultural Operations

2.3.1 | Field Preparation

A pre-sowing irrigation was applied to ensure optimal soil moisture for proper seed germination. After the harvesting of the previous crop toria, the field was prepared by ploughing twice with a disc harrow at optimum soil moisture conditions, followed by planking for *kharif* maize, and again after *kharif* maize toria was sown. The field was levelled to ensure proper irrigation and drainage. Farmyard manure and biochar were applied @ 20 tonnes per ha and @ 7.5 tonnes per ha, respectively, to the plots as shown in the layout before sowing.

2.3.2 | Sowing and Fertilizer Application

The sowing of the *kharif* maize and spring maize crop was done on 15th June 2019 and 4th February 2020 with a 20 kg ha⁻¹ of seed rate; seed treatment was given with Bavistin @ 3 g kg⁻¹ of seed. PMH10 variety was sown with the spacing of 60 cm between rows and 20 cm between plants. Phosphorus was applied as single super phosphate, potassium as muriate of potash, and zinc as ZnSO₄ in spring maize. The whole of the phosphorus, potassium, and zinc were applied as a basal dose before planting in the field, and nitrogen was applied in three splits at the recommended stages of the crop, i.e., at sowing, knee-high stage, and at pre-tasseling stage in the spring maize crop.

TABLE 3 Experimental details

Location	Soil Research Farms, Punjab Agricultural University, Ludhiana
Design	Split-Plot Design
Replications	Three
Treatments	Twelve
Gross Plot Size	4.30 m X 4.30 m
Net Plot Size	4 m X 4 m
Spacing	60 cm X 20 cm
Variety	PMH10

2.3.3 | Weeding and Irrigation

One spray of Atrataf 50 WP (atrazine) @ 800 g per acre in 200 litres of water was given up to 10 days after sowing, and then one hoeing was done at 30 days after sowing. Irrigation scheduling was made using IW/CPE (Irrigation water over cumulative open pan evaporation) method. Two irrigation regimes, i.e., IW/CPE = 0.6 and 0.9, were adopted for irrigation scheduling. The pan evaporation values were summed daily until they equaled the ratio of the amount of water applied as irrigation. Irrigation water was quantified using water meters installed in the field. Irrigation details are given in (Table 4).

2.4 | Crop Growth Measurements

Ten plants were randomly selected from each plot, and their height was measured from the ground surface to the top of the plant, including the flag leaf, at 80 days after sowing (DAS). Subsequently, the measurements were averaged for each individual plant. The SPAD value, which indicates chlorophyll content in the leaves, was determined using the Minolta SPAD 502 Chlorophyll Meter at 75 DAS. Stover and grain from a 9.6 square metre area in each plot were collected after harvesting, dried, and then weighed, and the weight was converted to metric tonnes per hectare.

2.5 | Statistical Analysis

To assess treatment effects, data collected across various parameters were subjected to analysis of variance (ANOVA) using a split-plot design in SAS software version 9.3 (SAS Institute Ltd, Cary, NC, USA). Treatment means were compared using the least significant difference (LSD) test at $P = 0.05$. F-values and associated P-values are reported alongside LSD values in the data tables. Mean separation letters (a, b, c...) are assigned such that means sharing the same letter are not significantly different at $P = 0.05$.

TABLE 4 Irrigation details according to the treatments during both seasons

	Rainy season I _{0.6}	Rainy season I _{0.9}	Spring season I _{0.6}	Spring season I _{0.9}
Number of irrigation per treatment	-	1	9	11
Water depth per irrigation event (mm)	0 mm	70 mm	70 mm	70 mm
Total irrigation water (mm)	-	70 mm	630 mm	770 mm
Rainfall during crop period (mm)	844.5 mm	844.5 mm	156.4 mm	156.4 mm
Rainfall + Irrigation (mm)	844.5 mm	914.5 mm	786.4 mm	926.4 mm

Water productivity (WP; kg ha⁻¹ mm⁻¹) was calculated as grain yield (kg ha⁻¹) divided by total water input, where total water input = seasonal rainfall + total irrigation applied in each treatment (as shown in Table 4).

3 | RESULTS AND DISCUSSION

The maize crop responded positively to biochar application along with nitrogenous (N) fertilizer with respect to plant height and SPAD value (Table 5). There was no significant difference between biochar-amended soil and unamended soil on plant height and SPAD value in *kharif* maize 2019. However, in the spring maize season 2020, a notable and statistically significant difference was observed. Significant statistical differences were recorded among treatments on plant height taken at 80 DAS, with maximum plant height observed in BN₂ (2.74 m) followed by BN₁ (2.65 m), FN₂ (2.58 m), FN₁ (2.54 m), N₂ (2.44 m), and N₁ (2.43 m), respectively, during spring maize 2020. The increase in plant height with the application of biochar, along with a higher N dose, could be attributed to adequate nutrient supply; N had a positive effect on vigorous vegetative growth. Biochar application is associated with improved plant growth, consistent with reported mechanisms of enhanced nutrient retention and soil structure (Rahayu *et al.*, 2022). On the other hand, a significantly higher SPAD value was obtained with BN₂ than with other treatments. Even biochar with lower N (BN₁) showed 6.47% increase in SPAD value over farmyard manure with higher N (FN₂) in 2020. An increase in SPAD value might be due to the application of biochar along with a higher dose of nitrogen, which supplies essential nutrients to the crop, as nitrogen is considered an essential constituent of chlorophyll (Ghosh & Dass, 2019). Numerous research studies have shown that the use of biochar can substantially enhance soil nutrient levels, thereby influencing crop growth (Cong *et al.*, 2023).

Biochar and farmyard manure, along with nitrogen, also increased maize cob and grain yields over unamended plots across all irrigation regimes (Table 6). Cob yield significantly increased under BN₂ (8.14 and 8.88 t ha⁻¹) than N₂ (6.63 and 7.39 t ha⁻¹) in the rainy season and the spring season. The grain yield increased from 4.41 t ha⁻¹ and 5.29 t ha⁻¹ under N₁ to 5.78 t ha⁻¹ and 6.95 t ha⁻¹ in BN₂ during the rainy season and the spring season, respectively. With the increase in irrigation frequency, the grain yield of maize also increased from 4.94 t ha⁻¹ in I_{0.6} to 5.52 t ha⁻¹ in I_{0.9} during the rainy season, while the corresponding increase during the spring season was from 5.87 t ha⁻¹ in I_{0.6} to 6.56 t ha⁻¹ in I_{0.9}. Significant interactive effects of different amendments with irrigation regimes were also observed for

both years. The increase in maize yield was associated with the positive effects of biochar on various soil properties — including reported improvements in water retention and nutrient adsorption — and on microbial activity, resulting in the supply of additional nutrients for plant growth, as reported by several studies (Sun *et al.*, 2023). The use of biochar combined with nitrogen had a notable positive impact on maize growth, likely due to enhanced nutrient availability provided by the biochar (Abukari *et al.*, 2018). It should, however, be noted that the biochar and FYM treatments also supplied substantial additional P and K beyond the inorganic basal fertilizer applications common to all treatments. Consequently, the superior performance of BN₂ and FN₂ relative to N₂ may partly reflect the combined NPK effect of these amendments, particularly the substantial potassium contribution from biochar, rather than enhanced nitrogen management alone. Future studies should balance P and K inputs across treatment groups to isolate the specific contributions of nitrogen- and carbon-based fractions.

Water productivity (WP) of the crop as affected by different amendments and irrigation regimes is presented in Table 6. Highest water productivity was observed under BN₂ (6.52 and 8.10 kg ha⁻¹ mm⁻¹), which was statistically at par with FN₂ (6.55 and 7.98 kg ha⁻¹ mm⁻¹) but was significantly higher than N₂ (5.36 and 6.35 kg ha⁻¹ mm⁻¹) and N₁ (4.99 and 6.2 kg ha⁻¹ mm⁻¹) during both 2019 and 2020. Whether biochar was applied in conjunction with nitrogen or with farmyard manure and nitrogen, the crop's water productivity showed no statistically significant difference, but it was notably higher than with nitrogen alone. In essence, both biochar and farmyard manure had an equivalent positive impact on the crop's water productivity. Additionally, the choice of irrigation regime had a substantial influence on water productivity, with higher water productivity observed under I_{0.6} (7.47 kg ha⁻¹ mm⁻¹) in contrast to I_{0.9} (7.08 kg ha⁻¹ mm⁻¹) during 2020. Under mild water stress (I_{0.6}), the crop likely developed a deeper root system, drawing moisture from deeper soil layers as opposed to frequent irrigation (I_{0.9}), resulting in higher yields per unit of water and consequently elevated water productivity (Alsayim *et al.*, 2013).

The benefits of organic amendment application were markedly stronger in the spring season of 2020 than in the kharif season of 2019, with grain yield improvements over the N₂ control increasing from approximately 22.7% to 28.5% for BN₂, and water productivity gains rising from 21.6% to 27.6% across the same comparison. Several factors likely explain this intensification of response. First, the contrasting seasonal conditions between the two years — kharif 2019 received 844.5 mm of rainfall, which may have diluted the amendment effects through leaching and waterlogging, whereas spring 2020 received only 156.4 mm — meant that the water-retention benefits of biochar were far more agronomically relevant in the drier spring

environment. Second, because biochar and FYM were reapplied in both years, the spring 2020 crop benefited from a cumulative increase in soil amendment load, potentially enhancing soil structural and nutrient-retention properties beyond what a single application could achieve. Third, the cooler, lower-humidity spring season environment reduces the rate of organic matter decomposition, allowing the amendments to contribute to nutrient supply over a longer period relative to the hot and humid kharif season. Taken together, these factors suggest that the agronomic value of biochar application is likely to be greatest in irrigated spring maize systems in the IGP, where seasonal aridity makes soil water retention a primary yield-limiting constraint.

TABLE 5 Effect of biochar and irrigation regimes on plant height, SPAD value, and stover yield of maize

[illegible]

TABLE 6 Effect of biochar and irrigation regimes on cob yield, grain yield, and water productivity of maize

Irrigation regime	Amendments													
	BN ₁	BN ₂	FN ₁	FN ₂	N ₁	N ₂	Mean	BN ₁	BN ₂	FN ₁	FN ₂	N ₁	N ₂	Mean
	Cob yield (t ha ⁻¹)						Cob yield (t ha ⁻¹)							
	Rainy season						Spring season							
I _{0.6}	7.60	6.64	7.47	7.56	5.58	6.85	6.95	8.09	7.79	7.91	7.94	6.75	7.33	7.63
I _{0.9}	7.41	9.64	7.14	7.43	7.24	6.41	7.55	9.66	9.97	7.92	8.07	6.92	7.46	8.33
Mean	7.50	8.14	7.31	7.49	6.41	6.63		8.87	8.88	7.91	8.01	6.83	7.39	
LSD	A= 0.33; I= 0.20; A X I= 0.50						A= 0.49; I= 0.36; A X I= 0.88							
	Grain yield (t ha ⁻¹)						Grain yield (t ha ⁻¹)							
	Rainy season						Spring season							
I _{0.6}	5.39	4.72	5.37	5.58	3.77	4.83	4.94	6.23	6.31	6.19	5.96	5.19	5.37	5.87
I _{0.9}	5.62	6.83	5.08	5.95	5.05	4.59	5.52	6.88	7.59	6.28	7.78	5.39	5.45	6.56
Mean	5.51	5.78	5.22	5.77	4.41	4.71		6.55	6.95	6.23	6.87	5.29	5.41	
LSD	A= 0.36; I= 0.14; A X I= 0.34						A= 0.49; I= 0.41; A X I= 1.01							
	WP (kg ha ⁻¹ mm ⁻¹)						WP (kg ha ⁻¹ mm ⁻¹)							
	Rainy season						Spring season							
I _{0.6}	6.38	5.65	6.35	6.60	4.46		5.85	7.92	8.02	7.87	7.57	6.59	6.82	7.47
						5.71								
I _{0.9}	6.14	7.46	5.55	6.50	5.52		6.03	7.42	8.19	6.77	8.39	5.81	5.88	7.08
						5.01								
Mean	6.26	6.55	5.95	6.55	4.99			7.67	8.10	7.32	7.98	6.20	6.35	
						5.36								
LSD	A= 0.28; I= 0.15; A X I= NS						A= 0.82; I=0.35; A X I=NS							

4 | Limitations

Despite benefits of biochar on water efficiency and crop yield, several study limitations exist. Key soil properties like organic carbon, water holding capacity (WHC), and cation exchange capacity (CEC) were not directly measured; thus, yield explanations are inferred from literature, not confirmed in-situ. Treatments weren't balanced for phosphorus and potassium, as organic amendments added extra P and K beyond basal fertilizers, confounding results. Root measurements were missing, limiting claims about deep root growth and water extraction under deficit irrigation. Biochar properties such as surface area and porosity weren't characterized, affecting reproducibility. Being a single-location, two-season study in Ludhiana, Punjab, caution is needed when applying findings elsewhere; multi-location trials are advised. No economic analysis was performed, so the cost-benefit of biochar for smallholders remains unassessed.

5 | CONCLUSIONS

This study demonstrated that the combined application of biochar with nitrogen fertilizer, under an irrigation regime

of IW/CPE 0.9, produced the highest maize grain yield and water productivity across both kharif and spring seasons. Results support three practical management scenarios depending on farmer objectives and resource availability:

1. Maximum Productivity Goal: BN₂ (biochar @ 7.5 t ha⁻¹ + N @ 150 kg ha⁻¹) combined with I_{0.9} (IW/CPE: 0.9) is the most effective practice for achieving the highest grain yield in northwest India. This treatment produced grain yields of 5.78 t ha⁻¹ (rainy season) and 6.95 t ha⁻¹ (spring season), representing 22.7% and 28.5% improvements over the N₂ control, respectively.

2. Water-Limited Conditions: Where irrigation water is scarce, BN₂ combined with I_{0.6} (IW/CPE: 0.6) offers a viable alternative. While grain yield under I_{0.6} was approximately 11% lower than under I_{0.9} in spring season (6.31 vs. 7.59 t ha⁻¹ for BN₂), water productivity was approximately 5.5% higher, making this combination suitable where maximizing output per unit of water is the priority.

3. Resource-Constrained Farmers: Where biochar is unavailable or economically prohibitive, FN_2 (farmyard manure @ 20 t ha^{-1} + N @ 150 kg ha^{-1}) combined with $\text{I}_{0.9}$ produced results comparable to BN_2 + $\text{I}_{0.9}$, particularly for grain yield and water productivity. This represents a practical, locally accessible alternative using on-farm organic resources.

It is important to note that the observed superiority of biochar-based treatments may partly reflect additional P and K contributions from the amendment rather than nitrogen and carbon effects alone. Economic analysis comparing amendment costs against yield benefits has not been conducted and is strongly recommended before blanket adoption recommendations are made, particularly for smallholder farming systems.

The findings also highlight the particular promise of biochar application in spring maize systems, where low seasonal rainfall makes soil water retention a primary yield-limiting factor. Future research should focus on long-term field experiments to evaluate the cumulative effects of biochar on soil hydraulic properties, carbon sequestration, and nutrient use efficiency in spring maize-based systems. Policy support for crop-residue-based biochar production, alongside incentives for water-saving technologies, can play a crucial role in making spring maize a climate-resilient and resource-efficient option in the Indo-Gangetic Plains.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

DATA AVAILABILITY

Data will be made available on request.

AUTHOR'S CONTRIBUTION

Ruchi Goyal: writing original draft, data analysis; M.S. Kahlon: supervision and editing.

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Evaluation of Different Biochar Sources on Growth, Yield and Soil Fertility of Okra and Brinjal in Inceptisol from Odisha : A Pot Study

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ABSTRACT

Declining soil organic carbon and nutrient imbalances in Inceptisols of eastern India have reduced productivity of intensive vegetable systems under sole chemical fertilizer use. However, limited information exists on the comparative effectiveness of different biochar sources integrated with farmyard manure (FYM) and recommended dose of fertilizers (RDF) for improving soil fertility and yield of okra and brinjal. In this context, a pot experiment was conducted during 2021–2022 at the ICAR–Indian Institute of Soil Science (IISS), Bhopal, India, to evaluate the effect of different biochar sources and application rates, alone and in combination with FYM and RDF on growth, yield, and soil fertility of okra and brinjal grown in an Inceptisol soil collected from Belpada, Odisha. The experiment was laid out in a Completely Randomized Design (CRD) with eleven treatments replicated four times, involving two biochar sources {crop residue biochar (CRB) of groundnut, mustard, and rice husk and mixed wood biochar (WCB) of *Prosopis juliflora* and coconut husk} applied at 0, 4, and 8 g kg⁻¹ soil, with and without FYM (5 g kg⁻¹ soil) and (RDF). Results revealed that integrated application of biochar, FYM, and RDF significantly ($p < 0.05$) improved plant height and yield of both the crops over the control (0) and fertilizer-alone treatments. The treatment crop residue biochar @ 8 g kg⁻¹ soil + FYM @ 5 g kg⁻¹ soil + RDF (F,CRB,M₁) consistently recorded the highest yields of okra (182.4 g pot⁻¹) and brinjal (262.5 g pot⁻¹), resulting in nearly two-fold higher fruit yield of okra and three- to four-fold higher fruit yield of brinjal compared to the control across both years. This treatment also improved N, P, and K uptake substantially, with N uptake increasing more than four fold in okra and over twofold in brinjal, accompanied by marked increases in P and K uptake across both crops. Biochar application moderated soil reaction, raising soil pH from near-neutral control levels (~7.26) to ~7.64, indicating its liming potential, while soil organic carbon (SOC), available P, and available K increased by 114%, 170%, and 27%, respectively, under integrated treatments. Unlike earlier studies focusing on single biochar sources or short-term responses, this study provides a comparative assessment of crop residue and mixed biomass biochars at graded rates under integrated application with FYM and RDF, highlighting their cumulative effects. The findings offer new insights into optimized biochar-based nutrient management strategies for sustaining vegetable productivity and soil fertility in Inceptisols. Although it is just a pot study but it concludes that biochar alone is insufficient, but its integration with FYM and RDF, particularly crop residue biochar at higher rates, is an effective and sustainable strategy for enhancing vegetable productivity and soil fertility in Inceptisol soils.

1 | INTRODUCTION

Vegetable crops are vital for ensuring nutritional security, income generation, and livelihood diversification in India, particularly for small and marginal farmers. Among them, okra (*Abelmoschus esculentus* L.) and brinjal (*Solanum melongena* L.) are widely cultivated owing to their high market demand, adaptability to diverse agro-climatic conditions, and significant contribution to dietary fiber, vitamins, and antioxidants (Hazra, 2023; Sudhanshu, 2025).

Despite their importance, the productivity of okra (12.1 t ha⁻¹) and brinjal (18.8 t ha⁻¹) crop often remains below potential (PJTAU, 2024; Ouedraogo *et al.*, 2024) due to declining soil fertility, low organic carbon content, and suboptimal nutrient management practices, especially in intensively cultivated vegetable-growing regions of India (Meena *et al.*, 2021; Chaudhari *et al.*, 2023).

Soils of eastern India, including Odisha, are predominantly Inceptisols characterized by low to medium

SOC, low available nitrogen, and emerging nutrient imbalances resulting from continuous cropping, removal of crop residues, and limited application of organic amendments (Bhattacharyya *et al.*, 2015). Several Indian studies have reported that long-term reliance on chemical fertilizers without adequate organic inputs has led to deterioration of soil physical structure, reduced nutrient use efficiency, and declining productivity of vegetable-based systems (Titirmare *et al.*, 2023). These concerns underline the need for integrated nutrient management strategies that combine mineral fertilizers with organic amendments to sustain soil health and crop yields.

Biochar, a carbon-rich material produced through pyrolysis of biomass under oxygen-limited conditions, has gained considerable attention as a soil amendment for improving soil quality and crop performance. Due to its porous structure, high surface area, and surface functional groups, biochar can enhance soil water-holding capacity, nutrient retention, microbial activity, and long-term carbon sequestration (Das *et al.*, 2019; Mishra *et al.*, 2023; Subha and Jeyamangalam, 2025). Study conducted in India have demonstrated that biochar application improves SOC, nutrient availability, and crop yields in degraded and low-fertility soils (Jayaraman *et al.*, 2024).

The agronomic effectiveness of biochar is strongly influenced by feedstock source, application rate, soil type, and interactions with fertilizers and organic manures. Crop residue derived biochar generally contains higher ash content and readily available nutrients, whereas woody or coconut-shell biochar is more recalcitrant and contributes primarily to carbon stabilization and soil structural improvement (Siddiqui, 2025). FYM a widely available organic input in Indian farming systems, supplies essential nutrients, improves soil aggregation, and stimulates microbial activity. Indian studies have reported that combined application of biochar and FYM enhances nutrient availability and crop productivity more effectively than their sole application due to synergistic effects on nutrient cycling and soil biological activity (Sharma *et al.*, 2025).

While the benefits of biochar have been extensively studied in cereal-based systems, information on its performance in high-value vegetable crops such as okra and brinjal remains limited, particularly under Inceptisol conditions of eastern India. Moreover, comparative evaluations of different biochar sources, such as crop residue and wood/coconut, in conjunction with FYM and recommended fertilizer doses are scarce. It is hypothesized that the integrated application of biochar with FYM and recommended doses of fertilizers would improve soil nutrient availability and result in superior growth and fruit yield of okra and brinjal compared to fertilizer-only treatments. It is further hypothesized that biochar derived from different feedstocks would differ in their effectiveness due to variations in physicochemical properties.

HIGHLIGHTS

- Integrated application of crop residue biochar (8 g kg⁻¹ soil or 17 t ha⁻¹) with FYM and RDF nearly doubled okra fruit yield and increased brinjal fruit yield by three- to four-fold compared with the control.
- Biochar-based integrated nutrient management significantly improved soil fertility, increasing SOC by 114%, available P by 170%, and available K by 27% over the control.
- Residual and cumulative effects of biochar were more pronounced in the second season, confirming its long-term role in sustaining vegetable productivity and soil health in Inceptisol.
- Enhanced carbon stabilization and nutrient retention under integrated biochar use provide a practical recommendation of crop residue biochar @ 8 g kg⁻¹ soil with FYM and RDF for sustainable vegetable production.

In this context, the present study was undertaken with the objective of evaluating the effect of different biochar sources and application rates, alone and in combination with FYM and recommended fertilizer doses, on growth and fruit yield of okra and brinjal grown in Inceptisol soil collected from the Belpada in Odisha under pot experiment. This study was funded by the GIZ through ICRAF. ICRAF had been taking up their research initiatives in this region with these crops, hence, we designed this study to evaluate biochar application in these soils. The study also aims to assess changes in soil available nutrients following biochar application and to identify suitable biochar-based integrated nutrient management strategies for enhancing vegetable productivity and soil fertility in eastern Indian soils.

2 | MATERIALS AND METHODS

2.1 | Study Location

A pot experiment was conducted during 2021–2022 at the ICAR–Indian Institute of Soil Science, Bhopal, Madhya Pradesh. The soil belonged to the Inceptisol soil order (Soil Survey Staff, 2014) and was collected from the Belpada tehsil in Balangir district of Odisha, India. These soils occupy approximately an area of 7.60 million hectare covering 49% area in the state (Mishra *et al.*, 2024). The experimental soil had a pH of 6.21, electrical conductivity of 0.11 dS m⁻¹, and SOC content of 0.45%. The soil was classified as low in available nitrogen (220 kg ha⁻¹), medium in available phosphorus (28.3 kg ha⁻¹), and high in available potassium (393 kg ha⁻¹). In the study, biochar was not only intended to treat the pH, but the objective was to assess its effect on vegetable production in conjunction with FYM also.

2.2 | Experimental Design

The experiment was laid out in a Completely Randomized Design comprising eleven treatments with four replications. The treatments included three levels of biochar (0, 4, and 8 g kg⁻¹ soil), two levels of FYM (0 and 5 g kg⁻¹ soil), one level of the (RDF), and a control. The RDF was applied to each pot based on the recommended rate of N:P₂O₅:K₂O *i.e.*

120:75:50 kg ha⁻¹ through urea, single super phosphate, and muriate of potash, respectively to both the crops. Two types of biochar, i.e. crop residue biochar (CRB) of groundnut, mustard, and rice husk and mixed wood biochar (WCB) of *Prosopis juliflora* and coconut husk were used in the study. The biochar was provided by ICRAF, New Delhi through procurement from private suppliers. Wood biochar was prepared from *Prosopis juliflora* and coconut husk and CRB

was prepared from mixed residues of groundnut, mustard and rice husk. Basic properties of the biochar and FYM have been mentioned in Table 1. Biochar was applied at the beginning of each crop season, i.e., it was added for every cropping cycle during the experimental period. The detailed treatment combinations are presented in (Table 2). Total nutrient added (mg pot⁻¹) in initial soil nutrient status through different sources have been mentioned in (Table 3).

TABLE 1 Basic properties of different biochar used in this experiment

Biochar	pH	EC (dS m ⁻¹)	TOC (%)	Total N (%)	Total P (%)	Total K (%)
WCB	8.16-9.20	1.78-5.48	31.9-46.2	0.58	0.09-0.25	0.59- 1.0
CRB	8.12-9.09	1.68-5.36	37.1-49.5	0.38	0.07-0.21	0.53-1.0
FYM	7.2-7.8	1.0-2.0	15-20	0.5-0.8	0.2-0.4	0.5-1.0

TABLE 2 Treatment structure for pot experiment

Treatments	Treatment combination	Biochar (g kg ⁻¹)	FYM (g kg ⁻¹)
T ₁	F ₀ B ₀ M ₀	0	0
T ₂	F ₁ B ₀ M ₀	0	0
T ₃	F ₁ B ₀ M ₅	0	5
T ₄	F ₁ WCB ₄ M ₀	4	0
T ₅	F ₁ WCB ₄ M ₅	4	5
T ₆	F ₁ WCB ₈ M ₀	8	0
T ₇	F ₁ WCB ₈ M ₅	8	5
T ₈	F ₁ CRB ₄ M ₀	4	0
T ₉	F ₁ CRB ₄ M ₅	4	5
T ₁₀	F ₁ CRB ₈ M ₀	8	0
T ₁₁	F ₁ CRB ₈ M ₅	8	5

TABLE 3 Total nutrient added (mg pot⁻¹) in initial soil nutrient status through different sources to each crop

Treatments	Treatment combination	N	P	K
T ₁	F ₀ B ₀ M ₀	0	0	0
T ₂	F ₁ B ₀ M ₀	600	327	415
T ₃	F ₁ B ₀ M ₅	925	477	790
T ₄	F ₁ WCB ₄ M ₀	832	395	735
T ₅	F ₁ WCB ₄ M ₅	1157	545	1110
T ₆	F ₁ WCB ₈ M ₀	1064	463	1055
T ₇	F ₁ WCB ₈ M ₅	1389	613	1430
T ₈	F ₁ CRB ₄ M ₀	752	383	719
T ₉	F ₁ CRB ₄ M ₅	1077	533	1094
T ₁₀	F ₁ CRB ₈ M ₀	904	439	1023
T ₁₁	F ₁ CRB ₈ M ₅	1229	589	1398

2.3 | Crop Management Practices

Surface soils (0-15 cm) was collected from the Belpada in Balangir district of Odisha, were ground and passed through 2 mm sieve. 10 kg air dry soil was mixed with required dose of WCB and CRB and FYM thoroughly and filled in plastic pots. Okra seeds (var. Supreme) were sown on 24 and 19 July in 2021 and 2022 respectively. Five seeds of okra were sown in each pot (oval shaped with diameter 30 cm and height 22 cm) and later on only two plants were maintained

(Plate 1). After harvest of okra in the month of November, soils were mixed thoroughly and refilled in the same pot with same treatment. About 20 days old single seedling of Brinjal (var. Kavya and Ankur hybrid 786) was transplanted (Plate 1) on 01 December and 19 December of 2021 and 2022, respectively. Full dose of P and K fertilizer and 50 per cent of N were applied at the time of sowing/transplanting of okra and brinjal, respectively. Remaining N was applied in two splits after 45 and 60 days after sowing/transplanting of

okra and brinjal, respectively. Pots were watered to maintain optimum moisture conditions during plant growth. Crops were raised with standard package of practices. Plants were sprayed with chemicals such as imidachloprid

(0.3 ml L⁻¹ water) and Abamectin (0.5 ml L⁻¹ water) for plant protection at time to time. The pots were kept in a net house of ICAR-IISS, Bhopal and same soil was used again for the next season.



PLATE 1 Some of the photos of the pot study

2.4 | Growth and Fruit Yield

Plant height was measured at periodic growth stages and at final harvest in okra and brinjal. The height of each plant was recorded in centimeters (cm) from the soil surface at the base of the plant to the apical growing point using a graduated measuring scale. Mean plant height per treatment was calculated using observations from all replications. Harvesting of okra fruits was carried out at the tender, marketable stage at regular intervals. Brinjal fruits were harvested at physiological maturity based on varietal characteristics. The fruits were harvested from each plant and their fresh weight was measured using an electronic balance and expressed as g pot⁻¹.

2.5 | Soil Analysis

After maturity of the crops, plants were harvested and the whole soil of pot was drawn out and thoroughly mixed and

sampled for analysis. The crop was harvested and the soil of the pot was drawn out and thoroughly mixed and sampled for analysis. SOC was determined by wet oxidation method (Walkley and Black, 1934). Available P was determined by the Olsen's method using 0.5 M sodium bicarbonate (NaHCO₃, pH 8.5) as extractant (Olsen *et al.*, 1954). Available K was extracted using neutral normal ammonium acetate (1 N NH₄OAc, pH 7.0). The K concentration in the extract was determined using a flame photometer (Jackson, 1973).

2.6 | Statistical Analysis

The study used one-way ANOVA in combination with DMRT (Duncan's Multiple Range Test) method to identify mean differences between various treatments for different parameters (Gomez and Gomez, 1984). Year-wise data analysis was performed separately not as pooled. Software

WASP 2.0 developed by ICAR-ICARI Goa was used to analyze the data statistically. Any p-values that were less than 0.05 were considered significant for deciding the significance of treatments.

3 | RESULTS AND DISCUSSION

3.1 | Effect on Growth of Okra and Brinjal

In both 2021 and 2022, plant height of okra increased progressively with crop age (30, 60, and 90 DAS), but the magnitude of increase varied significantly ($p < 0.05$) among treatments. In 2021, the maximum plant height (114.8 cm) at 90 DAS was recorded under $F_1CRB_8M_5$ (RDF + crop residue biochar @ 8 g kg⁻¹ soil + FYM @ 5 g kg⁻¹ soil) (Fig. 1a), which resulted in an increase of about 30.7% over the control ($F_0B_0M_0$). The treatments $F_1WCB_8M_5$ (112.8 cm) and $F_1CRB_4M_5$ (104.6 cm) followed, recording 19-28% higher plant height than the control, while RDF alone ($F_1B_0M_0$) showed only 1.92% improvement. Sole biochar application did not significantly enhance plant height compared to RDF with or without FYM. A similar and consistent response was observed in 2022, where $F_1CRB_8M_5$ again produced the tallest plants (128.9 cm) at 90 DAS, showing a 54.8% increase over the control (Fig. 1b), confirming the stability of integrated biochar-based nutrient management across seasons. Minor year-to-year variation was observed, but the relative ranking of treatments remained unchanged. The enhanced plant height under crop residue biochar + FYM integration can be attributed to improved soil physical conditions such as higher porosity and water retention, coupled with enhanced nutrient availability during the active vegetative phase. Biochar improves nutrient retention through increased cation exchange capacity, while FYM supplies readily mineralizable nutrients and stimulates microbial activity, together ensuring sustained nutrient availability at later growth stages (Zhang *et al.*, 2024). Recent studies under vegetable-based systems have also reported superior vegetative growth when biochar is integrated with organic and inorganic nutrient sources rather than applied alone (Effa *et al.*, 2023). Brinjal exhibited a response pattern similar to okra, with plant height increasing steadily at all growth stages during both 2021 and 2022. In 2021, the treatment $F_1CRB_8M_5$ recorded the significantly ($p < 0.05$) highest plant height (73 cm) at 90 DAS, showing a 56.9% increase over the control, followed by $F_1WCB_8M_5$, which resulted in a 54.8% increase (Fig. 1c). Treatments receiving RDF alone or biochar without FYM produced comparatively shorter plants. In 2022, the superiority of $F_1CRB_8M_5$ was further confirmed, with highest plant height (67.8 cm) remaining 56.8% higher than the control (Fig. 1d), indicating that the beneficial effects of biochar-based integration were more pronounced and sustained in the second year. The response of brinjal to integrated treatments was stronger at later growth stages, reflecting improved root growth and nutrient uptake under improved soil conditions. The improved plant height of brinjal under integrated treatments can be explained by enhanced soil moisture retention and nutrient synchronization with crop demand. Brinjal, being a long-duration and nutrient-exhaustive crop, responds strongly to

improved soil structure and continuous nutrient supply, both of which are facilitated by biochar + FYM combinations (Acharya *et al.*, 2023; Anusha *et al.*, 2025). Recent evidence suggests that biochar derived from crop residues, when co-applied with organic nutrient sources, enhances soil fertility, nutrient availability and vegetative vigor in vegetable systems compared with biochar alone (Acharya *et al.*, 2023; Anusha *et al.*, 2025). Across both years and crops, $F_1CRB_8M_5$ consistently emerged as the most stable and effective treatment, demonstrating that biochar alone is insufficient, but when integrated with FYM and RDF, it significantly enhances yield by improving soil quality, nutrient retention, and nutrient use efficiency. The stronger response observed in brinjal compared to okra highlights the importance of crop-specific nutrient demand and growth duration in determining biochar effectiveness.

3.2 | Effect on Yield of Okra and Brinjal

Fruit yield of okra differed significantly ($p < 0.05$) among treatments during both 2021 and 2022, indicating a strong response to integrated nutrient management involving biochar, FYM, and RDF (Table 4). In 2021, the highest fruit yield (185.4 g pot⁻¹) was obtained under $F_1CRB_8M_5$ (RDF + crop residue biochar @ 8 g kg⁻¹ soil + FYM @ 5 g kg⁻¹ soil), which resulted in an increase of about 98% over the control (93.5 g pot⁻¹). This treatment was followed by $F_1CRB_8M_0$ (159.2 g pot⁻¹) and $F_1CRB_4M_5$ (153.4 g pot⁻¹), which recorded yield increases of 70% and 64%, respectively. RDF alone ($F_1B_0M_0$) produced only a modest yield improvement (10%), while biochar application without FYM showed inconsistent effects. During 2022, a similar response pattern was observed, confirming treatment stability across years. The maximum fruit yield was again recorded under $F_1CRB_8M_5$ (145.0 g pot⁻¹), which was ~99% higher than the control (72.8 g pot⁻¹) (Table 4). Integrated biochar treatments consistently outperformed RDF alone, suggesting that biochar-mediated improvement in soil conditions plays a key role during reproductive development of okra. The yield enhancement under $F_1CRB_8M_5$ can be attributed to improved nutrient availability and reduced nutrient losses during flowering and fruit development. Biochar improves soil aggregation and nutrient retention, particularly for nitrogen and potassium, while FYM enhances microbial-mediated nutrient mineralization, together improving nutrient synchronization with crop demand (Premalatha *et al.*, 2023). Recent studies in vegetable-based systems have reported that biochar combined with organic amendments significantly improves fruit yield by enhancing nutrient use efficiency and root growth (Kesamreddy *et al.*, 2025).

Fruit yield of brinjal showed a stronger response to biochar-based treatments than okra in both years because the relative increase in plant height was 50% in brinjal compared to 30% in okra. In 2021, the highest fruit yield (96.7 g pot⁻¹) was recorded under $F_1CRB_8M_5$, representing an increase of about 213% over the control (30.9 g pot⁻¹) (Table 4).

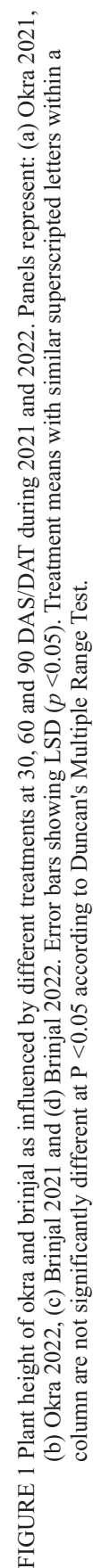


FIGURE 1 Plant height of okra and brinjal as influenced by different treatments at 30, 60 and 90 DAS/DAT during 2021 and 2022. Panels represent: (a) Okra 2021, (b) Okra 2022, (c) Brinjal 2021 and (d) Brinjal 2022. Error bars showing LSD ($p < 0.05$). Treatment means with similar superscripted letters within a column are not significantly different at $P < 0.05$ according to Duncan's Multiple Range Test.

TABLE 4 Effect of different biochar treatments on fruit yield of okra and brinjal during 2021 and 2022

Treatment	Okra (g pot ⁻¹)		Brinjal (g pot ⁻¹)	
	2021	2022	2021	2022
F ₀ B ₀ M ₀	93.5 ^f	72.8 ^f	30.9 ^g	46.0 ^c
F ₁ B ₀ M ₀	103.0 ^{ef}	87.3 ^{ef}	54.7 ^f	195.0 ^b
F ₁ B ₀ M ₅	122.8 ^{cd}	99.6 ^{de}	76.5 ^{cde}	229.2 ^{ab}
F ₁ WCB ₄ M ₀	118.5 ^{ef}	97.2 ^{de}	67.3 ^e	188.7 ^b
F ₁ WCB ₄ M ₅	121.6 ^c	106.1 ^{cd}	83.7 ^{bcd}	222.6 ^{ab}
F ₁ WCB ₈ M ₀	89.6 ^{de}	104.0 ^{cde}	75.1 ^{de}	258.3 ^a
F ₁ WCB ₈ M ₅	133.4 ^c	113.8 ^{bcd}	86.2 ^{bc}	261.2 ^a
F ₁ CRB ₄ M ₀	123.0 ^{cd}	102.3 ^{cde}	76.5 ^{cde}	189.9 ^b
F ₁ CRB ₄ M ₅	153.4 ^b	123.6 ^b	88.5 ^{ab}	200.7 ^b
F ₁ CRB ₈ M ₀	159.2 ^b	118.4 ^{bc}	85.1 ^{bcd}	218.8 ^{ab}
F ₁ CRB ₈ M ₅	185.4 ^a	145.0 ^a	96.7 ^a	262.5 ^{ab}

Treatment means with similar superscripted letters within a column are not significantly different at $p < 0.05$ according to Duncan's Multiple Range Test.

Treatments F₁CRB₄M₅ (88.5 g pot⁻¹) and F₁WCB₈M₅ (86.2 g pot⁻¹) also produced significantly higher yields, showing 178-186% increases, while RDF alone resulted in only a ~77% increase. In 2022, fruit yield increased substantially across treatments, with F₁CRB₈M₅ (261.5 g pot⁻¹) and F₁WCB₈M₅ (261.2 g pot⁻¹) (Table 4). Compared to the control (46.0 g pot⁻¹), F₁CRB₈M₅ resulted in a 470% increase, highlighting the cumulative and residual benefits of biochar application in the second year. Brinjal, being a long-duration and nutrient-intensive crop, benefits greatly from improved soil structure, moisture retention, and prolonged nutrient supply. Biochar enhances soil aeration and water availability, while FYM supports continuous nutrient release during extended flowering and fruiting phases (Xu *et al.*, 2025). Recent evidence suggests that residual biochar effects can substantially enhance yields of solanaceous crops by improving rhizosphere microbial activity and nutrient uptake efficiency (Zhang *et al.*, 2022). Across both crops and years, F₁CRB₈M₅ emerged as the most stable and effective treatment, demonstrating that biochar alone is insufficient, but when integrated with FYM and RDF, it significantly enhances yield through improved soil physical properties, nutrient retention, and nutrient use efficiency. The stronger response in brinjal compared to okra highlights the importance of crop duration and nutrient demand in determining biochar effectiveness.

3.3 | Effect on Nutrient Uptake

Biochar application significantly ($p < 0.05$) influenced N, P, and K uptake by both okra and brinjal during 2021 and 2022. Across treatments, nutrient uptake consistently increased with higher biochar rates and was generally greater under biochar + FYM combinations compared to FYM alone and control. N uptake showed a marked improvement with biochar addition. The lowest N uptake in okra (0.10 and 0.14 g pot⁻¹) was recorded under the control treatment (F₀B₀M₀) during both the years, while treatments receiving biochar at higher rates in combination with FYM (F₁CRB₈M₅) exhibited the highest N uptake in okra (0.42 and 0.86 g pot⁻¹) during both the years (Fig. 2). Brinjal recorded higher N

uptake than okra in both years, with maximum values observed during 2022 (2.82 g pot⁻¹) compared to 2021 (1.94 g pot⁻¹) under F₁CRB₈M₅ (Fig. 3). A similar trend was observed for P uptake, where biochar-amended treatments significantly enhanced P uptake over the control. F₁CRB₈M₅ consistently resulted in maximum P uptake in brinjal (0.13 and 0.20 g pot⁻¹) (Fig. 3) and okra (0.12 and 0.17 g pot⁻¹) (Fig. 2). The increase was more pronounced in the second year, suggesting improved P availability under biochar-amended acidic soil conditions. K uptake also increased significantly with biochar application. The highest K uptake in brinjal (0.93 and 1.64 g pot⁻¹) was recorded with F₁CRB₈M₅ during both the years, reflecting the contribution of biochar-derived K and improved soil chemical environment (Fig. 3). Brinjal showed greater K uptake than okra across all treatments and years, with higher uptake during 2022. Enhanced N uptake may be attributed to improved soil pH and nutrient retention, which reduce N losses and promote better synchronization between nutrient supply and crop demand (Agegnehu *et al.*, 2016). The higher uptake observed during the second year supports earlier findings that biochar effects become more pronounced over time. The increase in P uptake under biochar-amended treatments is likely due to reduced P fixation in acidic soils as a result of increased soil pH and the contribution of biochar-derived P, leading to greater P availability (Xu *et al.*, 2013). Similarly, enhanced K uptake reflects the inherent K content of biochar and improved cation exchange capacity, which helps retain K in the root zone and limits leaching losses (Major *et al.*, 2010). Brinjal consistently showed higher nutrient uptake than okra, likely due to greater biomass production and nutrient demand. Overall, the improved nutrient uptake aligns with observed changes in soil pH, EC, and nutrient availability, confirming that biochar application, especially when combined with FYM, plays a key role in improving nutrient use efficiency and crop performance in acidic soils.

3.4 | Effect on soil pH and EC

Biochar application significantly ($p < 0.05$) influenced soil pH and electrical conductivity (EC) across treatments (Fig. 4). Soil pH increased progressively with increasing biochar

rates and was higher under biochar + FYM combinations compared to the control. The lowest soil pH (7.26) was recorded under the control treatment, while the highest pH values (7.64) were observed under treatments receiving higher biochar doses, particularly $F_1CRB_8M_5$, indicating the liming effect of biochar in acidic soil. Soil EC also showed an increasing trend with biochar addition. Treatments amended with higher biochar rates exhibited greater EC values compared to the control and FYM-alone treatments, reflecting the contribution of soluble salts and ash-derived nutrients from biochar. The maximum EC (0.59 dS m^{-1}) was recorded under $F_1CRB_8M_5$, whereas the lowest EC (0.19 dS m^{-1}) occurred in the control treatment. The increase in soil pH with biochar application observed in this study confirms its effectiveness as an acidity-ameliorating amendment in acidic soils. Recent studies have shown that biochar raises soil pH through the release of base cations and ash components, thereby improving soil chemical conditions and nutrient availability, particularly when applied at higher rates or in combination with organic amendments (Deng *et al.*, 2025). The rise in soil EC with increasing biochar rates reflects the contribution of soluble ions and ash-derived nutrients from biochar. Similar moderate increases in EC without salinity risk have been reported in recent meta-analyses and are associated with improved nutrient pools and ion exchange processes (Asirifi *et al.*, 2025). Overall, the concurrent increase in soil pH and EC indicates an improvement in the soil chemical environment, which likely enhanced nutrient availability and contributed to improved crop performance in the present study.

3.5 | Effect on Soil Fertility

Soil fertility parameters, particularly SOC, P, and K, were significantly ($p < 0.05$) influenced by biochar-based treatments after harvest of okra and brinjal during both years. Across seasons, treatments integrating biochar with FYM and RDF consistently improved soil fertility compared to the control and sole fertilizer treatments. SOC content increased markedly under biochar-amended treatments, with the highest SOC (1.03%) recorded under $F_1CRB_8M_5$ (RDF + crop residue biochar @ 8 g kg^{-1} soil + FYM @ 5 g kg^{-1} soil). Compared to the control ($F_0B_0M_0$), SOC under $F_1CRB_8M_5$ increased by about 114%, followed by $F_1WCB_8M_5$ (0.91%) and $F_1CRB_8M_0$ (0.90%) (Fig. 4). The improvement was consistent in both years, indicating the persistent and cumulative nature of biochar-derived carbon in soil. CRB contributed more effectively to SOC build-up than WCB, likely due to its higher labile carbon fraction and ash content. The increase in SOC under biochar + FYM combinations can be attributed to the high aromatic carbon content and long mean residence time of biochar, which stabilizes soil carbon pools and protects native organic matter from microbial decomposition (Song *et al.*, 2024). FYM further enhances carbon inputs and promotes microbial aggregation, leading to greater physical protection of organic carbon within soil aggregates, while co-application of biochar with organic amendments improves nutrient retention and microbial biomass (Nkrumah *et al.*, 2025). Recent studies have emphasized

that integrating biochar with organic manures accelerates carbon sequestration while simultaneously improving soil biological activity and ecosystem multi-functionality in vegetable-based systems (Bi *et al.*, 2024). Available phosphorus also showed a significant ($p < 0.05$) improvement under biochar-amended treatments. The highest available P (70.5 kg ha^{-1}) was observed under $F_1CRB_8M_5$, recording an increase of about 170% over the control, followed by $F_1WCB_8M_5$ (70.1 kg ha^{-1}) (Fig. 5). The increase was more pronounced in the second year, suggesting a residual effect of biochar on P dynamics. Biochar is known to reduce P fixation by Fe and Al oxides in acidic to neutral soils and to enhance P availability through ash-derived P and improved microbial-mediated mineralization (Zhang *et al.*, 2025). The synergistic role of FYM further enhanced P solubilization through organic acid production and phosphatase activity, resulting in improved P availability to crops.

Similarly, soil available K increased significantly ($p < 0.05$) with biochar application, particularly under $F_1CRB_8M_5$ (353 kg ha^{-1}), which showed 27.7% higher available K than the control (Fig. 5). Crop residue biochar was more effective than woody biochar in enhancing soil K due to its higher inherent K content and ash fraction. The increase in available K was sustained across both years, indicating reduced K leaching losses and improved K retention in the soil exchange complex. Recent studies have highlighted biochar ability to act as a slow-release source of potassium while simultaneously enhancing K use efficiency through improved cation retention (Sharma *et al.*, 2025). Overall, the results clearly demonstrate that biochar alone is insufficient to maximize soil fertility, whereas its integration with FYM and RDF, particularly under $F_1CRB_8M_5$, substantially improves SOC sequestration and nutrient availability. The observed improvements in soil fertility provide a mechanistic explanation for the enhanced growth and yield of okra and brinjal under integrated biochar-based nutrient management and underline the importance of combining stable carbon inputs with organic and mineral nutrient sources for sustaining soil productivity in intensive vegetable systems.

4 | Limitations of The Study

The present study provides valuable insights into biochar-based integrated nutrient management. The experiment was conducted under controlled pot conditions, which restrict root proliferation and reduce environmental variability relative to open-field systems. Further the soils of Belpada, Odisha have been studied in Central India, these factors may alter nutrient retention and amplify treatment effects; therefore, the quantitative responses observed may not equally translate to field-scale productivity. Also, biochar is known for its long-term persistence and gradual soil interaction processes that extend over decades; however, this two-year study captures only initial responses and may not fully represent stabilization dynamics, long-term carbon sequestration, or sustained agronomic impacts.

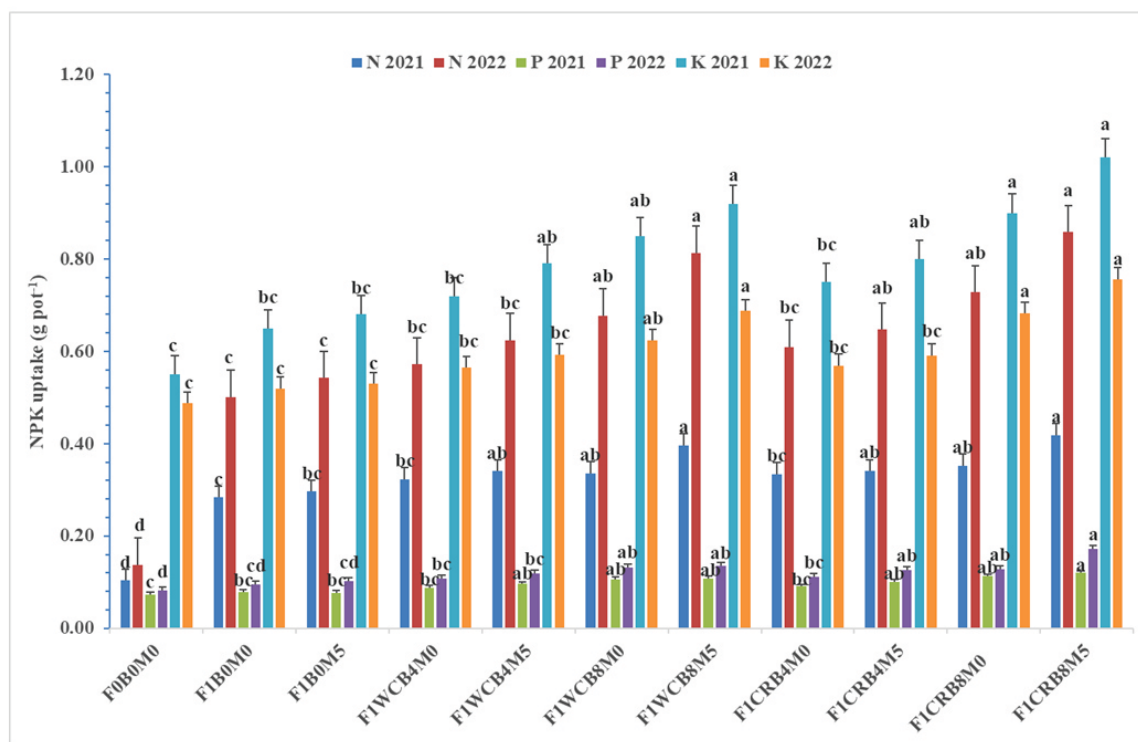


FIGURE 2 Nitrogen (a), phosphorus (b) and potassium (c) uptake (g pot⁻¹) by okra under different treatments during 2021 and 2022. Error bars indicate LSD ($p < 0.05$). Treatment means with similar superscripted letters within a column are not significantly different at $P < 0.05$ according to Duncan's Multiple Range Test.

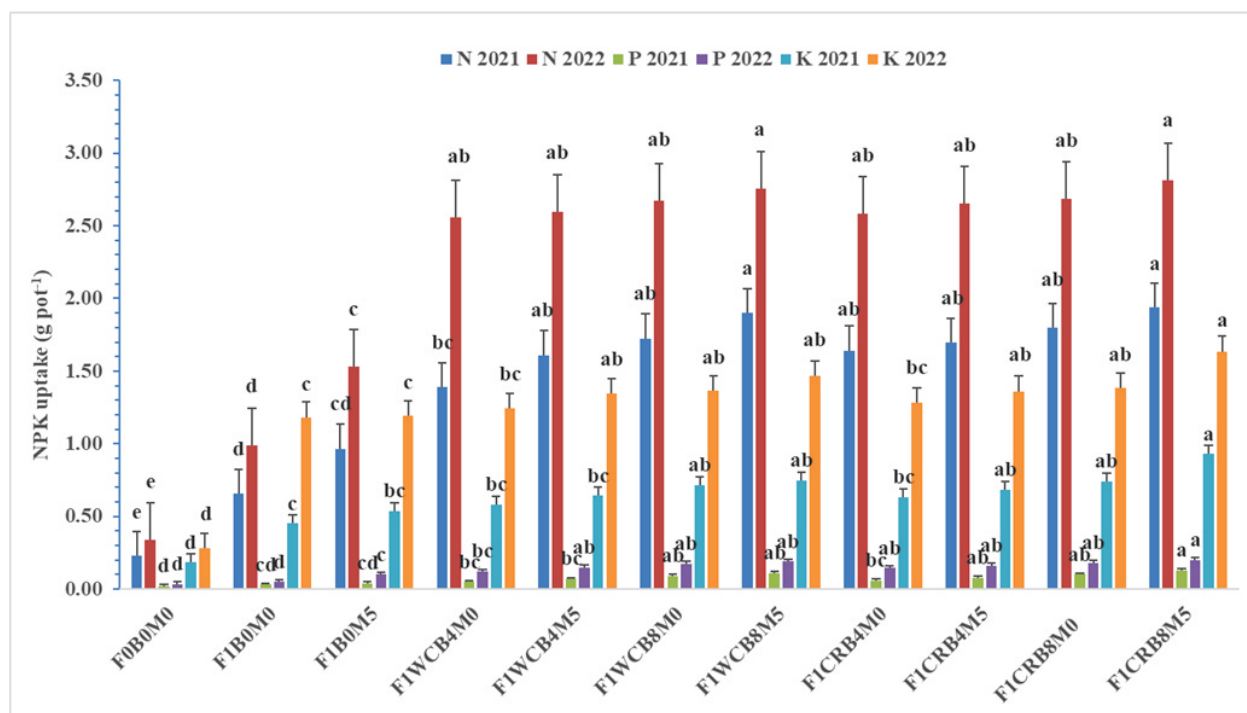


FIGURE 3 Nitrogen (a), phosphorus (b) and potassium (c) uptake (g pot⁻¹) by brinjal under different treatments during 2021 and 2022. Error bars indicate LSD ($p < 0.05$). Treatment means with similar superscripted letters within a column are not significantly different at $P < 0.05$ according to Duncan's Multiple Range Test.

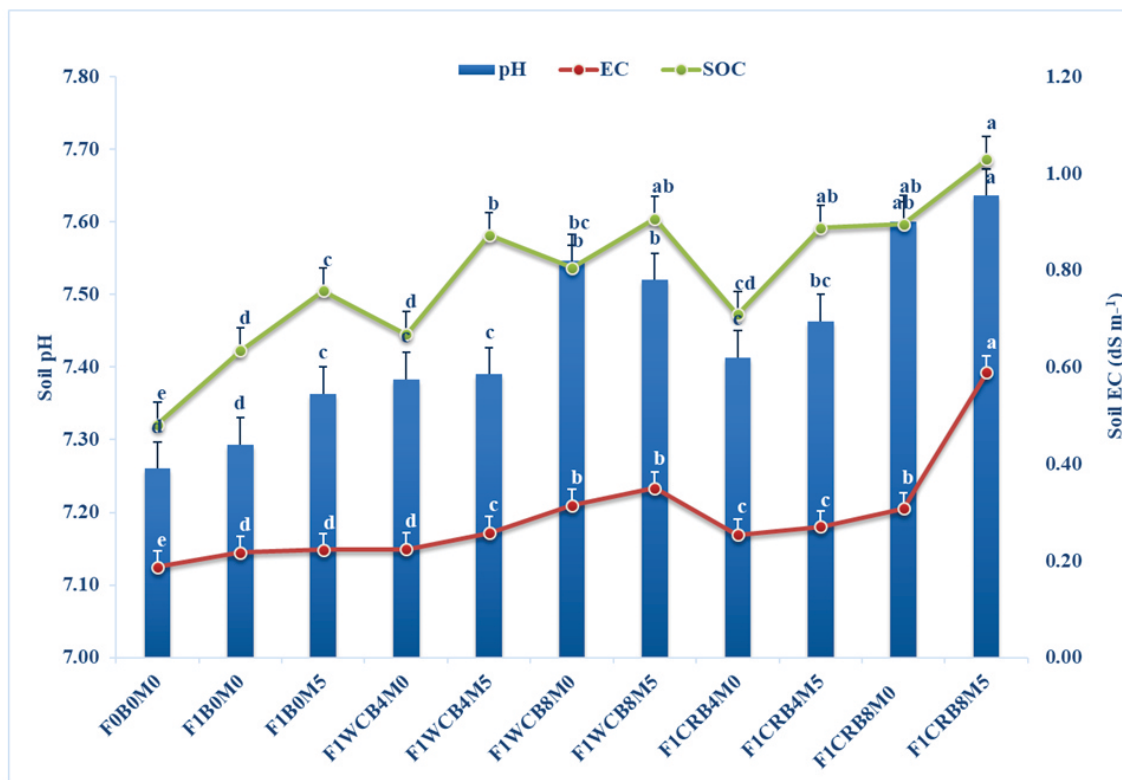


FIGURE 4 Effect of different biochar treatments on soil pH, EC, and SOC measured after two-years period (post-harvest). Error bars indicate LSD ($p < 0.05$). Treatment means with similar superscripted letters within a column are not significantly different at $P < 0.05$ according to Duncan's Multiple Range Test.

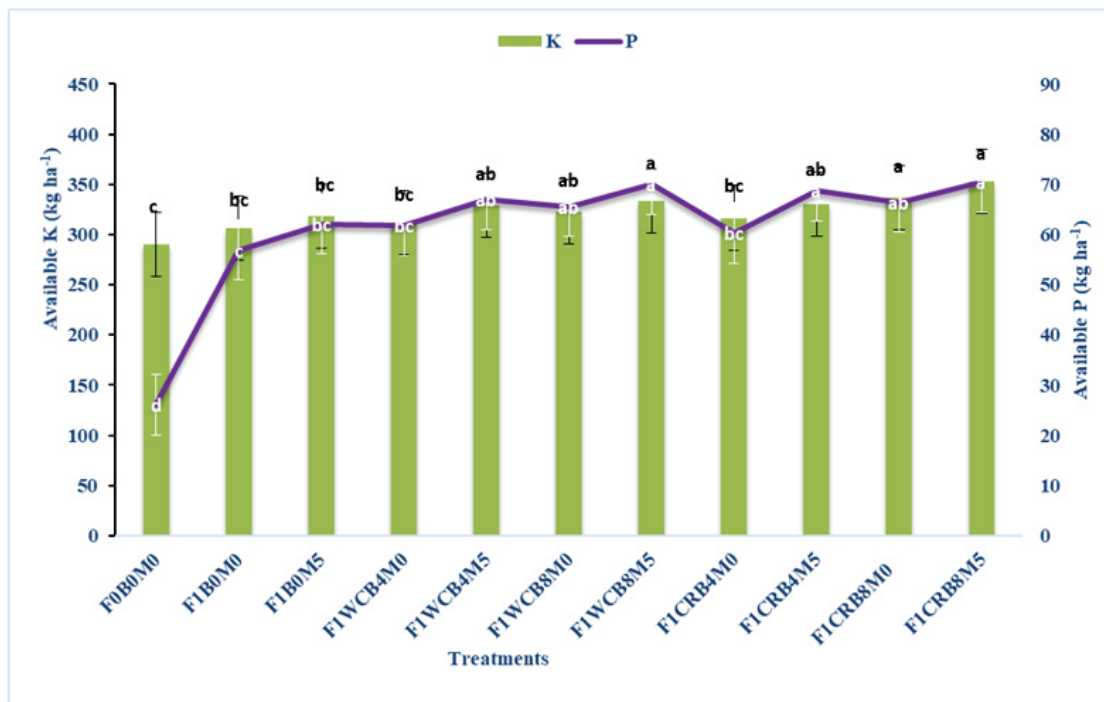


FIGURE 5 Effect of different biochar treatments on soil available P and K measured after two-years period (post-harvest). Error bars indicate LSD ($p < 0.05$). Treatment means with similar superscripted letters within a column are not significantly different at $P < 0.05$ according to Duncan's Multiple Range Test.

5 | CONCLUSIONS

The present pot study demonstrated that integrated application of biochar, FYM and RDF significantly enhanced growth, fruit yield, nutrient uptake and soil fertility of okra and brinjal grown in an Inceptisol. Among the treatments, CRB @ 8 g kg⁻¹ soil combined with FYM @ 5 g kg⁻¹ soil and RDF consistently produced the best results. Improvements in crop productivity were closely associated with enhanced SOC, nutrient availability, and improved soil chemical environment, confirming synergistic interactions between stable carbon inputs and nutrient amendments. The biochar rate used in the best treatment (8 g kg⁻¹ soil) corresponds to approximately 17 t ha⁻¹ under field conditions. Considering a typical biochar production efficiency of about 25–35% from dry biomass, producing 17 t ha⁻¹ of biochar would require roughly 50–70 t of crop residues such as groundnut shells, mustard residues, or rice husk. While this requirement is substantial, biochar production can be feasible in regions with surplus agricultural residues where alternative uses are limited. Although the findings are derived from controlled pot conditions and therefore require validation under field environments, the results clearly indicate that biochar alone is insufficient, whereas its integration with FYM and mineral fertilizers provides synergistic benefits for nutrient availability, carbon stabilization and vegetable productivity. Therefore, crop residue biochar @ 8 g kg⁻¹ soil integrated with FYM and RDF can be considered a promising component of sustainable nutrient management strategies for vegetable-based systems in Inceptisols. Future research should focus on long-term field trials, uniform varietal testing, expanded treatment structures, and multi-location validation to refine agronomic recommendations and quantify ecosystem-scale impacts.

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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 will be made available on request.

AUTHOR'S CONTRIBUTION

Brij Lal Lakaria, Pramod Jha, BP Meena, Vassanda Coumar, AK Vishwakarma: Conceptualization, conducting pot study, methodology, writing original manuscript; Brij Lal Lakaria: Lab analysis, data collection; Statistical analysis; Brij Lal Lakaria, Aqeel Hasan Rizvi, S.K. Dhyani, Javed Rizvi, Monitoring and supervision; Brij Lal Lakaria, Pramod Jha, Dinesh Jinger: Interpretations, writing and reviewing.

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Green Manuring with *Sesbania aculeata* for Weed Suppression, Rice Productivity, and Soil Carbon Sequestration in Central India

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ABSTRACT

Continuous monocropping coupled with suboptimal management practices accelerates soil degradation and exacerbates environmental stress. In this context, legume-based green manuring has emerged as a sustainable strategy for enhancing soil health, environmental quality, and crop productivity in rice-based systems. It was hypothesized that incorporation of 45-day-old *Sesbania aculeata* biomass (4.73–5.03 t ha⁻¹) prior to rice transplanting would enhance rice productivity and profitability, suppress weed infestation, and promote soil carbon stabilization. A three-year field study (2014–2016) was conducted on large plots (4000 m² per field) comparing rice fields with and without *S. aculeata* incorporation. The results revealed that *S. aculeata* incorporation significantly ($p < 0.05$) reduced weed density and biomass (41.7–57.3% and 36.6–38.4%, respectively), while substantially increasing rice grain and straw yields (5.84–7.52 and 6.84–8.65 t ha⁻¹, respectively). Furthermore, green manuring with *S. aculeata* improved soil physical properties, notably reducing bulk density (1.39 Mg m⁻³ from 1.42), and significantly enhanced soil organic carbon (SOC) content (0.37% to 0.45%). Continuous incorporation over three years contributed appreciable carbon to the soil profile, resulting in higher soil carbon stocks than in the non-incorporated system. Incorporation of *S. aculeata* as green manure effectively suppresses weeds, enhances rice yield, improves soil health, increases carbon sequestration, and allows a reduction of synthetic nitrogen fertilizer by ~20 kg N ha⁻¹, thereby lowering production costs and mitigating potential environmental pollution.

1 | INTRODUCTION

Rice (*Oryza sativa* L.) is a principal staple food for millions of people worldwide, with Asia accounting for the largest share of production and consumption (DES, 2024). Consequently, rice-based production systems are pivotal to food and nutritional security in the region. Compared with other crops of similar growth duration, rice cultivation is highly input-intensive, requiring substantial amounts of water (1100–1800 mm ha⁻¹), nutrients (100:60:40 kg N, P₂O₅, and K₂O ha⁻¹), and repeated tillage operations (3–4 numbers). In efforts to maximize yields, farmers frequently apply excessive quantities of fertilizers and irrigation, practices that strongly influence rice productivity and system performance (Choudhary *et al.*, 2022). However, the sustainability of rice production is largely determined by the nature and efficiency of agronomic management practices adopted.

Improper cultivation practices, such as excessive and repeated tillage, indiscriminate fertilizer use, prolonged flooding, inefficient water management, and other unsound interventions, and open-field burning of crop residues

poses serious threats to agricultural sustainability and environmental quality (Parihar *et al.*, 2018). Among these, residue burning is particularly detrimental, as it releases large quantities of greenhouse gases (GHGs) including methane (CH₄), nitrogen oxides (NO_x), and carbon- and sulfur-containing compounds into the atmosphere, thereby aggravating air pollution and climate change (Choudhary *et al.*, 2020). In addition to atmospheric impacts, residue burning accelerates soil degradation by increasing soil compaction, enhancing oxidation and depletion of soil organic carbon (SOC), reducing water-holding capacity, depleting readily available nutrients, and suppressing microbial activity within the soil profile.

Similarly, intensive tillage operations promote soil structural breakdown, erosion, and nutrient losses, ultimately leading to deterioration of soil quality. Such land degradation, largely driven by inappropriate land and crop management practices, threatens both crop productivity and long-term soil sustainability (Baskey *et al.*, 2025). Incorporation of green manure in transplanted rice is highly beneficial for improving soil fertility and crop productivity.

It enriches soil organic matter, enhances nitrogen availability through biological fixation, and improves soil structure. Green manure incorporation also suppresses weed growth during early crop stages and promotes better root development. Additionally, it reduces dependence on chemical fertilizers, lowers production costs, and supports sustainable rice cultivation in intensive cropping systems.

Transplanted rice is severely affected by weeds such as *Echinochloa crus-galli*, *Echinochloa colona*, *Cyperus difformis*, and *Monochoria vaginalis*. These weeds compete strongly for nutrients, light, and space, causing significant yield losses. The problem is intensified by continuous rice cultivation, poor water management, and the overuse of herbicides, which lead to shifts in weed flora and the development of herbicide resistance. Effective weed management is therefore essential for sustaining productivity. Green manure crops are typically fast-growing, exhibit rapid canopy closure, intercept solar radiation efficiently, and possess deep root systems that improve soil structure and nutrient acquisition (Baskey *et al.*, 2025). Although initial tillage and irrigation may stimulate the simultaneous emergence of weeds and green manure crops, the rapid biomass accumulation and canopy dominance of green manures subsequently suppress weed growth, reduce weed biomass, and gradually deplete the soil weed seed bank, thereby lowering weed pressure in the succeeding main crop (Hazbavi & Sadehi, 2016). In addition, incorporating green manure biomass can release allelochemicals that inhibit weed seed germination and early seedling growth (Farooq *et al.*, 2011). Incorporation of crop or weed biomass at an optimal growth stage, particularly before flowering in leguminous green manures, has been shown to enhance crop yield and improve produce quality by improving nutrient availability and soil biological activity (Ladha *et al.*, 2000).

Sesbania aculeata is an important leguminous green manure crop widely used in rice-based systems. It can be grown as a sole crop, intercrop, or mixed crop with cereals and is often utilized as a cover crop or brown manure when grown in association with rice (Capoen *et al.*, 2010). In most production systems, *S. aculeata* is incorporated into the soil or retained on the surface as mulch. Its extensive, deep root system enables efficient recycling of nutrients from deeper soil layers (Naher *et al.*, 2019). Incorporation of *S. aculeata* biomass stimulates microbial activity, accelerates nutrient mineralization, and enhances the availability of essential plant nutrients to the succeeding rice crop. Incorporation of 45–60 days old *S. aculeata* can contribute approximately 4.73–5.03 t ha⁻¹ of biomass and 60–90 kg ha⁻¹ of nutrients, particularly nitrogen, phosphorus, and potassium (Mirza *et al.*, 2005). Extended retention or incorporation of *S. aculeata* biomass improves soil moisture retention, suppresses weeds, supports rice growth and development, and enhances yield attributes, ultimately resulting in higher grain yield. Moreover, crop diversification through green

HIGHLIGHTS

- *Sesbania aculeata* incorporation reduced weed density (41.7–57.3%) and biomass (36.6–38.4%), boosting rice grain yield by 11.6–20.3% over three years.
- Green manuring added ~1,982.8 kg C ha⁻¹ yr⁻¹, significantly improving SOC, bulk density, and nutrient availability across the 0–15 cm soil profile.
- *S. aculeata* incorporation reduced synthetic nitrogen use by ~20 kg ha⁻¹ yr⁻¹, improving net profitability by 8.3–20.0%, supporting climate-smart rice production.

manuring reduces dependence on external inputs, improves soil health, conserves natural resources, enhances land-use efficiency, and disrupts pest and disease cycles (Gill & Ahlawat, 2006).

The return of organic biomass, including crop residues and green manures, to the soil improves the hydrothermal regime by increasing soil water retention, which has been associated with higher crop yields and improved water-use efficiency (WUE) in maize-based systems in northern China (Yu *et al.*, 2018). However, the magnitude of these benefits is influenced by soil type, climate, and management practices. Retention or incorporation of biomass also mitigates GHG emissions associated with residue burning, while simultaneously enhancing SOC content, improving soil physicochemical properties, increasing soil moisture storage, and improving bulk density (Li *et al.*, 2019).

Incorporation of *Sesbania aculeata* significantly reduced weed density and biomass while enhancing rice grain and straw yields under transplanted conditions. It also improved soil physical properties by lowering bulk density and increasing soil organic carbon content. Long-term incorporation enhanced soil carbon stocks and enabled a reduction of synthetic nitrogen fertilizer, supporting sustainable nutrient management. Despite the recognized benefits of green manuring, comprehensive and systematic evaluations of *S. aculeata* incorporation for weed suppression, soil water retention, rice productivity, profitability, and soil health remain limited. It was hypothesized that incorporation of *S. aculeata* biomass into the soil would enhance sustainable rice productivity while minimizing environmental pollution. Therefore, the present study was undertaken to assess the effects of *S. aculeata* incorporation on weed suppression, rice productivity and profitability, and soil carbon stabilization under transplanted rice conditions.

2 | MATERIALS AND METHODS

2.1 | Experimental Site and Soil Characteristics

A field experiment was conducted for three consecutive years (2014–2016) at the ICAR–National Institute of Biotic Stress Management, Raipur, Chhattisgarh, India. The experimental site is located at 21°22′50.4″ N latitude and 81°49′31.9″ E longitude, at an elevation of 289 m above

mean sea level. The region experiences a tropical sub-humid climate with a long-term mean annual rainfall of approximately 1250 mm, of which nearly 80% is received during the southwest monsoon period (June–September). The surface soil (0–20 cm) of the experimental field was clay loam in texture, neutral in reaction (pH 7.2), and low in soil organic carbon (SOC; 3.7 g kg⁻¹). The soil was characterized by low available nitrogen, medium available phosphorus, and high exchangeable potassium contents, with values of 215.2, 17.2, and 342.0 kg ha⁻¹, respectively.

2.2 | Experimental Design and Treatments

The experiment was laid out in a randomized complete block design (RCBD) with ten replications. Two treatments were evaluated (i) rice without *Sesbania aculeata* incorporation and (ii) rice with *S. aculeata* incorporation. Each treatment was applied to large plots of 4,000 m². *Sesbania aculeata* was sown at a seed rate of 25 kg ha⁻¹ in well-tilled soil during the third week of May, followed immediately by irrigation to ensure uniform germination. Additionally, two irrigations were provided based on need. At 45 days after sowing, the *S. aculeata* crop was incorporated into the soil using a rotavator under standing water conditions. The incorporated biomass was allowed to decompose for five days prior to transplanting rice.

2.3 | Crop Establishment and Nutrient Management

Rice seedlings (21–23 days old) of the variety 'Swarna' (MTU 7029; parentage: Vasista × Mahsuri; medium duration of 145 days with short, bold grains) were transplanted in the second week of July. The recommended fertilizer dose of 80–100 kg N ha⁻¹, 60 kg P₂O₅ ha⁻¹, and 40 kg K₂O ha⁻¹ was applied. The entire phosphorus dose and three-fourths of the potassium were applied as basal at transplanting. Nitrogen was applied in three split doses at establishment, maximum tillering, and panicle initiation stages. In plots without *S. aculeata*, nitrogen was applied at 30, 40, and 30 kg ha⁻¹, whereas in *S. aculeata* incorporated plots, reduced nitrogen doses of 25, 30, and 25 kg ha⁻¹ were applied at the respective stages. The remaining one-fourth of potassium was applied along with nitrogen at the panicle initiation stage. All other agronomic and crop management practices were followed as per regional recommendations (Choudhary & Dixit, 2024).

2.4 | Weed Observations

Weed density and biomass of grasses, broad-leaved weeds, and sedges were recorded at 60 days after transplanting (DAT). Observations were made using a quadrat of 0.5 m × 0.5 m placed at ten randomly selected locations in each plot. To assess natural weed infestation, three permanent weed-infested strips (5 m wide) were maintained in each field without any weed control measures, and samples were drawn from these strips. Weeds were categorized by functional groups, oven-dried at 65 ± 2 °C for 48 h, and weighed using an electronic balance to determine dry biomass.

2.5 | Crop Growth and Yield Attributes

Crop growth parameters, including plant height,

aboveground biomass, and leaf area, were recorded from three randomly selected locations within each plot, and mean values were used for analysis. Leaf area index (LAI) was computed using the following equation 1:

$$\text{LAI} = \text{Leaf area (cm}^2\text{)} / \text{Ground area (cm}^2\text{)} \quad \text{eq (1)}$$

Yield attributes such as number of tillers per hill, panicles per m², panicle length and weight, and number of filled and unfilled grains per panicle were recorded at maturity.

2.6 | Soil Water Dynamics

Perforated polyvinyl chloride (PVC) pipes were installed in each plot to monitor standing water depth. At the booting stage, 5 cm of irrigation water was applied, and daily water depletion was recorded for 15 consecutive days during a rain-free period to assess soil water retention.

2.7 | Yield and Economic Analysis

Grain and straw yields were harvested from three randomly selected areas of 25 m² (5 m × 5 m) in each plot for more precision, and mean values were used for interpretation. Harvest index was calculated as the ratio of grain yield to total aboveground biomass (grain + straw).

Economic parameters, including cost of cultivation, gross returns, net returns, and benefit–cost (B: C), were computed. In *S. aculeata* incorporated plots, the cost incurred for raising *S. aculeata* was included in the total production cost of rice. Gross returns were calculated using prevailing market prices for grain and straw, while net returns and B:C were estimated using standard procedures described by Choudhary and Kumar (2013).

2.8 | Soil Analysis and Carbon Estimation

Soil bulk density (pb) was determined using the core method with a core sampler of 5.8 cm height and 5.4 cm diameter. Soil organic carbon, available nitrogen, and phosphorus were analyzed using standard laboratory procedures. Soil carbon stock was calculated using equations 2 and 3 proposed by Lee *et al.* (2009):

$$\text{C stock (Mg ha}^{-1}\text{ year}^{-1}\text{)} = \text{Concentration (\%)} / 100 \times \text{Depth (m)} / 100 \times \text{pb (Mg m}^{-3}\text{)} \times \text{Area (10000 m}^2\text{)} / \text{ha} \quad \text{eq (2)}$$

Carbon addition through *S. aculeata* biomass was estimated as:

$$\text{C added (kg ha}^{-1}\text{ year}^{-1}\text{)} = \text{Dry biomass of } S. aculeata \text{ (sum of three years)} \times 40 / 100 \quad \text{eq (3)}$$

assuming that plant biomass contains approximately 40% carbon. Carbon stabilization was calculated as the difference between the final and initial SOC values, and annual carbon stock change (kg ha⁻¹.year⁻¹) was estimated by dividing this difference by the study duration.

2.9 | Statistical Analysis

Data on all measured parameters were subjected to analysis

of variance (ANOVA) using the F-test as described by Gomez and Gomez (1984). Treatment means were compared using the least significant difference (LSD) test at the 5% probability level ($p = 0.05$). Standard deviation values were computed within plots to assess variability.

3 | RESULTS AND DISCUSSIONS

3.1 | Weed Flora

The experimental rice fields were infested with a diverse weed flora comprising grasses, broad-leaved weeds, and sedges. Dominant grassy weeds included jungle rice [*Echinochloa colona* (L.) Link], barnyardgrass [*E. crus-galli* (L.) P. Beauv.], crabgrass [*Digitaria sanguinalis* (L.) Scop.], and knotgrass (*Paspalum distichum* L.). The major broad-leaved weeds were water clover (*Marsilea quadrifolia* L.), water primrose (*Ludwigia prostrata* Roxb.), sessile joyweed (*Alternanthera sessilis* (L.) R. Br.), joyweed (*Alternanthera paronychioides* Forssk.), pink node flower (*Caesulia axillaris* Roxb.), creeping cradle plant [*Cyanotis axillaris* (L.) D. Don], false daisy (*Eclipta alba* L.), and benghal dayflower (*Commelina benghalensis* L.). The sedge population was mainly represented by smallflower umbrella sedge (*Cyperus difformis* L.), rice flat sedge (*C. iria* L.), and pipewort (*Eriocaulon sieboldianum* L.).

3.2 | Weed Prevalence and Suppression Mechanisms

Incorporation of *Sesbania aculeata* markedly reduced the density and biomass of different weed groups as well as total weed infestation compared with plots without green manuring (Table 1). Grassy weeds were significantly suppressed under *S. aculeata* incorporation, with densities ranging from 3.8 to 9.2 plants m^{-2} , representing a reduction

of 36.1–58.2% relative to non-incorporated plots (8.9–14.4 plants m^{-2}). Similarly, densities of broad-leaved weeds and sedges were substantially lower in *S. aculeata* incorporated plots, with reductions of 20.8–60.0% and 26.1–51.7%, respectively. Consequently, total weed density was reduced to 13.1–28.2 plants m^{-2} under *S. aculeata* incorporation, compared with 30.7–48.4 plants m^{-2} in plots without incorporation. A parallel trend was observed for weed biomass. Total weed biomass in *S. aculeata* incorporated plots ranged from 12.2 to 17.7 g m^{-2} and consistently declined over the years, whereas substantially higher biomass (19.8–27.9 g m^{-2}) was recorded in plots without green manuring. Overall, incorporation of *S. aculeata* resulted in a reduction of 41.7–57.3% in total weed density and 36.6–38.4% in total weed biomass across the study period (Table 1).

The pronounced weed suppression can be attributed to several interacting mechanisms. Establishment of *S. aculeata* during the pre-monsoon period promoted synchronized germination of weed seeds, which were subsequently destroyed upon incorporation of the green manure before flowering, thereby depleting the soil weed seed bank. In addition, decomposition of *S. aculeata* biomass generates heat and gaseous by-products that can reduce weed seed viability (Dahlquist *et al.*, 2006). Enhanced soil organic matter following green manuring stimulates microbial activity and diversity, which may further suppress weeds through competitive and allelopathic effects. Broad-leaved weeds, in particular, were more sensitive to *Sesbania* incorporation, corroborating earlier findings that early-stage incorporation or intercropping of *Sesbania* effectively controls broad-leaved weed flora in rice systems (Singh *et al.*, 2007).

TABLE 1 Effect of *S. aculeata* incorporation on group-wise and total weed density and total weed biomass on puddled transplanted rice

Weed parameters	Treatment	2014	2015	2016
Grasses (no. m^{-2})	Without	14.4a $\pm$ 2.1	8.9a $\pm$ 2.4	9.1a $\pm$ 2.0
	With	9.2b $\pm$ 1.0	3.9b $\pm$ 0.9	3.8b $\pm$ 1.2
Broadleaf weeds (no. m^{-2})	Without	24.8a $\pm$ 3.8	16.0a $\pm$ 1.5	16.6a $\pm$ 1.8
	With	12.2b $\pm$ 1.6	6.4b $\pm$ 1.1	6.8b $\pm$ 1.6
Sedges (no. m^{-2})	Without	9.2a $\pm$ 2.4	5.8a $\pm$ 1.3	5.4a $\pm$ 1.3
	With	6.8b $\pm$ 0.6	2.8b $\pm$ 0.8	3.0b $\pm$ 0.9
Total weed density (no. m^{-2})	Without	48.4a $\pm$ 4.0	30.7a $\pm$ 5.2	31.1a $\pm$ 5.1
	With	28.2b $\pm$ 2.3	13.1b $\pm$ 2.9	13.6b $\pm$ 3.6
Total weed biomass (no. m^{-2})	Without	27.9a $\pm$ 2.9	21.6a $\pm$ 3.6	19.8a $\pm$ 3.3
	With	17.7b $\pm$ 0.6	13.6b $\pm$ 1.7	12.2b $\pm$ 1.6

3.3 | Growth and Yield Attributes

Incorporation of *S. aculeata* significantly improved rice growth parameters, including plant height, total aboveground biomass, and LAI (Table 2). Plant height ranged from 108.0 to 116.1 cm under *S. aculeata* incorporation, compared with 100.6–112.8 cm in non-incorporated plots. Total plant biomass (17.6–18.6 g hill⁻¹) and LAI (2.70–2.74) were 17.0–25.7% and 10.0–14.0% higher, respectively, than those recorded without incorporation. The enhanced growth may be attributed to the release of phytohormones and improved nutrient availability following *Sesbania* decomposition (Naher *et al.*, 2013), which promoted taller plants with larger and more numerous leaves. Increased LAI enhanced interception of solar radiation and photosynthetic efficiency, resulting in greater biomass production and improved assimilate translocation to reproductive organs.

Improved vegetative growth translated into superior yield attributes under *S. aculeata* incorporation. The number of tillers (7–8 hill⁻¹), panicles (300–315.7 m⁻²), panicle length (23.2–23.7 cm), panicle weight (2.70–3.59 g), and number of filled grains per panicle (114–121) were significantly higher, while the number of unfilled grains (10–29 panicle⁻¹) was markedly lower than in non-incorporated plots. Compared with the control, *S. aculeata* incorporation increased tillers per hill by 21.2–31.0%, panicles per m² by 10.7–17.7%, panicle length by 3.1–4.9%, panicle weight by 7.6–17.4%, and filled grains per panicle by 8.1–14.8%, while reducing unfilled grains by 19.5–25.0%. These findings are consistent with earlier reports demonstrating improved growth and yield attributes in rice-based systems following green manuring with *Sesbania* (Paul *et al.*, 2014).

TABLE 2 Effect of *S. aculeata* incorporation on growth and yield attributes and yield of puddled transplanted rice

Parameters	Treatment	2014	2015	2016
<i>Growth parameters</i>				
Plant height (cm)	Without	100.6b±4.04	112.5a±4.51	112.8b±2.65
	With	108.0a±2.74	116.5a±5.11	116.1a±2.91
Total plant biomass (g hill ⁻¹)	Without	14.0b±2.35	15.9b±2.33	15.2b±2.1
	With	17.6a±0.95	18.6a±0.83	18.1a±0.8
Leaf area index	Without	2.39b±0.04	2.49b±0.09	2.42b±0.04
	With	2.70a±0.09	2.74a±0.1	2.76a±0.09
<i>Yield attributes</i>				
Tillers (no. hill ⁻¹)	Without	5.7b±1.04	5.8b±0.29	6.6b±1.14
	With	7.0a±1.22	7.6a±0.31	8.0a±0.71
Panicle (no. m ⁻²)	Without	267.4b±9.40	271.0b±9.31	276.7b±9.07
	With	314.6a±6.91	300.0a±55.70	315.7a±25.32
Panicle length (cm)	Without	22.9b±0.44	22.5a±0.93	22.6a±0.70
	With	23.8a±0.28	23.2a±0.55	23.7a±0.78
Panicle weight (g panicle ⁻¹)	Without	2.3b±0.12	3.29b±0.13	3.32b±0.13
	With	2.7a±0.11	3.54a±0.25	3.59a±0.23
Sound grain (no. panicle ⁻¹)	Without	105.8b±5.12	100.4b±11.29	105.7b±8.33
	With	114.4a±5.13	115.3a±3.51	120.7a±3.21
Unfilled grain (no. panicle ⁻¹)	Without	10.4a±1.82	29.0a±2.51	26.6a±2.51
	With	7.8b±1.92	22.9b±4.35	21.4b±4.09

3.4 | Grain and Straw Yield and Harvest Index

Enhanced growth and yield attributes under *S. aculeata* incorporation culminated in significantly higher rice yields (Table 3). Grain yield increased by 11.6–20.3% compared with non-incorporated plots, with yield gains becoming more pronounced over successive years. Straw yield also increased by 5.0–7.1%, while harvest index improved by 2.2–7.0% under *S. aculeata* incorporation. The sustained yield advantage reflects improved nutrient recycling, enhanced SOC, and better soil physical conditions resulting from repeated green manuring. Green manuring with *S. aculeata* has been shown to exert residual benefits on succeeding crops and can partially substitute synthetic nitrogen fertilizers, thereby enhancing system sustainability

(Wabi *et al.*, 2016). The addition of *S. aculeata* biomass to the plow layer increased nutrient availability and SOC content, which are critical determinants of rice productivity in intensively cultivated systems. Previous studies have similarly reported improved rice grain yield, nutrient-use efficiency, and long-term sustainability with integrated use of *Sesbania* green manuring and inorganic fertilizers (Kannan *et al.*, 2025). Long-term experiments in South Asia have demonstrated yield increases of 9–11% with continuous green manuring, along with improved soil carbon status compared with sole reliance on chemical fertilizers (Shah *et al.*, 2011).

3.5 | Economic Performance

Economic analysis indicated that *S. aculeata* incorporation

marginally increased the cost of cultivation by ₹4.11–4.25 × 10³ ha⁻¹ compared with non-incorporated plots (Table 3). However, the higher grain yield obtained under *S. aculeata* incorporation substantially increased gross returns (by 11.2–19.3%) and net returns (by ₹4.6–15.0 × 10³ ha⁻¹),

resulting in 8.3–20.0% higher net profitability. The B: C remained comparable between treatments, indicating that the additional investment in green manuring was economically justified.

TABLE 3 Effect of *S. aculeata* incorporation on yield and economic parameters on puddled transplanted rice

Parameters	Treatment	2014	2015	2016
<i>Yield parameters</i>				
Grain yield (kg ha ⁻¹)	Without	5228b ± 63.9	6344b ± 712.8	6250.0b ± 809.6
	With	5836a ± 100.7	7383a ± 337.1	7521.1a ± 445.1
Straw yield (kg ha ⁻¹)	Without	6428b ± 83.2	8234b ± 489.48	8073.3b ± 636.8
	With	6843a ± 82.6	8647a ± 568.0	8647.2a ± 600.0
Harvest index	Without	0.45a ± 0.002	0.43b ± 0.04	0.44b ± 0.04
	With	0.46a ± 0.005	0.46a ± 0.01	0.47a ± 0.02
<i>Economic parameters</i>				
Cost of production (x 10 ³ ₹ ha ⁻¹)	Without	22.69	23.89	25.04
	With	26.84	28.04	29.29
Net returns (x 10 ³ ₹ ha ⁻¹)	Without	55.36 ± 0.94	73.81 ± 12.62	74.91 ± 11.19
	With	59.96 ± 1.40	84.71 ± 12.97	89.92 ± 6.77
Benefit-cost ratio	Without	3.44 ± 0.04	4.09 ± 0.53	3.99 ± 0.47
	With	3.23 ± 0.05	4.02 ± 0.46	4.07 ± 0.23

Seed price of Sesbania ₹50 kg⁻¹; each irrigation charges, ₹500 ha⁻¹; price of rice, ₹14.7 kg⁻¹; straw price, ₹1 kg⁻¹

3.6 | Soil Water Dynamics

Soil water depletion patterns differed markedly between treatments and across years (Fig. 1). In the initial year, differences between treatments were minimal; however, with continued *S. aculeata* incorporation, the gap widened progressively in subsequent years. Plots without *S. aculeata* lost water more rapidly after soil saturation, whereas *S. aculeata*-incorporated plots retained higher moisture levels throughout the observation period. Improved soil aggregation, porosity, and structural stability following green manuring enhanced soil water-holding capacity. In addition, *S. aculeata* incorporation reduced soil compaction, erosion, and surface runoff, thereby improving moisture retention within the soil profile (Sahoo *et al.*, 2023).

3.7 | Soil Physical and Chemical Properties

After three years, incorporation of *S. aculeata* significantly improved soil physical properties. Bulk density decreased by 2.7% in the 0–5 cm layer and by 1.9% and 1.8% in the 5–10 and 10–15 cm layers, respectively, compared with non-incorporated plots (Fig. 2a). Soil organic carbon content increased substantially with *S. aculeata* incorporation, particularly in surface soil layers. SOC increased by 29.4% at 0–5 cm depth, followed by 20.8% and 10.8% increases at 5–10 and 10–15 cm depths, respectively, relative to the control (Fig. 2b). On average, *S. aculeata* incorporation contributed approximately 1982.8 kg C ha⁻¹ year⁻¹ through biomass addition. Continuous incorporation resulted in higher carbon stocks in the upper 0–15 cm soil profile, whereas plots without green manuring exhibited a decline in SOC, especially in surface layers. Shallow incorporation using rotavators facilitated SOC

accumulation, enhanced carbon stability, and promoted carbon sequestration (Table 4), in agreement with earlier findings (Choudhary *et al.*, 2020), (Meena *et al.*, 2021, Singh *et al.*, 2021).

3.8 | Carbon Dynamics and Sequestration

Annual production of aboveground *S. aculeata* biomass ranged from 4729 to 5029 kg ha⁻¹, contributing 1939.2–2011.6 kg C ha⁻¹ year⁻¹ (Table 4). After three years, carbon stocks increased by 0.26, 0.16, and 0.07 Mg ha⁻¹ year⁻¹ at 0–5, 5–10, and 10–15 cm depths, respectively. Carbon stabilization was highest in surface soils (780.3 kg ha⁻¹ year⁻¹ at 0–5 cm) and declined with depth. Similarly, carbon sequestration rates were significantly higher under *S. aculeata* incorporation, with gains of 260.1, 157.0, and 67.4 kg ha⁻¹ year⁻¹ at respective depths compared with non-incorporated plots. These results underscore the role of green manuring in enhancing soil carbon storage and mitigating carbon losses in intensively cultivated rice systems.

3.9 | Available Nitrogen and Phosphorus

Incorporation of *S. aculeata* significantly improved soil available nitrogen and phosphorus across soil depths (Fig. 2c, d). Available N increased by 18.6%, 20.4%, and 17.2% at 0–5, 5–10, and 10–15 cm depths, respectively, compared with non-incorporated plots. Similarly, available P increased by 11.6%, 9.3%, and 14.8% at corresponding depths. The improvement in nutrient availability reflects enhanced mineralization of *Sesbania* biomass, increased microbial activity, and improved nutrient retention in soils with higher SOC. The sustained addition of *S. aculeata* biomass replenished nutrients removed by successive crops, reduced reliance on synthetic fertilizers, and minimized environmental contamination. Approximately

25% of the crop nitrogen requirement could be met through *S. aculeata* incorporation, allowing a reduction of about 20

kg N ha⁻¹ year⁻¹ without compromising grain yield (Wang *et al.*, 2009).

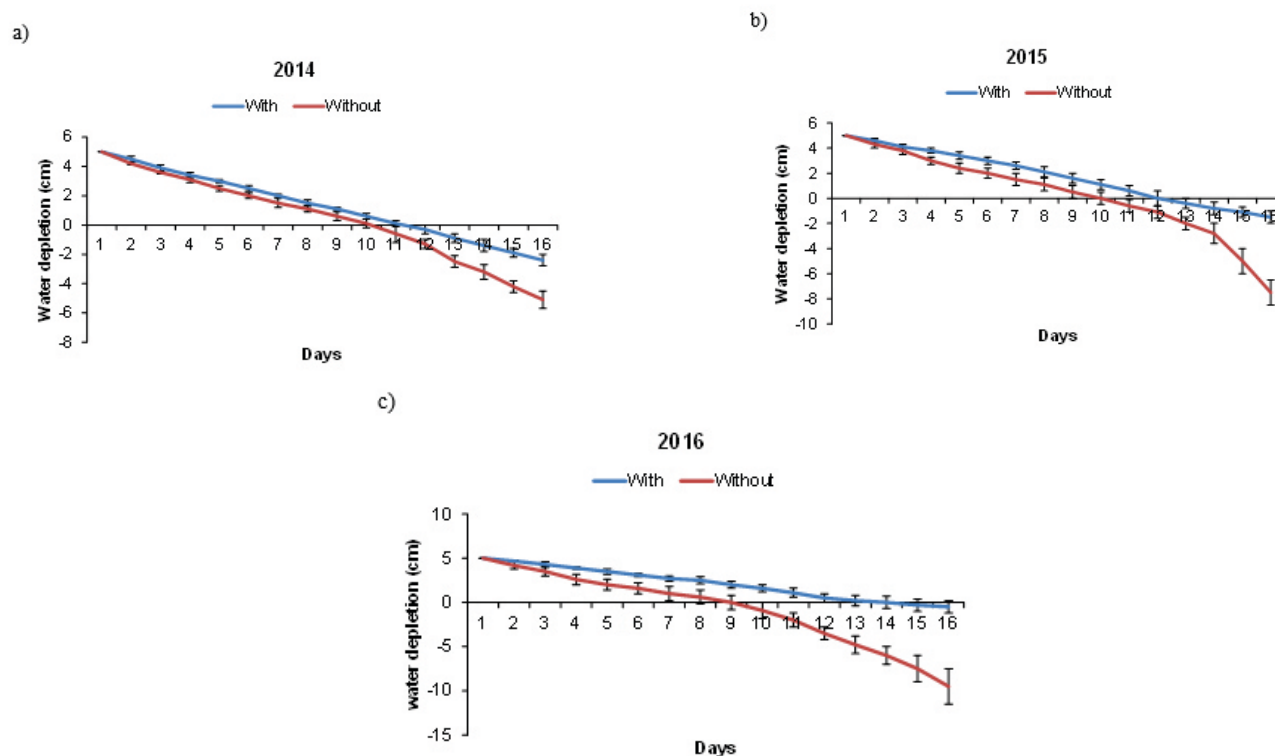


FIGURE 1 Effect of with and without *S. aculeata* incorporation on water depletion pattern on rice field during panicle initiation stage during a) 2014, b) 2015 and c) 2016.

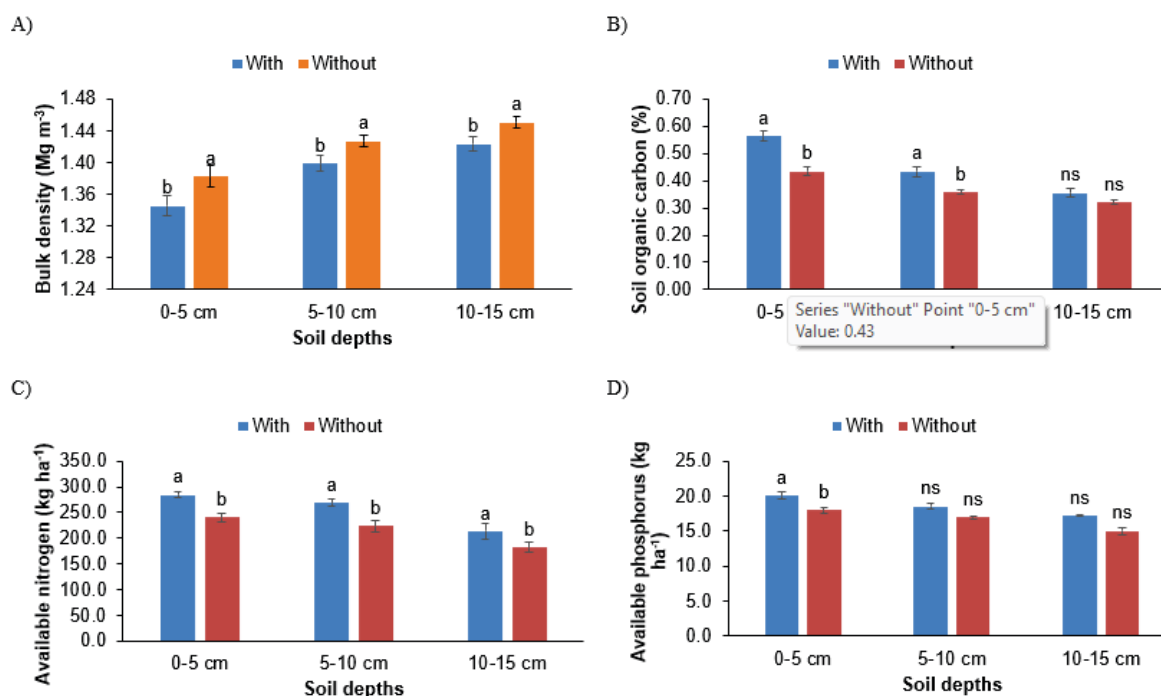


FIGURE 2 Effect of incorporation of *S. aculeata* on A) bulk density, B) soil organic carbon, C) available nitrogen and D) available phosphorus (three years after study).

TABLE 4 Carbon stabilization and carbon sequestration under *S. aculeata* incorporated plots without incorporation

Parameter	2014	2015	2016
Biomass of <i>S. aculeata</i> (kg ha ⁻¹)	4729.0±121.0	4994.0±260.1	5029.0±158.1
Carbon input (kg ha ⁻¹)	1939.2±64.19	1997.6±109.66	2011.6±63.23
	0-5 cm	5-10 cm	10-15 cm
Carbon stock (Mg ha ⁻¹ year ⁻¹)	0.26±0.04	0.16±0.04	0.07±0.04
Carbon stabilization (kg ha ⁻¹ year ⁻¹)	780.3±112.47	470.9±105.65	202.2±129.44
C sequestration ((kg ha ⁻¹ year ⁻¹)	260.1±37.49	157.0±35.22	67.4±43.15

4 | CONCLUSIONS

The present study demonstrates that incorporation of *Sesbania aculeata* is an effective and sustainable approach for enhancing weed control, rice productivity, and soil health in transplanted rice systems. Incorporation of *S. aculeata* reduced total weed density by 41.7–57.3% and weed biomass by 36.6–38.4% compared with non-incorporated plots, indicating strong biological weed suppression and depletion of the weed seed bank. These effects resulted in improved crop performance, with rice grain yield increasing by 11.6–20.3% and greater soil water retention due to improved soil physical properties. The practice also contributed substantially to soil carbon dynamics and fertility. Incorporation of *S. aculeata* added 1,982.8 kg C ha⁻¹ yr⁻¹, increased soil porosity by 2.14%, and enhanced soil organic carbon by 21.3% in the 0–15 cm soil layer. Carbon sequestration and stabilization were estimated at 161.5 and 484.5 kg C ha⁻¹ yr⁻¹, respectively. Additionally, soil nitrogen and phosphorus contents increased by 18.8% and 11.8%, allowing a reduction of at least 20% in synthetic nitrogen fertilizer use. Overall, *S. aculeata* incorporation offers a viable, climate-smart strategy to improve productivity, profitability, and environmental sustainability in rice-based systems.

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CONFLICT OF INTEREST

The author has no conflict of interest.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTION

VKC: Conducted the experiment, data recording, statistical analysis, prepared the original manuscript.

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Extent of Awareness, Utility and Constraints in Adoption of Site-Specific Land Resource Inventory Information in New Generation Watersheds

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Sujala-III

ABSTRACT

The Land Resource Inventory (LRI), a scientific farm-level planning tool introduced under Karnataka's Sujala-III watershed project, has low field adoption among farmers despite its strengths. This study examines awareness, dissemination, utility, and adoption barriers across 20 micro-watersheds using surveys of 900 farmers and focus groups with Project Implementing Agencies (PIAs). Findings show a steep drop from awareness to actual use, with only 22% of farmers knew about LRI, 20.2% received LRI cards, 11.4% had training, and only 6.56% used LRI information for crop or nutrient decisions. Just 2.89% had read their LRI card more than once, and only 5.89% remembered LRI details of their land. Major LRI adoption constraints include lack of awareness of site-specific information (70%), insufficient training, conservatism and illiteracy among watershed farmers. From the PIAs perspective, key challenges included difficulty in promoting adoption of site-specific crop suitability, securing acceptance of recommendations among farmers, and timing issues with LRI card delivery. Overall, low adoption stems from systemic institutional, logistical, and behavioral gaps, requiring farmer-focused dissemination, stronger extension links, integration of LRI with existing systems, and participatory planning to align scientific advice with local needs.

1 | INTRODUCTION

In the context of climate change, watershed management plays a crucial role in reducing weather-related risks, building resilience, and enhancing adaptive capacities (NABARD, 2023). In regions with low rainfall, watershed management is vital for protecting the environment and maintaining the standard of living (Zerga, 2025). Integrated watershed management has become a climate-smart approach to tackling various agricultural sustainability challenges by improving soil and water conservation (Jayaraman *et al.*, 2024). Effective watershed management requires strengthening institutional capacity, integrated water resources management, strong monitoring, strategic partnerships (Mishra *et al.*, 2024), climate adaptation strategies, economic valuation, and advocacy (Jat *et al.*, 2025). Additionally, India invests millions of rupees to promote sustainable growth in rainfed areas through effective watershed management programs. However, despite significant investments, many traditional watershed programs in India have not delivered expected outcomes due to lack of site-specific planning, inefficient resource use, and limited farmer awareness (Lalitha *et al.*, 2016; Hegde *et al.*, 2018). Several studies highlight the need for comprehensive land resource databases that match site-specific conditions (Bandyopadhyay *et al.*, 2009; Kumar *et al.*, 2014; Ramamurthy *et al.*, 2016; Bandyopadhyay *et al.*,

2018; Hegde *et al.*, 2018). As a solution, the Sujala-III watershed project adopted a site-specific and scientifically based Land Resource Inventory (LRI) approach for planning and implementation across multiple districts in Karnataka. This innovative project uses modern Remote Sensing (RS) and GIS data combined with field survey to gather land resource data at the farm level. The project aims to provide farm-specific crop recommendations, develop location-specific soil and water conservation measures, and generate datasets and inputs for planning, implementation, and monitoring of all land-based developmental programs. The LRI database offers information on suitable areas for specific crops, limitations, site-specific nutrient status, and other parameters. It assists Project Implementing Agencies (PIAs) in identifying appropriate, site-specific watershed interventions (Hegde *et al.*, 2018; Ravi *et al.*, 2022b). Moreover, the innovative idea in Sujala-III involves distributing LRI cards for individual land survey numbers to farmers and training them to follow LRI recommendations. The LRI card includes details such as the farmer's name, micro-watershed name, sampling year, average rainfall, soil physical properties, land capability class, and limitations. Based on this information, soil nutrient and pH status are described, and the crop suitability class (Highly suitable, Moderately suitable, Slightly suitable, and Unsuitable) with management options is indicated on the card (Ravi *et al.*, 2022b). This approach helps farmers plan scientifically

at the farm level and adjust land use according to crop and soil suitability, optimizing resources, reducing waste, mitigating climate change impacts, and maximizing benefits (Singh *et al.*, 2022) and these benefits can only be realized through proper understanding and implementation of LRI recommendations at the field level. Therefore, the study was conducted in LRI-based watersheds to assess awareness, utility, and constraints related to the adoption and implementation of LRI under the Sujala-III watershed project across different districts in Karnataka. This was the first study to investigate the adoption, utility, and constraints of LRI-based watershed management.

2 | MATERIALS AND METHODS

2.1 | Study Watersheds

An impact assessment of the Land Resource Inventory (LRI) watersheds was conducted from 2021 to 2024 to examine LRI information dissemination, adoption, utility, and constraints associated with its adoption and implementation. The average annual rainfall of selected micro-watersheds ranged from 580 to 939 mm, with most watersheds falling in low to medium rainfall regions (Table 1). All watersheds were implemented during 2014-2019 under World Bank-aided Karnataka Watershed Development Programme (KWDP)-II, popularly known as Sujala-III project, with the newly adopted site-specific LRI in watershed planning.

2.2 | Sample Technique

The household survey has been conducted in seven Sujala-III project implemented districts of Karnataka, covering a total of 900 sample households, with 45 households per micro-watershed and 20 micro-watersheds per sub-watershed, using a stratified random sampling technique, as shown in Table 1. Further, seven Focus Group Discussions (FGDs) were conducted with Project implementing Agencies, involving a diverse group of team members, including Assistant Agriculture officers and Watershed Assistants from each micro-watershed across all 7 districts, to understand the constraints and their severity in adoption and implementation of LRI interventions.

2.3 | Statistical Tools and Technique

Descriptive statistics were used to capture LRI awareness, capacity building status and utility of information among farmers. Constraints on various parameters were identified through the household survey, and the frequency of each constraint was presented to highlight the major issues affecting farmers across watersheds. Since the project was the first of its kind and no earlier studies had documented LRI-related constraints, farmers were asked open-ended questions rather than a pre-defined list. This helped to capture a broader range of possible constraints and their severity among the majority of farmers. Meanwhile, the list of implementation constraints was discussed among PIAs, and common constraints were grouped for data collection. Each FGD had 6-12 members, based on availability. For each identified constraint, the group jointly assigned a single severity score based on a five-point Likert scale,

HIGHLIGHTS

- Awareness was the binding constraint. Only 22% of 900 surveyed farmers were aware of LRI; 78% never engaged with the programme at all.
- Training, not card delivery, drove adoption. Trained farmers utilised LRI information at 57.3% — nearly double the rate of card recipients overall (32.4%).
- Overall utilisation was critically low. Despite farm-level site-specific recommendations, only 6.6% of farmers actually used LRI information to make a cropping or nutrient decision.
- Recommendations conflicted with farmer realities. Promoting crop suitability change was the most severe implementation constraint (MSS 4.86), reflecting a fundamental mismatch between technically derived prescriptions and local farming priorities.

where 1 = Very Low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very High, representing how serious the constraint was perceived to be in hindering the implementation of LRI activities at the field level. Further, a simple mean severity score is computed for each constraint to quantify the perceived severity of constraints by focus group members using the following formula

Mean Severity Score = (Sum of severity scores of all FGD groups for each constraint)/(Number of FGD groups)

To facilitate interpretation, the computed severity score values (ranging from 1 to 5) were categorized into five descriptive levels based on the mean scores, as 1.00 – 1.79 as Very Low; 1.80 – 2.59 as Low, 2.60 – 3.39 as Moderate, 3.40 – 4.19 as High and 4.20 – 5.00 as Very High. These categories helped to identify which constraints were most severe and required priority attention. The final data was presented as a ranked list for easy understanding.

3 | RESULTS AND DISCUSSIONS

The Land Resource Inventory (LRI) developed for each micro-watershed and individual land parcel represents a substantive scientific investment — a farm-level planning tool intended to provide site-specific soil physical and chemical data, crop suitability classifications, and nutrient management guidance directly to farmers and Project Implementing Agencies (PIAs). Its potential to support evidence-based land use decisions, mitigate climate change impacts, and optimise resource use is widely suggested in the literature (Hegde *et al.*, 2018; Ravi *et al.*, 2022b; Singh *et al.*, 2022). However, this potential can only be realised through effective dissemination, adequate capacity building, and actual farmer-level adoption. The results presented below systematically examine where, and by how much, the Sujala-III LRI programme fell short of this objective.

3.1 | LRI Information Dissemination and Awareness

Data gathered from household surveys across all 20 micro-watersheds (n = 900) reveal critically low levels of LRI awareness among watershed beneficiaries.

Only 198 farmers (22.0%) reported are aware of LRI or its recommendations. The remaining 78% had no knowledge of either the LRI or its operations. Qualitative interactions during the survey further indicated that the majority of unaware respondents believed the watershed project to be primarily a government programme for physical infrastructure like building farm ponds and bunding. However, no knowledge of any site-specific farm-level LRI information. This finding is consistent with the earlier monitoring and terminal evaluation of 12 Sujala-III micro-watersheds in four districts of Karnataka (Ravi *et al.*, 2022 b), confirming that poor LRI dissemination is not an isolated or localised phenomenon but a systemic limitation of the programme's implementation. Of the 900 households

surveyed, 182 (20.2%) had received LRI cards generated for their individual land parcels — a marginal shortfall even relative to the already-low awareness figure, suggesting that a small number of farmers possessed cards without having been meaningfully informed about their purpose or content. Only 103 farmers (11.4%) reported receiving LRI training, reflecting limited contact with LRI extension managers and insufficient capacity-building outreach across the watersheds. The high farmer-to-extension-manager ratio within the programme appears to have structurally constrained the frequency and quality of interaction between project staff and beneficiaries.

TABLE 1 Basic details of micro-watersheds selected for Impact assessment

District	Selected MWS	Average Annual Rainfall	Sample Size	
			MWS	SWS
Bidar	Babulgaon-2 (UR)	900	45	
	Kharanji Khurd (MR)	900	45	135
	Raipalli-2 (LR)	900	45	
Vijayapura	Mulwad-1 (UR)	625	45	
	Mulwad-3 (MR)	625	45	135
	Mulwad Tanda-2 (LR)	625	45	
Koppal	Chikkamyageri-3 (UR)	581	45	
	Ryavanaki-1 (MR)	581	45	135
	Bedwatti-6 (LR)	581	45	
Ballari (erstwhile Davanagere)	Vaddarahalli (UR)	722	45	
	Hallikeri-2 (MR)	608	45	135
	Honnenahalli (LR)	580	45	
Tumkur	Lingapura (UR)	990	45	
	Kalyanpura (MR)	990	45	135
	Huliyapura-1 (LR)	990	45	
Chikkamagaluru	Dasarahalli-1 (UR)	939	45	
	Dasarahalli 2 (MR & LR)	939	45	90
	Harve -2 (UR)	751	45	
Chamarajanagara	Sagade (MR)	751	45	
	Kumachahalli-1 (LR)	751	45	135

Note: UR – Upper Reach; MR – Middle Reach; LR – Lower Reach; MWS – Micro-watershed; SWS – Sub-watershed.

TABLE 2 LRI information dissemination, capacity building, and awareness status among watershed farmers (n = 900)

Particulars	Frequency	Percentage (%)
Awareness of Land Resource Inventory	198	22.00
Farmers who received an LRI card	182	20.22
Farmers who received LRI training	103	11.44
Farmers who utilised LRI information for crop selection or nutrient decisions	59	6.56
Farmers who read their LRI card more than once	26	2.89
Farmers who could recall site-specific LRI details of their own land parcel (at time of survey, 2024)	53	5.89
Farmers with LRI card present at time of survey	140	15.56

3.2 | The Dissemination-to-Adoption Chain: A Funnel Analysis

To understand the cumulative attrition from programme investment to actual farmer-level use, the dissemination data are best examined as a sequential chain rather than as isolated statistics. Table 3 presents the LRI adoption funnel, tracing the movement of farmers from initial survey population through awareness, card receipt, training, and active utilisation.

First, the overwhelming majority of programme loss occurs at the very first stage. Of the 900 farmers surveyed, 702 (78.0%) never became aware of LRI at all. Every failure downstream of this point is secondary to this foundational dissemination deficit. No amount of improvement in card quality, training content, or extension messaging can benefit farmers who have never heard of the site-specific land resource information.

Second, the drop between card receipt and training (43.4% of card recipients did not receive training) represents the critical conversion bottleneck in the chain. At this stage, the project had already invested in physical card delivery yet nearly half of card recipients received no follow-up capacity building. This gap between physical delivery and meaningful engagement is a key leverage point for intervention.

Third, and most analytically significant, training was the

most decisive factor in driving utilisation. Among all farmers who received LRI cards, only 32.4% (59 of 182) went on to use the information. Among farmers who received training specifically, 57.3% (59 of 103) utilised the information — a utilisation rate nearly double that of the overall card-recipient group. This finding, strongly suggests that training, not card distribution, was the programme's primary adoption mechanism. It implies that expanding card distribution without a commensurate investment in training would yield diminishing returns.

Fourth, sustained engagement was low even among successful first adopters. Of the 59 farmers who used LRI information at least once, only 26 (44.1%) read their card more than once. This pattern suggests that even successful initial adoption did not lead to habitual reference behaviour, indicating a need for periodic follow-up contact rather than single-instance training events.

The LRI adoption efficiency ratios calculated for different indicators were presented in (Table 4) shows overall utilisation rate of 6.6% appears modest, the training conversion rate of 57.3% indicates that the intervention itself, when delivered, was reasonably effective. The problem is not that LRI recommendations are inherently difficult to adopt; it is that the conditions enabling adoption (awareness, card delivery, and particularly training) reached only a small fraction of the intended beneficiaries.

TABLE 3 Dissemination-to-adoption funnel and stage-wise attrition in LRI uptake

Stage	Number	% of Total (n=900)	Loss from Prior Stage	Loss (% of Prior Stage)
Total surveyed	900	100.0	-	-
Aware of LRI	198	22.0	702	78.0%
Received LRI card	182	20.2	16	8.1%
Received LRI training	103	11.4	79	43.4%
Utilised LRI information at least once	59	6.6	44	42.7%
Read LRI card more than once	26	2.9	33	55.9%

TABLE 4 LRI adoption efficiency indicators

Indicator	Numerator (observed outcome)	Denominator (Intervention exposure)	Value
Card utilisation rate (among card recipients)	59 used information	182 received cards	32.4%
Training conversion rate (among trained farmers)	59 used information	103 received training	57.3%
Training coverage rate (among card recipients)	103 trained	182 received cards	56.6%
Sustained engagement rate (among first adopters)	26 read card > 1 time	59 utilised at least once	44.1%
Overall programme utilisation rate	59 utilised	900 surveyed	6.6%

3.3 | LRI Card Availability and Utility at the Time of Survey

Physical availability of LRI cards at the time of the 2024 survey presented in (Table 2) provides a further indication of programme engagement. Of the 182 households that received LRI cards during implementation (2014–2019), 140 (15.6% of total respondents; 76.9% of card recipients) still had their card present at the time of the survey. Approximately 5% of respondents reported receiving a card but were unable to produce it, suggesting cards had been misplaced or discarded shows these results are consistent with low utility and engagement. Survey interactions indicated that in the majority of cases where cards were retained, they were stored at home and had not been actively utilized. Only 5.89% of all surveyed farmers could spontaneously recall site-specific LRI details of their own land parcel, confirming that card retention did not translate into card use. These findings corroborate (Ravi *et al.*, 2022b), who noted that LRI cards were treated by many

farmers as administrative documents rather than functional planning tools. The absence of repeated extension contact after initial distribution appears to have been a primary reason for this outcome.

3.4 | Farmer-Level Constraints in the Adoption of LRI Interventions

Data on adoption constraints were collected through open-ended questioning of all 900 household respondents, allowing farmers to identify constraints in their own terms rather than selecting from a pre-defined list. Since no prior literature had documented LRI-specific adoption constraints, this approach was necessary to capture the full range of perceived constraints. Responses were grouped into three thematic categories: knowledge and awareness constraints; constraints in adopting horticulture and agroforestry interventions; and constraints in adopting site-specific soil and water conservation (SWC) measures. Multiple constraints per respondent were counted. Findings are presented in Table 5 and discussed below.

TABLE 5 Farmer-level constraints in the adoption of LRI interventions (n = 900, multiple responses counted)

Constraint	Frequency	Percentage (%)	Rank
Knowledge and awareness constraints			
Lack of awareness of site-specific LRI information	630	70.00	I
Not interested in adopting new practices (conservatism/traditional mindset)	36	4.00	VII
Lack of training on utilisation and adoption of LRI card	28	3.11	IX
Lack of education / illiteracy in understanding LRI	22	2.44	XI
Horticulture and agroforestry adoption constraints			
Water scarcity limiting survival of horticulture and agroforestry plantings	315	35.00	II
Lack of follow-up care by farmers after planting	96	10.67	III
Poor seedling quality leading to low survivability	86	9.56	IV
Unseasonal distribution of horticulture and forestry saplings	52	5.78	VI
Soil and water conservation adoption constraints			
Lack of farmer priority or need alignment in intervention selection	68	7.56	V
Land shortage or small holdings limiting adoption of SWC measures	32	3.56	VIII
Poor construction quality of SWC structures	27	3.00	X
Difficulty in movement between fields due to bunds	12	1.33	XII

3.4.1 | Knowledge and Awareness Constraints

Most respondents (70%) reported lack of awareness of site-specific LRI information as the main constraint, reflecting dissemination issues discussed in Section 3.1. This shows awareness, is the key constraint. Many farmers weren't resisting adoption but simply uninformed of available farm-level information. Among those with LRI cards, 3.11% lacked training on interpretation, indicating delivery without instruction led to uninformed possession. This aligns with Ravi and Patil (2022a), who found skills gaps among extension workers hinder effective dissemination.

Without confidence among frontline workers, farmers struggle to understand LRI data. Illiteracy was a barrier for 2.44%, given the technical content requiring numeracy and literacy. An additional 4.0% cited conservatism or traditional mindsets as barriers, though real livelihood risk often underpins risk aversion among smallholders, which LRI doesn't address.

3.4.2 | Constraints in Adopting Horticulture and Agroforestry Interventions

Water scarcity was the most significant sector-specific constraint, reported by 315 respondents (35.0%). Most study watersheds are in low-to-medium rainfall zones (580–939 mm annual average), and many experienced chronic water stress before project start. Under these conditions, the survival of newly planted horticulture and agroforestry saplings, which need reliable moisture during establishment, was seriously affected. This matches Ramesha *et al.*, (2024), who found below-average survival rates for planted saplings in LRI watersheds and partly blamed this on shorter implementation periods that led to rushed activity without enough survival-support measures. Lack of follow-up care by farmers after PIA-led planting was reported by 10.67% of respondents, and poor seedling quality by 9.56%. Both issues point to the same core problem. The shift from project-managed planting to farmer-managed maintenance lacked proper support, either in motivation or input quality. The unseasonal distribution of planting material, cited by 5.78%, further shortened survival windows by causing mismatches between planting timing and ideal conditions for establishment.

3.4.3 | Constraints in Adopting site-specific SWC Measures

A misalignment between recommended SWC interventions and farmer priorities or needs was reported by 7.56% of respondents — the fifth-ranked constraint overall. This figure, though smaller in absolute terms, carries significant qualitative weight. It indicates that some project interventions were implemented in ways that did not reflect farmers' expressed needs, reducing acceptance and long-term commitment to maintenance. Specifically, trench-cum-bunding (TCB) activities repeatedly caused conflicts; 3.56% of farmers said their small landholdings made large-scale TCB recommendations impractical, as they viewed them as reducing their productive land. An additional 3.0%

reported poor construction quality of SWC structures, which weakened both functionality and farmer confidence in the technical recommendations supporting them.

3.5 | Project Implementation Constraints: Evidence from Focus Group Discussions

Seven Focus Group Discussions (FGDs) were conducted with PIAs across all seven study districts, each involving 6–12 project staff members, including Assistant Agriculture Officers and Watershed Assistants. Participants jointly assessed five key implementation constraints using a five-point Likert scale (1 = Very Low to 5 = Very High), and a mean severity score was computed across FGDs for each constraint. Results are presented in (Table 6).

The biggest challenge, rated Very High by PIAs, was convincing farmers to adopt crop suitability based on LRI recommendations. Unlike awareness issues, farmers actively resisted altering established cropping patterns, especially in annual crops, where multi-year commitments make farmers cautious. However, PIAs strongly agree that farmers can be easily persuaded to adopt recommended horticultural crops. Poor acceptance of site-specific advice was rated High, highlighting a gap between scientific recommendations and farmers' experience and risk management. This gap stems from lack of farmer input during planning, leading to recommendations that often didn't fit local needs or priorities. Constraints also included deviations from site-specific advice and farmers' perception of land loss from conservation, both rated High. Field staff sometimes adapted recommendations to gain farmer approval, but this reduced implementation fidelity and scientific consistency. Delays in receiving LRI cards from partners, rated Moderate, caused delays in training and capacity-building, negatively impacting adoption.

TABLE 6 Implementation constraints identified by Project Implementing Agencies

Constraint	Severity Level	Mean Severity Score (MSS)	Rank
Difficulty in promoting crop suitability adoption among farmers	Very High	4.86	I
Poor acceptance of site-specific recommendations by farmers	High	4.14	II
Deviation of site-specific interventions as per farmer preference	High	3.71	III
Smallholders' perceived loss of productive land from adopting conservation measures	High	3.86	IV
Untimely receipt of LRI details (LRI cards) from LRI partner agencies	Medium	3.28	V

Note: Severity categories: 1.00–1.79 = Very Low; 1.80–2.59 = Low; 2.60–3.39 = Moderate; 3.40–4.19 = High; 4.20–5.00 = Very High. MSS = Mean Severity Score computed across seven FGDs.

3.5.1 | Supply-side Versus demand-side Constraint Classification

Constraints in Sections 3.4 and 3.5 fall into two categories with different policy implications. Supply-side constraints stem from institutional failures, such as delayed LRI card delivery, limited training, poor seedling quality, seasonal

distribution issues, and subpar construction of SWC structures. These can be addressed through administrative improvements within the current framework. Demand-side constraints relate to farmer behaviour, attitudes, and conditions *viz.* lack of awareness, conservatism, illiteracy, water scarcity, small land sizes, and misalignment with farmer priorities. These requires participatory, farmer-

centric approaches, like identifying appropriate behavior change communication methods for LRI dissemination and peer learning, rather than administrative fixes. Findings suggest supply-side issues, especially in dissemination and training, are major—causing 78% of awareness deficits. However, demand-side barriers become more influential as farmers progress, especially in crop adaptation and sustained engagement. Effective strategies should address both, starting with supply-side improvements, followed by demand-side engagement for lasting adoption.

3.6 | Where the LRI Programme Lost Its Farmers

Overall, the findings from Sections 3.1 to 3.5 depict a program with a solid scientific design that ultimately failed during various stages of implementation. Figure 1 and Table 3 explicitly illustrate this: out of every 100 farmers enrolled in the watershed program, about 22 became aware of LRI, 20 received a card, 11 attended training, and only 7 then used that information for farming decisions. The remaining 93 did not engage meaningfully with the LRI component. This isn't mainly due to farmer resistance. Data show that more than half of trained farmers used the information provided. The main issues were institutional—poor dissemination, limited training coverage, delayed card delivery, and a planning process that didn't sufficiently involve farmers in shaping recommendations. Improving program impact in future versions requires stronger extension links, earlier and ongoing farmer engagement, and integrating LRI data into existing agricultural services.

4 | CONCLUSIONS

This study is the first systematic effort to document LRI-related adoption hurdles in these watersheds, and its results are clear: despite the scientific rigor and genuine potential of the LRI approach, translating it into farmer practice has been seriously limited. The adoption funnel analysis, based on household survey data from 900 farmers across 20 micro-watersheds, shows a pattern of increasing attrition at each stage of the dissemination- to- adoption process. The overall usage rate of 6.6% despite investments in soil surveys, digital databases, and land resource cards highlights a significant gap between scientific design and actual field impact. This failure is not only due to farmer resistance or structural barriers. The cross- stage ratios indicate that training was the most critical factor for utilization: among trained farmers, 57.3% used LRI information, 32.4% among all card recipients. This shifts the focus of the adoption challenge *viz.* understating and awareness, card distribution, and especially training reached only a small portion of intended farmers. The constraints analysis supports this interpretation. From farmers' perspective, lack of awareness was the main barrier, reported by 70%, far exceeding all other constraints combined. From the PIA viewpoint, the biggest challenge was the difficulty in promoting crop suitability changes, rated Very High severity (mean score 4.86), indicating a deeper structural issue: LRI recommendations were created without enough participatory input from farmers, leading to a mismatch between scientific prescriptions and local

farmer needs. Delays in delivering LRI cards from partner agencies (Moderate severity, MSS 3.28), though ranked lower among implementation constraints, directly impacted training opportunities by reducing the time available for capacity building. Overall, these findings suggest that the Sujala- III LRI programme faced shortfall on two levels. Supply- side issues such as dissemination, training coverage, timing of card delivery, and input quality which prevented most farmers from accessing the programme's information. Demand- side barriers like conservatism, illiteracy, water scarcity, small landholdings, and misalignment with farmer priorities which restricted adoption among those who did receive information. Addressing both types of barriers is essential for future LRI programmes to reach their full utilization potential and justify the scientific investments made.

Based on the findings of this study, the following recommendations are ordered by intervention priority, based on severity from FGD data and the funnel analysis's attrition structure. They target three levels: programme design, institutional integration, and field implementation.

4.1 | Prioritize training over card distribution as the main adoption method

The study finds that training, not card delivery, drives LRI use. Future programs should focus on training as the main investment, with card distribution supporting rather than leading. Coverage must increase from 11.4% to at least 60–70%, monitored based on outcomes, not just card counts. Training should involve multiple, repeated contacts, not single sessions are essential to turn initial use into sustained practice.

4.2 | Deploy progressive farmers as para-extension workers for LRI dissemination

The high farmer-to-LRI extension manager ratio limits individual contact, which cannot be fixed by just adding more professional staff. Instead, identify and train successful farmers as community-level para-extension workers, a model used in Indian agriculture under ATMA. They can provide peer demonstrations and support cheaper than formal extension and are more credible among neighbours due to shared experience. Further training should start early in the programme, not after it ends.

4.3 | Integrate LRI data into existing agricultural systems

Currently, the LRI database is a standalone resource used only within the Sujala-III programme. Its effectiveness would increase if integrated into routine service delivery of state agricultural institutions. LRI data should connect to subsidy and input processes at Raitha Samparka Kendras (RSKs) and State Agriculture Department points, so farmer-specific LRI recommendations are accessible when registering for seeds, fertilisers, or crop insurance. This model, similar to Aadhaar-enabled targeting, would institutionalize LRI access and enhance transparency by offering site-specific recommendations instead of generic

advisories.

4.4 | Reform planning to include participatory farmer input during LRI design

The main implementation challenge identified by PIAs are difficulty in promoting crop suitability change is a planning issue, not communication. LRI recommendations conflicting with cropping patterns, landholding, and water conditions won't be adopted unless farmers are involved early in shaping these plans. Future planning should involve structured consultations with farmer groups before finalising site-specific recommendations, ensuring crop suitability and SWC prescriptions are co-developed with communities.

4.5 | Address logistical issues in card delivery and planting material distribution

The delayed receipt of LRI cards from partners, rated Moderate, hampers training and capacity building timelines. Programme agreements should include binding delivery deadlines, with cards available to PIAs before the first implementation season. Unseasonal distribution of horticulture and agroforestry planting material, which hurt sapling survival, should be managed through procurement calendars aligned with optimal planting windows and quality nursery materials.

4.6 | Develop accessible, multi-format LRI communication materials

Since 2.44% of farmers reported illiteracy and many lacked the vocabulary to interpret LRI outputs, a suitable extension communication methods to be evolved to make farmers to understand LRI science in local language. Digital delivery through farmer mobile apps, linked to geo-referenced land data, would improve accessibility for smartphone users while reducing the risk of card loss.

4.7 | Establish LRI as a continuous resource instead of a project-based one

Currently, LRI is a project deliverable produced during implementation and distributed at the end of funding. This model hinders sustained use, as it lacks mechanisms for updating recommendations, addressing farmer queries after project closure, or integrating outputs into ongoing planning. Hence government should develop a framework for ongoing maintenance and public access, with periodic updates and integration into the National Soil Health Card scheme to utilize existing infrastructure and farmer familiarity.

4.8 | Future research should address several gaps

Comparing adoption rates and outcomes in LRI versus non-LRI watersheds can clarify LRI's specific impact. Documenting the gap between LRI crop recommendations and farmer decisions at the field level can reveal whether inadequate advice, poor communication, or farmer adaptation is to blame. Finally, evaluating extension functionaries' skills in LRI interpretation and communication can identify capacity gaps and guide

targeted training.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest related to this work.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the first author and corresponding author upon reasonable request.

AUTHOR'S CONTRIBUTION

All authors contributed to the conception and design of the study. Material preparation, data collection and analysis were performed by all authors. The first draft of the manuscript was written by the first author and the corresponding author, who contributed equally to this work. All authors provided substantial inputs, reviewed and revised previous versions of the manuscript. All authors read and approved the final manuscript.

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Comparative Effects of Crop Residue Mulches on Weed Dynamics, Soil Moisture, and Yields of Chickpea (*Cicer arietinum* L.) Under Rainfed Conditions

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ABSTRACT

In rainfed chickpea cultivation, soil moisture stress and severe weed infestation are major constraints limiting productivity, while open-field burning of crop residues poses serious environmental concerns. With this background, an experiment was conducted during the winter or *Rabi* season of 2022-23 at Agricultural Research Farm, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh, to evaluate the effects of different crop residue mulches on weed dynamics, soil moisture conservation, growth, and yield of chickpea. The experiment was laid out in a randomized block design (RBD) with seven treatments and three replications. The treatments included: without mulch, dust mulch, paddy straw mulch @ 5 t ha⁻¹, maize stover mulch @ 5 t ha⁻¹, *Leucaena* twigs mulch @ 5 t ha⁻¹, paddy straw mulch @ 2.5 t ha⁻¹ + *Leucaena* twigs mulch @ 2.5 t ha⁻¹, maize stover mulch @ 2.5 t ha⁻¹ + *Leucaena* twigs mulch @ 2.5 t ha⁻¹. Results revealed that the application of paddy straw mulch at 5 t ha⁻¹ was the best treatment for reducing weed density and biomass at 60 and 90 DAS of chickpea. Although dust mulching recorded lower weed density and biomass at 30 DAS, it was ineffective during the subsequent crop growth period due to rapid flushes and proliferating weed germination. The maximum mid-season surface soil moisture (16.7%) was recorded under paddy straw mulch @ 5 t ha⁻¹ at 60 DAS, and it was found at par with paddy straw mulch @ 2.5 t ha⁻¹ + *Leucaena* twigs mulch @ 2.5 t ha⁻¹ while the minimum was observed under no mulch treatment. Moreover, paddy straw mulch @ 2.5 t ha⁻¹ + *Leucaena* twigs mulch @ 2.5 t ha⁻¹ excelled over all other treatments in terms of growth, yield parameters, and yield. Hence, application of paddy straw mulch @ 2.5 t ha⁻¹ + *Leucaena* twigs mulch @ 2.5 t ha⁻¹ may be recommended for higher growth and yield of chickpea under rainfed conditions similar to the experimental site.

1 | INTRODUCTION

Crop residue burning in India, especially in the Indo-Gangetic Plains, is a major environmental and agricultural issue, with nearly 100 million tonnes burned annually (Lan *et al.*, 2022), including 22.38 MT in Uttar Pradesh (Bhuvaneshwari *et al.*, 2019). Despite strict monitoring, incidents increased by over 18% in 2025 compared to 2024 (Times of India, 2025). Burning facilitates quick field clearing but releases greenhouse gases and particulate matter, contributing to pollution, health risks, and climate change (IPCC, 2019). This underscores the urgent need for sustainable residue management. Alternatives like in-situ incorporation, mulching, composting, biochar, and bioenergy are promoted. Among these, surface mulching improves soil microclimate, conserves moisture, suppresses weeds, and boosts soil organic carbon (Meshram

et al., 2022). It's especially useful in rainfed systems where moisture is limited and evaporation causes water loss, helping to improve resource efficiency and crop stability in water-scarce environments (Madhu and Jinger 2025 a, b).

Chickpea (*Cicer arietinum* L.) is a major pulse crop in India, accounting for 32.3% of the global pulse area and 40.9% of production. It is valued for its high protein content (18–22%) and nutritional importance (Jukanti *et al.*, 2012). However, productivity in rainfed regions remains low due to limited soil moisture during critical growth stages and severe weed competition, especially early in crop establishment (Patel *et al.*, 2024). Preserving residual soil moisture from the previous rainy season is therefore vital for successful rainfed chickpea cultivation (Rajak & Prasad, 2017). Mulching has been shown to reduce evaporation

(Ramos *et al.*, 2024), improve soil moisture retention (Kumari *et al.*, 2024), and enhance soil health and productivity (Singh & Dhillon, 2022). Although many studies highlight the benefits of individual mulch materials (Rajak & Prasad, 2017; Rao *et al.*, 2021), there is limited information on the comparative and combined effects of different residue mulches in rainfed chickpea systems. Specifically, the potential benefits of combining multiple residue types have not been thoroughly explored.

In this context, using crop residues as surface mulches offers an environmentally friendly alternative to burning residues. It also helps in managing soil moisture stress and weeds. This study was conducted to evaluate how different crop residue mulch treatments affect soil moisture retention, weed behavior, plant growth, and chickpea yield in rainfed conditions. The hypothesis was that optimal residue combinations could increase soil moisture, reduce weed growth, and boost chickpea productivity.

2 | MATERIALS AND METHODS

2.1 | Experimental Site and Weather Conditions

The experiment was conducted during the winter or *Rabi* season of 2022-23 at the Agricultural Research Farm, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh. Varanasi is located in a semi-arid to sub-humid climate belt. The decadal (2012–2023) mean climatic parameters were 31.07 °C for maximum temperature, 19.39 °C for minimum temperature, and 6.48 h day⁻¹ for sunshine duration (Fig. 1). Analysis of monthly climatic data (2012–2023) revealed that the mean annual rainfall and PET were 946.6 mm and 1407.6 mm, respectively. The rainy season (June–September) received an average rainfall of 803.7 mm, resulting in a moisture surplus of 335.7 mm, whereas the post-rainy season (October–February) received only 87.8 mm, resulting in a moisture deficit of 219.4 mm. This place typically experiences semi-arid to sub-humid climates, with high and low precipitation, moderate humidity, and seasonal temperature fluctuations. The sandy clay loam soil in the experimental field exhibited low levels of nitrogen (200 kg ha⁻¹), moderate levels of soil organic carbon (0.47%), phosphorus (19.75 kg ha⁻¹), and potassium (140.56 kg ha⁻¹). Both pH (7.44) and electrical conductivity (0.26 dS m⁻¹) of the soil were within the typical range.

2.2 | Experimental Design and Treatments

The experiment was laid out in a randomized block design (RBD) with three replications. The study included seven treatments, viz. without mulch (T₁), dust mulch (T₂), paddy straw mulch @ 5 t ha⁻¹ (T₃), maize stover mulch @ 5 t ha⁻¹ (T₄), *Leucaena* twigs mulch @ 5 t ha⁻¹ (T₅), paddy straw mulch @ 2.5 t ha⁻¹ + *Leucaena* twigs mulch @ 2.5 t ha⁻¹ (T₆), maize stover mulch @ 2.5 t ha⁻¹ + *Leucaena* twigs mulch @ 2.5 t ha⁻¹ (T₇). Paddy straw, maize stover, and *Leucaena* twigs mulch were applied immediately after sowing of the chickpea. Paddy straw and maize stover from the preceding crops grown in the experiment were utilized, as they were not required for livestock feeding. Additionally, *Leucaena*

HIGHLIGHTS

- Paddy straw mulch @ 5 t ha⁻¹ most effectively suppressed weeds, recording the lowest weed density and biomass.
- Integrated mulching with paddy straw mulch @ 2.5 t ha⁻¹ + *Leucaena* twigs mulch @ 2.5 t ha⁻¹ significantly enhanced chickpea growth and productivity.
- Residue-based mulching improved soil moisture conservation mid-season, with paddy straw mulch at 5 t ha⁻¹ showing the highest soil moisture (16.7%).

twigs were collected from boundary plantations at Banaras Hindu University, Varanasi, Uttar Pradesh. The gross and net plot sizes were: 5 m × 4 m and 4.0 m × 3.1 m, respectively.

2.3 | Crop Management Practices

After the final field preparation, the seeds of the Chickpea variety “RVG-202” were sown at the rate of 80 kg ha⁻¹ at a uniform distance of 30 cm between rows and 10 cm distance between plants by seed drill on 15th October 2022. The field was fertilized with recommended doses of N: P₂O₅: K₂O (20: 40: 20 kg ha⁻¹), applied as Di Ammonium Phosphate and Muriate of Potash, respectively. All the doses of nitrogen, phosphorus, and potassium were applied as basal at the time of sowing. Dust mulch (5-8 cm) was applied with a dryland weeder, and weeds were removed once at 25 DAS at a depth of 3-4 cm. This created a finely textured layer of soil. Paddy straw, maize stover, and *Leucaena* twigs were used as mulches to cover the soil between chickpea rows @ 5 t ha⁻¹ on a dry biomass basis. The mulch thickness was 4-5 cm. This practice was done immediately after germination, i.e., 10 days after sowing (DAS). The combination of mulches (paddy + *Leucaena*) and maize + *Leucaena* was applied @ 2.5 t ha⁻¹ each. The crop was harvested on 20th February 2023 when the plants turned yellow-brown, and the pods became dry and hard. The crop was cut close to the ground with a sickle and sun-dried for five days. After drying, the seeds were separated using a mechanical thresher and cleaned before storage. No incidence of insect pests or diseases was observed during the experimental period. Apart from the prescribed treatments, no additional weed management practices were followed.

2.4 | Data Recording

In each plot, 5 plants were tagged for observations. Weed populations (grasses, broad-leaved weeds, and sedges) were counted in 0.25 m² quadrats, transformed using $\sqrt{x} + 0.5$ to reduce variability. Weed biomass was measured at 30, 60, and 90 DAS from two quadrates per plot, sun-dried, then oven-dried at 70 ± 2 °C for 48 hours, expressed as total weed density and biomass, and transformed similarly. Root nodule numbers and branches per plant were recorded at 50% flowering (60 DAS). Yield attributes (pods, seeds per plant, seed index) were recorded at harvest. Seed and stover yields were extrapolated to kg ha⁻¹ from net plot data. Soil moisture at 60 DAS was measured once using the gravimetric method at the 0–15 cm depth, following Reynolds (1970), with sampling via auger and oven drying

at 105 °C for 24 hours.

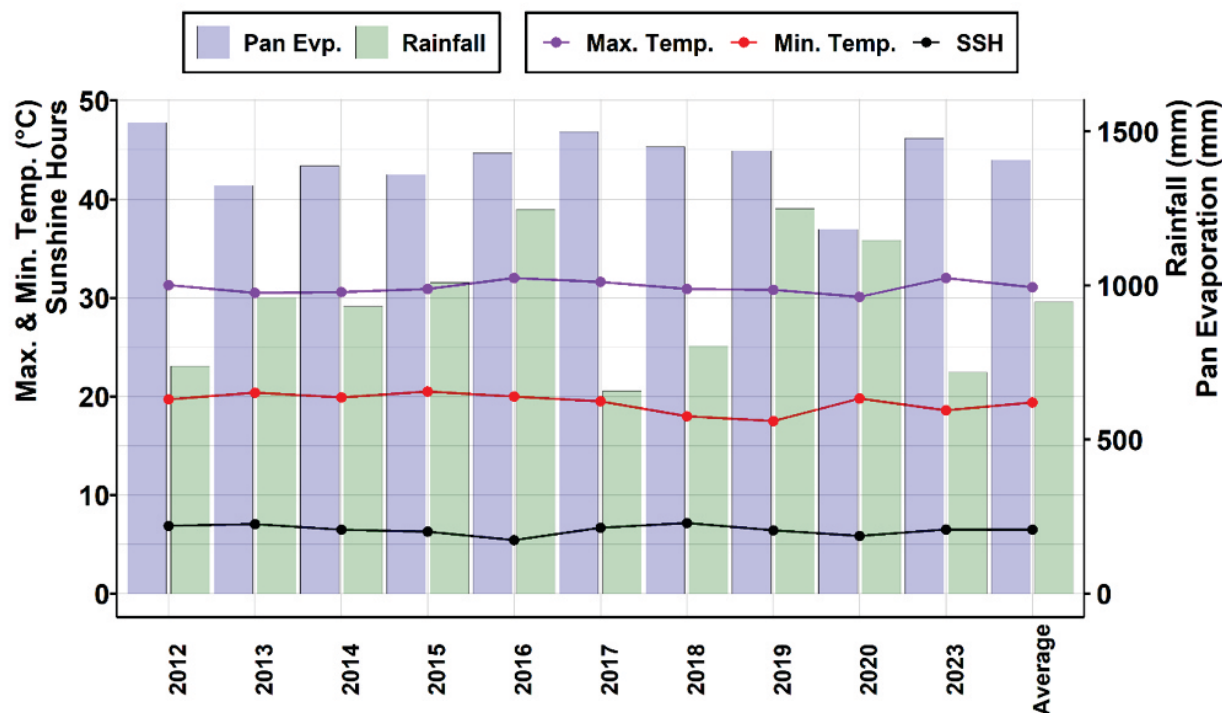


FIGURE 1 Annual variation in rainfall, PET, temperature, and sunshine hours (SSH) from 2012-2023

2.5 | Statistical Analysis

Statistical analysis was carried out to assess the significance of differences between treatment means and to draw valid conclusions. Data from various observed parameters were analyzed using an appropriate Analysis of Variance (ANOVA) technique. The treatment effects were tested for significance using the 'F' test. Mean values were calculated following the methods described by Gomez and Gomez (1984). Additionally, mean comparisons were performed using Tukey's Honestly Significant Difference (HSD) test at a 5% probability level.

3 | RESULTS AND DISCUSSION

3.1 | Effect On The Total Weed Density And Biomass

Mulching treatments exerted a pronounced influence on weed density and weed dry biomass in chickpea at different crop growth stages. Across all observations, mulched plots significantly reduced weed infestation compared with the plot without mulch, which consistently recorded the highest weed density and dry matter accumulation at 30, 60, and 90 DAS (Table 1). Among the treatments, paddy straw mulch @ 5 t ha⁻¹ proved most effective, observed the lowest weed density and weed dry biomass at both 60 and 90 DAS, indicating its sustained weed-suppressive potential throughout the crop growth period. Treatments like maize stover mulch @ 5 t ha⁻¹, paddy straw mulch @ 2.5 t ha⁻¹ + *Leucaena* twigs mulch @ 2.5 t ha⁻¹, and maize stover mulch @ 2.5 t ha⁻¹ + *Leucaena* twigs mulch @ 2.5 t ha⁻¹ also demonstrated moderate effectiveness in suppressing weed growth, though their performance remained inferior to paddy straw mulching.

At 30 DAS, dust mulch recorded the lowest weed density and weed dry biomass. This initial reduction in weed infestation may be attributed to repeated soil disturbance by the dryland weeder, which physically uprooted or buried newly emerged weeds, thereby disrupting early weed establishment (Verma *et al.*, 2017). However, this suppressive effect was transient. At later growth stages (60 and 90 DAS), weed density and dry biomass increased under dust mulching due to soil inversion and loosening, which enhanced light penetration and created favorable conditions for weed seed germination and subsequent growth. In contrast, paddy straw mulch @ 5 t ha⁻¹ consistently maintained significantly lower weed density and dry biomass at 60 and 90 DAS (Table 1). The superior weed suppression under paddy straw mulch may be attributed to its mat-like physical barrier, which restricted light transmission to the soil surface, thereby inhibiting germination of light-sensitive weed seeds. Additionally, the physical persistence of paddy straw ensured prolonged soil cover, reduced soil temperature fluctuations, and limited space for weed emergence throughout the crop period. Sahu *et al.* (2022) reported that application of paddy straw mulch at 5 t ha⁻¹ significantly reduced the weed density and weed biomass in chickpea, indicating the effectiveness of organic residue mulching in suppressing weeds through physical obstruction, allelopathic effects, and modification of the soil microenvironment.

3.2 | Effect On the Growth Attaining Characters

The growth attributes of chickpea were significantly

influenced by different mulch treatments throughout the crop growth period (Table 2). Among all treatments, the combined application of paddy straw mulch @ 2.5 t ha⁻¹ + *Leucaena* twigs mulch @ 2.5 t ha⁻¹ consistently resulted in the highest plant height at all growth stages. Plant height under this treatment reached 26.3 cm, 36.0 cm, and 59.0 cm at 30, 60, and 90 DAS, respectively (Table 2), indicating a sustained positive effect on vegetative growth. This superior performance may be attributed to improved mid-season surface soil moisture conservation and moderated soil temperature under residue mulching, which created a favourable microenvironment for continuous crop growth (Archana *et al.*, 2021).

The number of branches per plant, a critical determinant of yield potential in chickpea, was also significantly affected by mulch treatments. Application of paddy straw mulch @ 2.5 t ha⁻¹ + *Leucaena* twigs mulch @ 2.5 t ha⁻¹ recorded the highest number of branches per plant (17.0) compared to other treatments (Table 2). The enhanced branching under residue mulching may be attributed to reduced evaporative losses, improved soil physical conditions, and increased availability of mid-season surface soil moisture and nutrients. Furthermore, effective weed suppression under this treatment reduced crop-weed competition, thereby facilitating improved nutrient uptake and assimilate partitioning, ultimately supporting robust plant architecture. Kumar and Angadi (2016), observed improved plant height and leaf area of chickpea with mulching of maize stalk (4 t ha⁻¹) at Dharwad region of Karnataka.

Mulching-induced improvements in soil hydrothermal conditions may have contributed to better root development and overall plant growth. Although soil temperature, root architecture, and soil physical properties were not directly measured in the present study, mulching may have enhanced surface soil moisture at 60 DAS, thereby indirectly supporting improved root growth and resource acquisition. The combined effects of improved moisture availability and a moderated soil environment under mulched treatments may have facilitated more efficient water and nutrient uptake. Similar positive associations between organic mulching and improved chickpea growth have been reported by Angmo *et al.* (2018).

The number of root nodules per plant was significantly higher under mulched treatments, with paddy straw mulch @ 2.5 t ha⁻¹ + *Leucaena* twigs mulch @ 2.5 t ha⁻¹ observed the maximum number of nodules (19.4 plant⁻¹), followed by paddy straw mulch @ 5 t ha⁻¹ with 18.2 nodules plant⁻¹. The enhanced nodulation observed under these treatments may be associated with reduced weed infestation, which could have minimized competition for soil nutrients and moisture, thereby creating more favourable conditions for Rhizobium activity. Additionally, although microbial activity and nitrogen dynamics were not directly measured in the present study, crop residue decomposition may have influenced rhizosphere microbial processes, including temporary

nitrogen immobilization. Such conditions could potentially stimulate biological nitrogen fixation and nodulation in chickpea, as suggested in earlier studies. Similar explanations have been reported by Sahu *et al.* (2022).

In contrast, the lowest number of root nodules (7.50 plant⁻¹) was recorded in the without-mulch plot. This reduction may be associated with higher weed density and greater weed biomass under no mulching, which could have increased competition for soil moisture and nutrients, thereby adversely influencing crop growth and nodulation. Although soil temperature and microbial activity were not directly measured in the present study, the absence of mulch may have resulted in less favourable surface soil moisture conditions at 60 DAS, potentially affecting Rhizobium activity and root development. Similar trends of reduced nodulation under weedy and moisture-limited conditions have been reported by Rao *et al.* (2021).

3.3 | Effect On the Yield Attributing Characters

Mulching treatments significantly influenced yield attributes and chickpea productivity. The combined application of paddy straw mulch @ 2.5 t ha⁻¹ + *Leucaena* twigs mulch @ 2.5 t ha⁻¹ recorded the highest number of pods plant⁻¹ (60.6) and grains pod⁻¹ (1.70), whereas the plot without mulch consistently showed significantly lower values for these yield components (Table 3). The improvement in reproductive parameters under this treatment indicates enhanced assimilate availability and effective partitioning towards sink development under favorable mid-season surface soil moisture and thermal regimes created by residue mulching. Test weight was statistically unaffected by mulching treatments, suggesting that seed size is primarily governed by genetic factors and less responsive to soil surface management practices under the prevailing agro-climatic conditions. Similar observations have been reported in chickpea, where mulching improved yield mainly through increased pod number plant⁻¹ and seed number pod⁻¹ under rainfed agroecosystems of the semi-arid tropics of India (Sahu *et al.*, 2023).

The superiority of paddy straw mulch @ 2.5 t ha⁻¹ + *Leucaena* twigs mulch @ 2.5 t ha⁻¹ was further reflected in seed yield (1749 kg ha⁻¹), stover yield (2606 kg ha⁻¹), and biological yield (4355 kg ha⁻¹), all of which were significantly higher than those obtained under the plot without mulch. The enhanced yields under combined mulching may be associated with higher surface soil moisture content observed at 60 DAS and effective weed suppression, which together could have promoted better crop growth and more efficient utilization of available resources.

Although soil temperature and nutrient dynamics were not directly measured in the present study, the inclusion of *Leucaena* twigs may have improved nutrient availability through their nutrient-rich biomass. Although the harvest index was highest under this treatment (40.2%), differences

among treatments were statistically non-significant, indicating that mulching primarily enhanced total biomass production rather than altering biomass partitioning patterns. These findings suggest that integrated organic mulching improves chickpea productivity by increasing

both vegetative and reproductive growth without adversely affecting harvest efficiency. These results are in close agreement with recent studies reporting increased chickpea yield under integrated residue-based mulching systems in rainfed environments (Parmar *et al.*, 2023).

TABLE 1 Effect of different mulches on total weed density (no. m⁻²) and total dry biomass in chickpea (g m⁻²)

Treatment	Density of total weeds (no. m ⁻²)			Dry biomass of total weeds (g m ⁻²)		
	30 DAS*	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS
Without mulch	13.36 (178) ^a	16.26 (264) ^a	20.65 (426) ^a	8.86 (78.06) ^a	11.41 (129.7) ^a	14.76 (217.5) ^a
Dust mulch	4.30 (18) ^f	14.02 (196) ^b	19.51 (380) ^{ab}	2.50 (5.74) ^f	9.33 (86.9) ^b	11.75 (137.5) ^b
Paddy straw mulch @ 5 t ha ⁻¹	5.05 (25) ^e	6.52 (42) ^f	9.82 (96) ^e	3.32 (10.5) ^e	4.30 (18) ^e	5.14 (25.9) ^e
Maize stover mulch @ 5 t ha ⁻¹	7.91 (62) ^e	10.51 (110) ^d	14.98 (224) ^c	5.27 (27.3) ^c	5.99 (35.4) ^e	7.69 (58.6) ^e
<i>Leucaena</i> twigs mulch @ 5 t ha ⁻¹	9.72 (94) ^b	12.27 (150) ^c	18.23 (332) ^b	6.69 (44.3) ^b	8.03 (64) ^c	11.19 (124.6) ^c
Paddy straw mulch @ 2.5 t ha ⁻¹ + <i>Leucaena</i> twigs mulch @ 2.5 t ha ⁻¹	6.04 (36) ^d	8.40 (70) ^e	12.75 (162) ^d	3.95 (15.1) ^d	4.89 (23.4) ^f	6.51 (41.8) ^f
Maize stover mulch @ 2.5 t ha ⁻¹ + <i>Leucaena</i> twigs mulch @ 2.5 t ha ⁻¹	8.22 (67) ^c	10.79 (116) ^d	15.70 (246) ^c	5.44 (29.0) ^c	7.18 (51.1) ^d	9.77 (95) ^d

* DAS = Days After Sowing

Treatment means with similar superscripted letters within a column are not significantly different at $p < 0.05$ according to Turkey's honestly significant difference test

TABLE 2 Effect of different mulches on plant height (cm), number of branches plant⁻¹ and number of nodules plant⁻¹ of chickpea

Treatment	Plant height (cm)			Branches (no. plant ⁻¹)	Nodules (no. plant ⁻¹)
	30 DAS*	60 DAS	90 DAS		
Without mulch	17.7 ^c	29.7 ^d	41.0 ^d	7.33 ^d	7.5 ^f
Dust mulch	19.0 ^d	31.0 ^c	52.9 ^c	11.0 ^{cd}	8.7 ^e
Paddy straw mulch @ 5 t ha ⁻¹	24.3 ^b	34.2 ^b	58.0 ^{ab}	15.3 ^{ab}	18.2 ^b
Maize stover mulch @ 5 t ha ⁻¹	21.3 ^c	31.7 ^c	53.6 ^{bc}	12.7 ^{bc}	12.4 ^d
<i>Leucaena</i> twigs mulch @ 5 t ha ⁻¹	23.2 ^b	34.0 ^b	55.1 ^{bc}	13.3 ^{abc}	17.3 ^b
Paddy straw mulch @ 2.5 t ha ⁻¹ + <i>Leucaena</i> twigs mulch @ 2.5 t ha ⁻¹	26.3 ^a	36.0 ^a	59.0 ^a	17.0 ^a	19.4 ^a
Maize stover mulch @ 2.5 t ha ⁻¹ + <i>Leucaena</i> twigs mulch @ 2.5 t ha ⁻¹	21.6 ^c	33.3 ^b	54.3 ^{bc}	13.0 ^{abc}	15.7 ^c

*DAS=Days after sowing

Treatment means with superscripted letters within a column are not significantly different at $P < 0.05$ according to Tukey's honestly significant difference test

TABLE 3 Effect of different mulches on yield attributes and yield of chickpea

Treatment	Yield attributes			Yield (kg ha ⁻¹)			Harvest Index (%)	Soil moisture (%) at 60 DAS
	Pods (no. plant ⁻¹)	Grains (no. pod ⁻¹)	100 seed weight (g)	Seed	Stover	Biological		
Without mulch	29.3 ^f	1.3 ^c	25.2 ^b	988 ^g	1570 ^f	2558 ^g	38.6 ^a	5.33 ^f
Dust mulch	40.7 ^e	1.6 ^{ab}	26.2 ^b	1104 ^f	1778 ^e	2882 ^f	38.3 ^a	7.67 ^e
Paddy straw mulch @ 5 t ha ⁻¹	55.0 ^b	1.7 ^a	28.5 ^a	1567 ^b	2429 ^b	3997 ^b	39.2 ^a	16.7 ^a
Maize stover mulch @ 5 t ha ⁻¹	43.7 ^{de}	1.5 ^b	28.0 ^a	1200 ^e	1908 ^d	3103 ^e	38.7 ^a	13.3 ^{bc}
<i>Leucaena</i> twigs mulch @ 5 t ha ⁻¹	49.0 ^c	1.6 ^{ab}	27.5 ^a	1402 ^c	2314 ^b	3717 ^c	37.7 ^a	11.0 ^d
Paddy straw mulch @ 2.5 t ha ⁻¹ + <i>Leucaena</i> twigs mulch @ 2.5 t ha ⁻¹	60.7 ^a	1.7 ^a	29.2 ^a	1749 ^a	2606 ^a	4355 ^a	40.2 ^a	13.7 ^b
Maize stover mulch @ 2.5 t ha ⁻¹ + <i>Leucaena</i> twigs mulch @ 2.5 t ha ⁻¹	46.7 ^{cd}	1.5 ^b	28.0 ^a	1312 ^d	2112 ^c	3424 ^d	38.3 ^a	12.0 ^c

Treatment means with similar superscripted letters within a column are not significantly different at P<0.05 according to Tukey's honestly significant difference test

3.4 | Effect On Soil Moisture

Mulching treatments significantly influenced mid-season surface soil moisture content at 60 DAS (Table 3). The maximum mid-season surface soil moisture (16.7%) was recorded under paddy straw mulch @ 5 t ha⁻¹ at 60 DAS, while the minimum was observed in without mulch. Soil moisture under paddy straw @ 5 t ha⁻¹ was significantly higher than all other treatments, indicating the superior moisture-conserving ability of paddy straw mulch. This improvement may be attributed to the formation of a uniform, continuous mat over the soil surface, which reduces direct exposure to solar radiation, minimizes wind velocity at the soil-atmosphere interface, and suppresses evaporative water losses (Pawar *et al.*, 2019; Ramos *et al.*, 2024). Similar enhancements in soil moisture retention under straw mulching have been widely reported, particularly during mid-season stages when evaporative demand is high (Kumari *et al.*, 2024). In contrast, the lowest mid-season surface soil moisture content under the treatment without mulch may be due to rapid evaporation from the exposed soil surface, leading to faster depletion of soil water reserves. The absence of surface cover leads to greater temperature fluctuations and accelerates soil drying, especially under warm, dry conditions (Meshram *et al.*, 2022).

4 | Limitations Of The Study

While the present study provides useful insights into the effectiveness of crop residue mulching on weed suppression, soil moisture conservation, and chickpea productivity, certain limitations should be acknowledged. The experiment was conducted during a single cropping season at one location, and therefore the results may not fully capture inter-annual climatic variability or site-specific soil-crop interactions; consequently, extrapolation

of findings to other agro-ecological regions should be done cautiously. In addition, practical constraints associated with residue mulching may limit large-scale adoption by farmers. Crop residues often serve as an important source of livestock feed, and their competing use for fodder can restrict availability for mulching. Dry residue mulches may also attract termites or other pests, potentially creating management challenges in farmers' fields. The application and uniform spreading of mulches require additional labour, and the unavailability or high cost of manpower during peak agricultural operations can discourage their use. Furthermore, increasing the utilization of crop residues for alternative purposes, such as biofuel or energy production, reduces the quantity available for in-situ conservation practices. These socioeconomic and operational factors should be considered when interpreting the results and highlight the need for multi-location, multi-season studies that integrate agronomic effectiveness with practical feasibility under real farming conditions.

5 | CONCLUSIONS

The present study demonstrated that mulching significantly influenced weed suppression, crop growth, and chickpea yield under rainfed conditions in Varanasi, Uttar Pradesh, during the rabi season of 2022-23. Among the treatments, paddy straw mulch @ 5 t ha⁻¹ was most effective in reducing total weed density, weed dry biomass, and conserving mid-season surface soil moisture during critical growth stages of chickpea (peak flowering or early pod development stage). However, the combined application of paddy straw mulch @ 2.5 t ha⁻¹ + *Leucaena* twigs mulch @ 2.5 t ha⁻¹ resulted in superior performance with respect to plant height, number of branches, nodules per plant, seed yield, and harvest index compared to other treatments evaluated. Based on the findings of this single-season, single-location study, the

integrated mulching approach using both organic residues showed promising potential to enhance chickpea productivity under rainfed conditions similar to those at the experimental site. However, further multi-season and multi-location studies are required to validate the consistency and wider applicability of these results under diverse agro-ecological conditions.

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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 will be made available on request.

AUTHOR'S CONTRIBUTION

Kareti Harika: Conceptualization, writing original manuscript; Sudhir Kumar Rajpoot: Data analysis; S.K. Verma: Software; Udaya Lakshmi D: Formal analysis; Ambikesh Tripathi: methodology; Dinesh Jinger: Writing and reviewing.

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