



RESEARCH ARTICLE

Delineation of potential zones for makhana (*Euryale ferox* L.) cultivation through the integrating of multi-criteria evaluation and GIS in Northern Bihar

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Abstract

Cultivation suitability of makhana (*Euryale ferox* L.) in Northern Bihar was evaluated using a multi-criteria evaluation (MCE) framework integrating the analytical hierarchy process (AHP) and geographic information systems (GIS). Critical factors such as soil texture, slope, land use, soil drainage and water quality were considered, with their relative importance quantified using AHP. Soil and water analyses revealed soils ranging from sandy loam to sandy clay loam, pH values varying from slightly acidic to alkaline, organic carbon (OC) contents between 0.29 % and 0.87 % and electrical conductivity (EC) values ranging from 0.07 to 0.38 dS m⁻¹. Water quality is crucial for safe drinking water and agricultural use; however, contamination of iron poses significant health and environmental risks. This study assessed water quality by analysing the sodium adsorption ratios and iron concentrations. While sodium adsorption ratios remained within acceptable limits, the iron concentrations in groundwater exceeded the permissible thresholds, indicating potential risks that require urgent attention. Overlaying all nine parameters identified 1826 ha (7.24 %) as suitable makhana growing areas, primarily in Purnia East District. The AHP results classified 480.23 ha (26.30 %) as highly suitable (S₁), 846.53 ha (46.36 %) as moderately suitable (S₂) and 422.90 ha (23.16 %) as marginally suitable (S₃), while 73.77 ha (4.04 %) and 2.556 ha (0.14 %) were classified as currently unsuitable (N₁) and permanently unsuitable (N₂) respectively. These findings demonstrate the effectiveness of AHP-based MCE combined with GIS as a robust tool for identifying potential cultivation zones, facilitating targeted agricultural planning and sustainable resource management in the region, while highlighting the need to address groundwater iron contamination to ensure safe and sustainable makhana cultivation.

Keywords: analytical hierarchy process; geographic information systems; land suitability analysis; makhana; multi-criteria evaluation; soil and water quality

Introduction

Makhana, also referred to as fox nut or gorgon nut (*Euryale ferox* L.) is an important aquatic crop in India with well-recognised traditional medicinal uses (1). Popping enhances the nutritional quality of makhana seeds by increasing their protein and dietary fibre content while reducing anti-nutritional factors, such as phytic acid and tannins (2). Makhana, a key aquatic crop belonging to the family Nymphaeaceae, possesses notable antioxidant properties and has been reported to play a role in the management of diabetic nephropathy (3). Owing to these nutritional and medicinal attributes, makhana cultivation is economically rewarding and contributes to health and sustainability in the region.

The complex riverine and wetland systems of Northern Bihar provide a unique environmental framework for the cultivation of makhana. Major rivers, such as the Ganga and Burhi Gandak, have exhibited significant southward channel migration over the past five decades, resulting in the formation of oxbow lakes and abandoned channels. These geomorphological features create favourable wetland habitats for makhana growth. Furthermore, rivers in the Himalayan foreland of Northern Bihar are classified as mountain, foothill, plain and mixed-fed systems, each exhibiting distinct channel morphologies, hydrological characteristics and suspended sediment loads. Most rivers show active channel movement, primarily through avulsion and local cut-offs (4), which play crucial roles in the formation and evolution of wetlands in the region.

Wetlands in Northern Bihar are closely linked to frequent flooding. The presence of natural depressions (chaurs), oxbow lakes (moins) and ponds (pokhara and taals) influences flood patterns and inundation duration, highlighting the complex interactions between river systems and land-bound wetland environments in this region. These environmental variables directly affect wetland stability, nutrient dynamics and hydrological conditions, which are critical determinants of site suitability for makhana cultivation. Integrating these hydrological and geomorphological characteristics within a multi-criteria evaluation (MCE) framework enables systematic spatial analysis to identify and map optimal cultivation zones. Geographic information systems (GIS) facilitate the integration of river morphology, sediment characteristics and hydrological data to generate a comprehensive suitability assessment.

Makhana cultivation in Bihar spans over 27000 ha, accounting for approximately 85 % of India's total production. The major makhana-producing districts include Darbhanga, Madhubani, Sitamarhi, Supaul, Saharsa, Madhepura, Araria, Kishanganj, Purnea and Katihar. Notably, several of these districts, particularly Darbhanga and Katihar, are highly flood-prone. Darbhanga was identified as one of the most severely affected districts during the 2017 floods in Northern Bihar (5).

Incorporating temporal analysis can further reveal seasonal variations and long-term trends in land suitability for makhana cultivation (6, 7). Although makhana is produced on a large scale in areas such as Purnea East, its contribution to the regional economy remains relatively low. Climatic and biophysical factors play a dominant role in influencing makhana productivity and suitable cultivation areas can be identified through the integrating of these parameters. Approximately 80 % of processed makhana production originates from the districts of Darbhanga, Madhubani, Purnea and Katihar.

The integration of MCE with GIS has emerged as a robust approach for addressing complex decision-making problems in land suitability assessment and spatial planning (8–11). This approach enables the evaluation of multiple criteria to identify optimal locations for diverse applications, including crop suitability analysis, urban planning and environmental management (12–14). Several studies have demonstrated that combining remote sensing data with GIS-based MCE provides a more accurate delineation of cultivation zones than conventional methods (15–18). Within the MCE-GIS framework, the analytical hierarchy process (AHP) is widely used to systematically assign relative importance to different criteria (19, 20).

Despite advancements in remote sensing and GIS applications, comprehensive studies integrating multiple environmental and socio-physical criteria for the delineation of makhana cultivation zones remain limited. Existing research has primarily focused on individual factors or conventional methods, lacking a systematic approach that combines diverse parameters, such as sediment characteristics, hydrology and climatic and biophysical factors within an MCE framework. This gap hinders the accurate identification of optimal and sustainable areas for makhana cultivation.

Practical implications for stakeholders include enabling farmers to adopt more precise site selection for makhana cultivation, thereby enhancing yield and sustainability. For planners and policymakers, the integrated MCE-GIS approach supported by AHP facilitates informed decision-making to promote sustainable

agricultural practices and optimise resource allocation. Addressing this limitation is essential to enhance makhana production and promote sustainable cultivation practices in Northern Bihar.

Materials and Methods

Study area

The Purnea East Block is a geographical subdivision of the Purnea District in Northern Bihar, India. The study area was delineated using Survey of India toposheets Nos. 72O and 72N and lies between 25°43' N and 26°12' N latitude and 86°99' E and 87°86' E longitude (Fig. 1). According to the Planning Commission of India, the Purnea District falls within the Middle Gangetic Plain Region (Agro-climatic Zone IV).

Weather and climate

The climatic conditions in Northern Bihar are favourable for makhana cultivation. The region experiences a moist, humid subtropical climate that is well suited for makhana production. Summer extends from April to June, while winter occurs between December and January. The southwest monsoon begins in mid-June and continues until early October. Summer temperatures range from 25–47 °C, whereas winter temperatures vary from 4–25 °C. The weather condition, relative humidity, fluctuates between 41 % during summer and approximately 70 % during winter. The area receives most of its rainfall from the southwest monsoon, with an average annual precipitation of 1470.4 mm and approximately 54 rainy days (≥ 2.5 mm rainfall) per year (Department of Agronomy, Bihar Agricultural University, Sabour, Bhagalpur, India).

Physiography

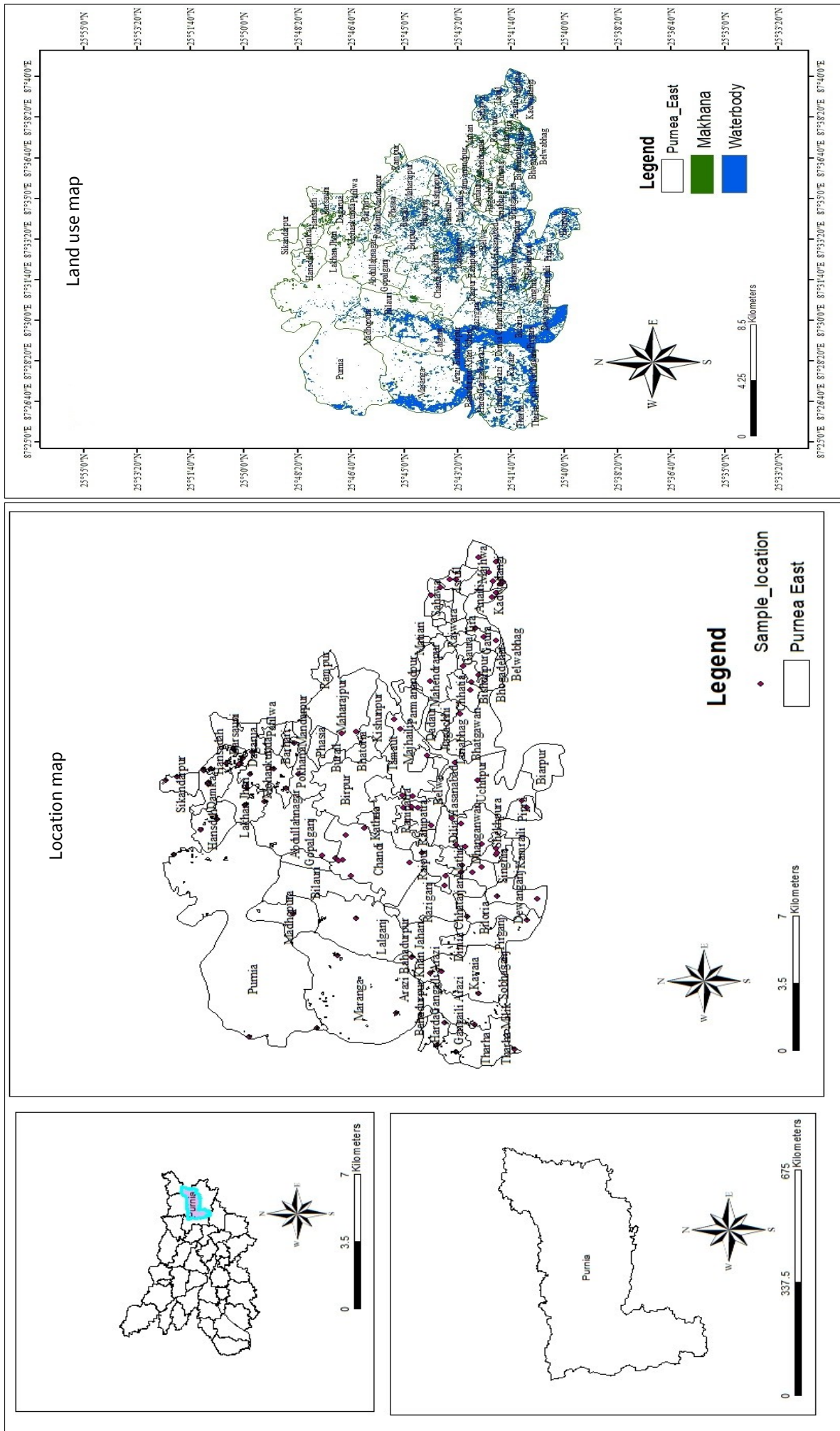
The Purnea East Block is characterised by flat topography due to extensive alluvial deposits. The area has a gentle south-eastward slope and is highly prone to flooding. Elevation ranges from 30–57.8 m above mean sea level. The soils of the district are classified as active alluvial plains, recent alluvial plains and Kosi alluvial cones, with textures varying from sandy to coarse loamy in the active alluvial plains. Frequent channel shifts in river systems contribute to recurrent flooding. The Mahananda river serves as a major water source in the northern part of the district, while the Kosi main canal network provides surface water irrigation. Groundwater is the primary source of irrigation, followed by canal water.

Land use

The major crops grown in the area include jute, rice, wheat, potato, maize, banana and makhana. The region follows four agricultural seasons: Bhadaï, Aghani, Rabi and Garmā. The kharif season comprises Bhadaï and Aghani crops, followed by the Rabi and Garmā seasons, with irrigation supported by both surface and groundwater sources.

Soil and water sampling

Soil and water samples were collected from *ex situ* and *in situ* (pond system) cultivation conditions in fields under makhana cultivation with a water depth of approximately 6 inches. A total of 54 soil and water samples were collected using a grid-based (1.0 × 1.0 km²) sampling approach. Sampling locations were selected based on the availability of irrigation water sources and the presence of makhana cultivation in the area. Land use information for makhana cultivation was derived from Landsat 8 imagery obtained from the USGS Earth Explorer Portal.



Soil and water quality parameters

Soil texture was determined according to standard guidelines (21). Soil pH (SpH) and electrical conductivity (EC) were measured using the potentiometric method with a glass electrode (22). Oxidisable organic carbon (OC) was estimated using the modified Walkley-Black spectrophotometric method (23). The sodium adsorption ratio (SAR) and residual sodium carbonate (RSC) were calculated following the United States salinity laboratory (USSL) guidelines (24). Calcium and magnesium concentrations were determined using the ethylenediaminetetraacetic acid (EDTA) titration method (25) and total iron (Fe) content was estimated using the perchloric-hydrochloric acid digestion technique (26). Spatial data processing and analysis were performed using ArcGIS 10.3 software. Geographic information systems (GIS) tools were employed for map generation, spatial overlay analysis and terrain evaluation to support a comprehensive assessment of the land-use patterns and environmental characteristics of the study area.

Methodology for delineation of potential areas for makhana crop

The AHP was employed to assign relative weights to environmental and soil-related factors influencing the suitability of the area for makhana cultivation. A total of nine governing factors, identified as highly relevant to the model, were selected for the analysis. A pairwise comparison matrix based on Saaty's scale, ranging from 1 to 9 and their reciprocals (1/9), was used to calculate factor weights and establish interrelationships among the criteria (27). Factors such as soil texture, slope, land use, soil drainage, physicochemical properties and water quality were classified into suitability classes and assigned numerical scores to reflect their relative importance.

Land suitability analysis

The land suitability analysis (LSA) system categorises land based on

its suitability for optimum makhana production by considering soil and environmental factors. The classes are as follows: S_1 (highly suitable): Land without significant limitations, supporting optimal crop growth. S_2 (moderately suitable): Land with minor limitations requiring moderate input or management. S_3 (marginally suitable): Land with severe limitations requiring substantial inputs or management changes. N_1 (not suitable): Land unsuitable for agricultural use under current conditions. A soil suitability model was developed using a weighted overlay analysis to integrate all selected factors. Both descriptive and inferential statistical analyses were performed to evaluate the significance of the individual parameters influencing the suitability of makhana cultivation.

Statistical analysis

Statistical analysis was performed using the Shapiro-Wilk test to assess the normality of the soil parameters, where a p -value greater than 0.05 indicated failure to reject the null hypothesis of normality. Skewness values close to ± 0.1 and kurtosis values near ± 0.3 suggested that the distribution approximated a symmetric bell-shaped curve. A p -value ≤ 0.05 indicated deviation from normality, often associated with moderate skewness (0.2–0.4) and slightly heavier tails (28).

Results and Discussion

Status of soil and water quality attributes in makhana growing areas

The distribution of soil and water quality attributes, including sand, silt, clay fractions, soil properties (pH, EC and OC) and water quality parameters (water pH (WpH), water electrical conductivity (WEC), SAR, RSC and total Fe), were analysed using descriptive statistics (Fig. 2 and Table 1) and Shapiro-Wilk test showed sand content, SAR

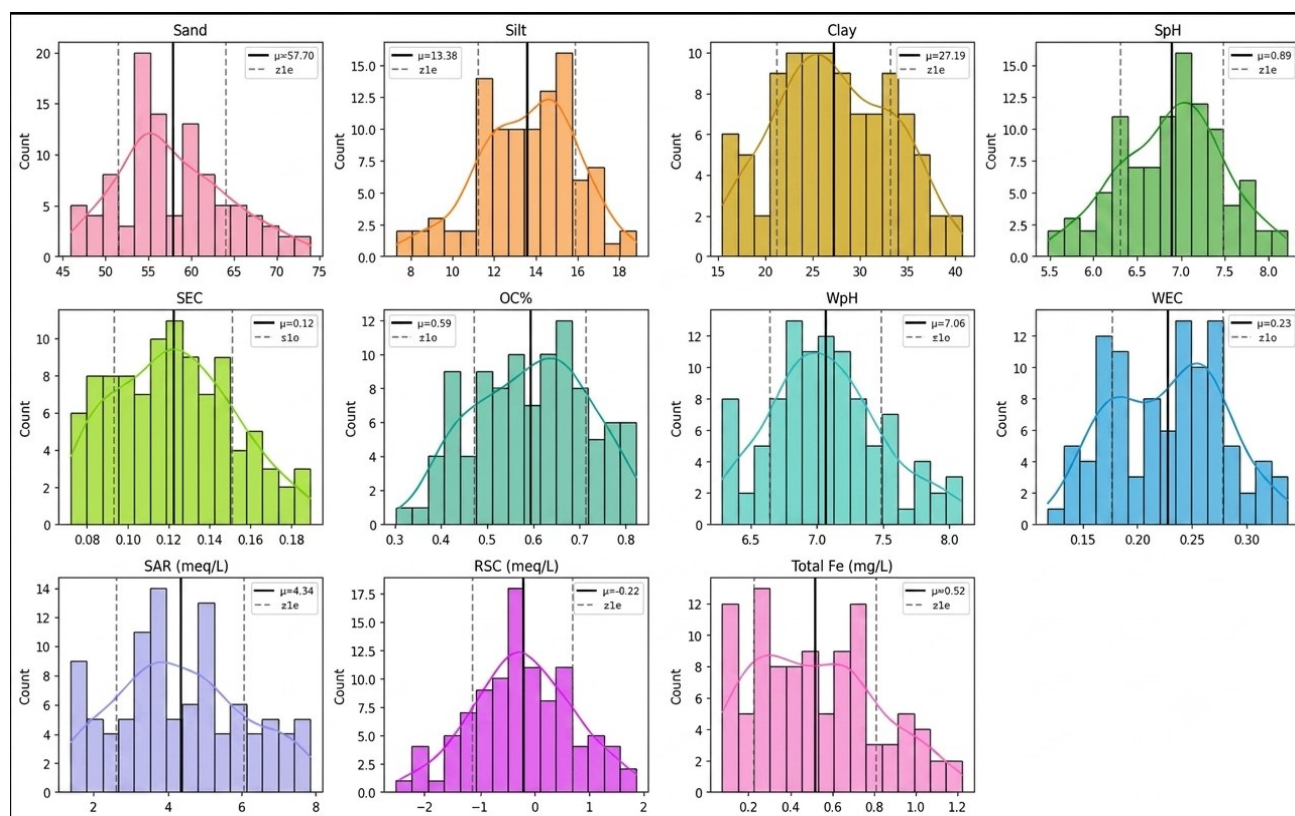


Fig. 2. Soil and water samples distribution in makhana growing areas in the Purnea East.

SpH: soil pH; SEC: soil electrical conductivity; OC: organic carbon; WpH: water pH; WEC: water electrical conductivity; SAR: sodium adsorption ratio; RSC: residual sodium carbonate; total Fe: total iron.

Table 1. Descriptive statistics of makhana growing areas of Purnea East

Parameters	Maximum	Minimum	Range	Standard deviation	Coefficient of variation
Silt + Clay (%)	54.96	25.96	40.91	8.89	21.73
Clay (%)	40.96	14.96	27.33	8.22	30.10
Silt (%)	21.00	7.00	13.58	2.64	19.47
Sand (%)	74.04	45.04	58.99	8.79	14.92
SpH	7.95	5.45	6.90	0.68	9.88
SEC	0.25	0.07	0.1165	0.03	31.51
OC (%)	0.87	0.285	0.60705	0.13	22.87
WpH	8.35	6.12	7.1095	0.45	6.45
WEC	0.34	0.113	0.23343	0.05	23.03
SAR (meq/L)	8.18	1.03	4.3271	1.76	40.78
RSC (meq/L)	1.90	-3.5	-0.2743	0.98	-359.71
Total Fe (mg/L)	5.84	0.28	1.8336	1.37	74.90

SpH: soil pH; SEC: soil electrical conductivity; OC: organic carbon; WpH: water pH; WEC: water electrical conductivity; SAR: sodium adsorption ratio; RSC: residual sodium carbonate; total Fe: total iron.

(meq L⁻¹) and total Fe (mg L⁻¹) deviated significantly from normality ($p \leq 0.05$), while silt, clay, SpH, soil electrical conductivity (SEC), OC, WpH, WEC and RSC did not normality ($p < 0.05$) (Fig. 2). Overall, 73 % of the observations satisfied the normality assumption, while the remaining variables required distribution-free methods to maintain Type I error rates at the nominal 5 % level. This finding confirmed that the data for each parameter did not exhibit significant deviations from normality. Moreover, the normal distribution of these variables suggests that the sampling and measurement processes were consistent and reliable, thereby mitigating concerns regarding skewed data or outliers that could potentially bias the results of the study. These results enhanced the validity of any inferences made concerning soil texture, chemical properties and related environmental factors in the study area.

In addition, soil texture analysis indicated that the soils were predominantly sandy loam to sandy clay loam, with sand being the dominant fraction. Higher silt and clay were observed in low-lying areas due to deposition by floodwaters and rainfall. Sand content ranged from 45.04–74.04 %, while silt content varied between 7.0 % and 21.0 % (Fig. 3a). These findings are consistent with previous studies conducted in the semi-arid East Asian steppe (29, 30). Some high-elevation areas also showed high clay content, possibly due to geological influences (31–34). Therefore, variations in soil texture may be attributed to both geomorphological processes and anthropogenic activities (35).

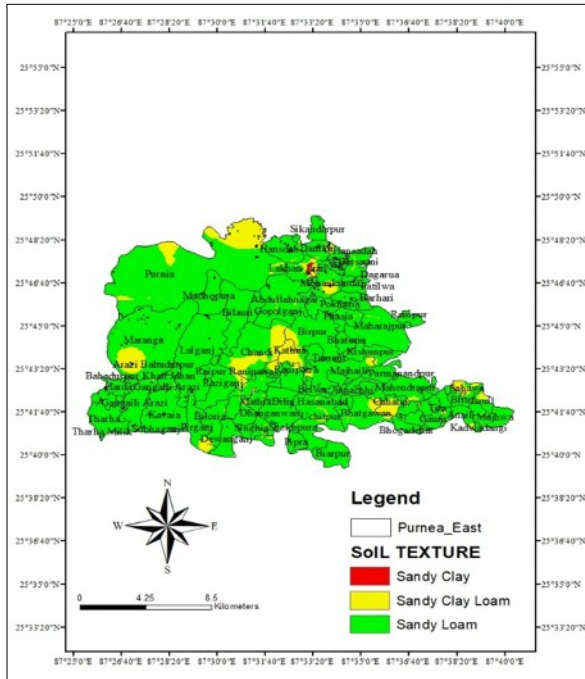
The physicochemical properties of the soils ranged from slightly acidic to alkaline, with pH values between 5.45 and 8.42. The highest soil pH in cultivated pond samples was 8.20 and the lowest was 5.45 (Fig. 3c). Most samples were neutral to slightly alkaline, favourable for makhana cultivation. These findings are consistent with earlier studies (36, 37), indicating that mineral composition and soil-water interactions influence pH variability and plant responses. The slightly higher pH observed in soil-water suspension than in soil may be attributed to NH₄⁺ and hydrolysable salts under reducing conditions, supporting the observation that makhana absorbs nitrogen in the ammonium form (38). Electrical conductivity (EC) values in pond soil samples ranged from 0.07 to 0.25 dS m⁻¹ (Fig. 3b), indicating a low salinity risk and corroborating previous findings (39, 40). Higher pre-monsoon EC values may result from increased evaporation, elevated temperatures, limited water availability and enhanced ion dissolution. Rainfall and runoff during post-monsoon likely contributed to lower EC values (41). Soil OC content, an important indicator of soil fertility, varied from 0.29–0.87 % (Fig. 3d).

These values are comparable to those reported in similar agro-ecological settings (42–44), highlighting the importance of OC-based soil assessment for agricultural planning and land-use management.

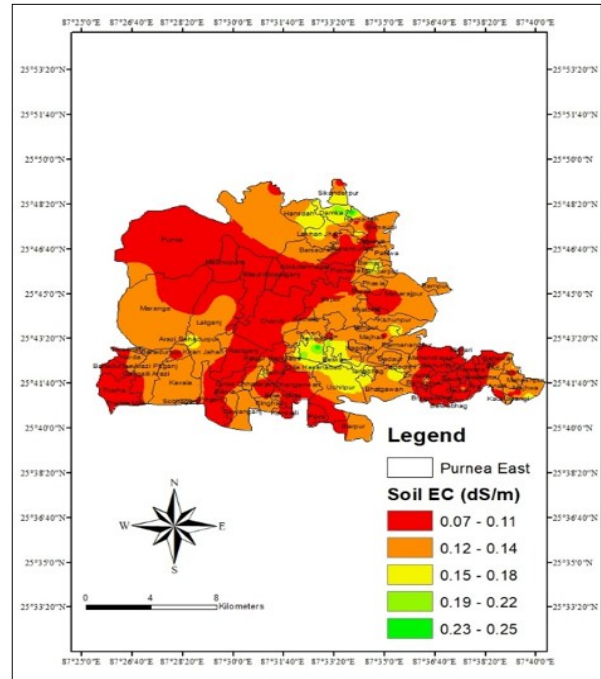
The water samples exhibited pH values ranging from 6.12 to 8.35 and EC values from 0.11 to 0.38 dS m⁻¹ (Fig. 3e, f). The SAR ranged from 0 to 10 meq L⁻¹, indicating suitability for makhana cultivation (Fig. 3g) with minimal sodicity-related constraints, similar to observations reported for palm groves in Southern Algeria (45). Carbonate (CO₃²⁻) concentrations ranged from 0 to 1 meq L⁻¹, bicarbonate (HCO₃⁻) concentrations from 0.78 to 4.35 meq L⁻¹ and RSC -1.37 to 1.86 meq L⁻¹. Water with RSC $\leq$ 1.25 meq L⁻¹ was suitable for irrigation, supporting makhana cultivation (Fig. 3h), consistent with GIS-based assessments (46). Seasonal variations showed increasing Ca²⁺, Mg²⁺, NH₄⁺ and K⁺ concentrations from March to June, while Na⁺ concentrations increased from July to September, reducing the availability of Ca²⁺ and Mg²⁺. The increase in calcium during summer may result from the oxidation of organic matter, whereas its decline during winter may be attributed to uptake by macrophytes and phytoplankton (47). Groundwater iron (Fe) ranged from 0.24–1.68 mg L⁻¹, surpassing the BIS limit of 0.3 mg L⁻¹ in most samples (48). Elevated Fe may originate from geological sources like ferric oxides and anthropogenic inputs from domestic effluents, industries and agriculture (49, 50). Similar studies in Baojixia, China, show deteriorating groundwater quality affects crop yields and causes economic losses (51).

Delineation of potential sites and suitability evaluation using analytic hierarchy process for makhana cultivation

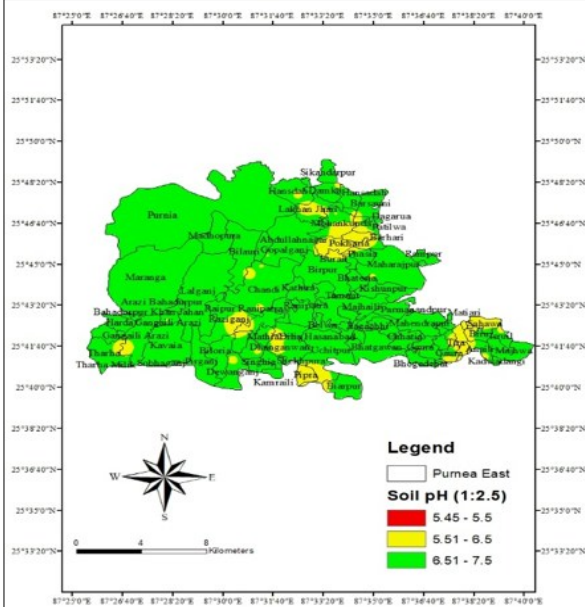
Criteria selection is crucial for maintaining consistency in the AHP model. Careful selection and clear definition of criteria are essential for ensuring consistent pairwise comparisons and reliable priority vectors. In AHP, consistency ensures the logical validity of pairwise comparisons. An inappropriate or excessively large set of criteria complicates the evaluation process, introducing subjective judgments and increasing the likelihood of inconsistencies. Well-defined, relevant and limited criteria help maintain coherence in judgments, thereby improving consistency ratios (CR) and enhancing model reliability. Irrelevant or overlapping criteria may lead to contradictions, causing the CR to exceed the acceptable threshold of 0.10 and necessitating re-evaluation. Techniques such as sensitivity analysis and consistency improvement methods can be employed to adjust criteria to restore consistency. The AHP analysis determined the relative importance of nine factors



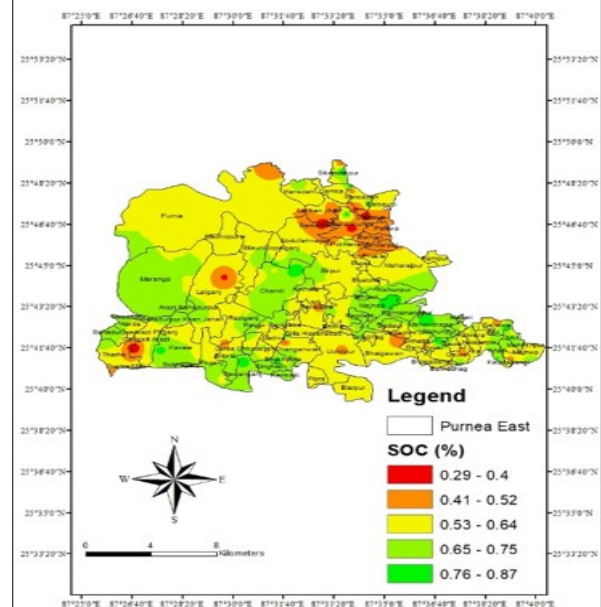
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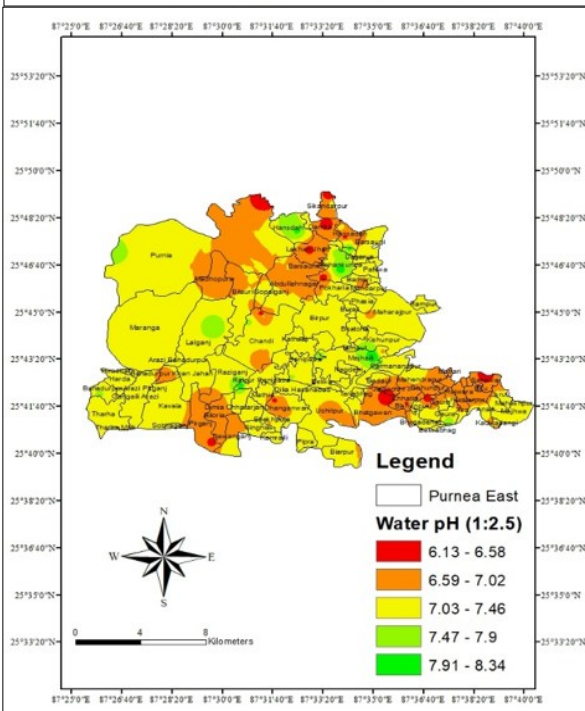
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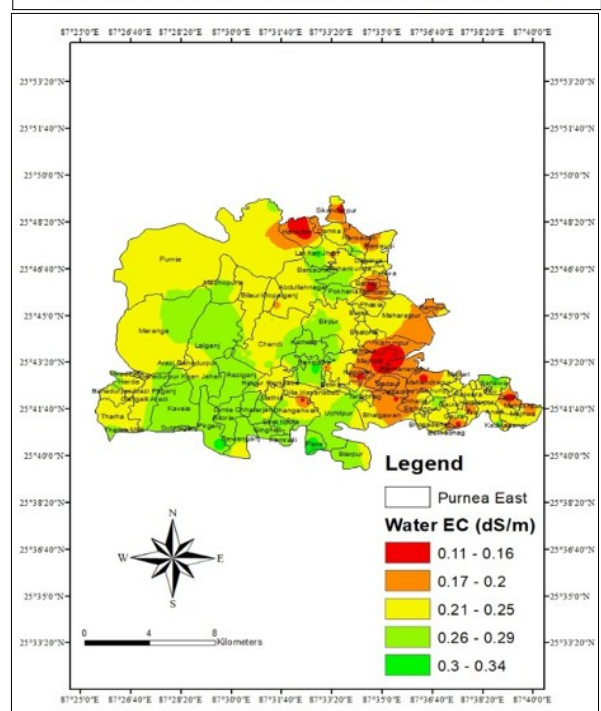
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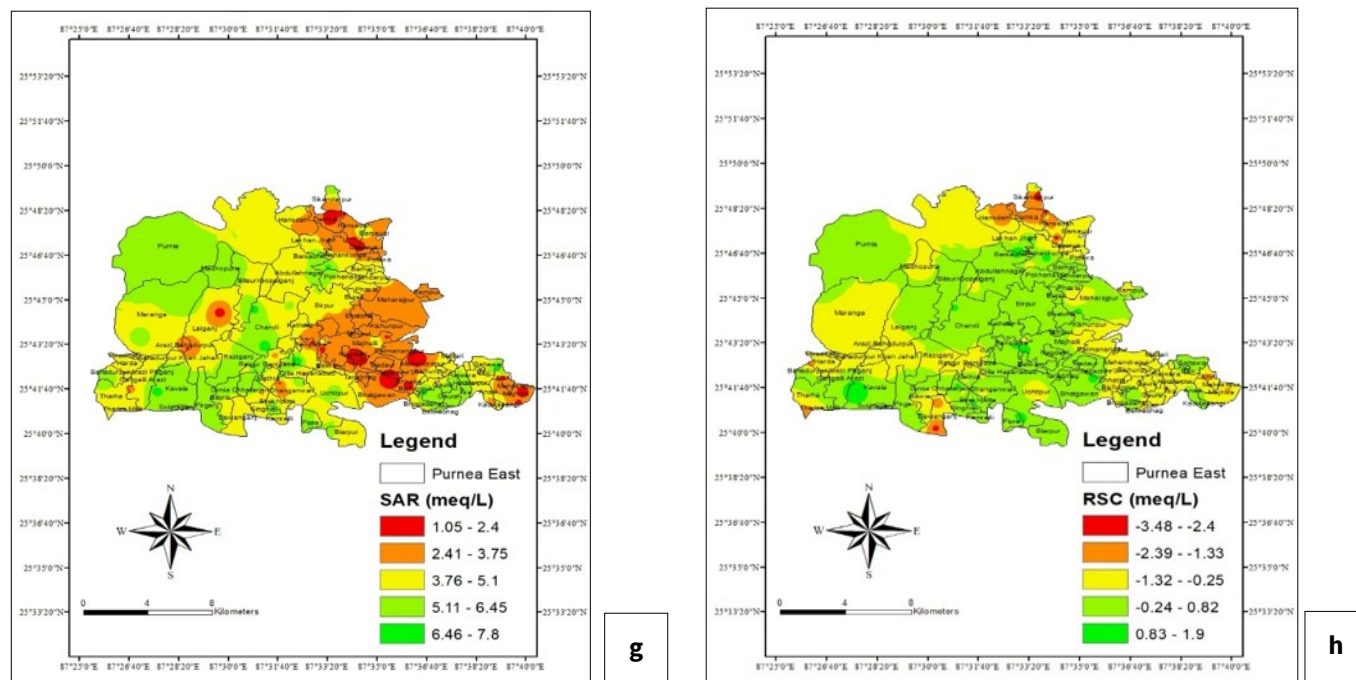


Fig. 3. Spatial map of (a) soil texture; (b) soil electrical conductivity; (c) soil pH; (d) Soil organic carbon; (e) water pH; (f) water electrical conductivity; (g) sodium adsorption ratio; (h) residual sodium carbonate. [Source: Makhana Development Scheme, RKVY, Bihar, Government.]

influencing makhana cultivation suitability: slope, soil texture, soil drainage, soil pH, OC, SAR, RSC, total Fe and land use. Among these, slope was identified as the most influential factor, followed by soil texture and soil pH, highlighting their dominant roles in suitability assessment.

Fig. 4 presents the assigned and normalised ranks for each variable, highlighting their relative significance in the suitability assessment. For the suitability classes (rank 0–5), the 0–1 interval exhibited the highest normalised rank (0.33), indicating its predominant influence, whereas the 4–5 interval showed the lowest rank (0.08). Among soil texture classes, sandy clay loam was the most significant (0.50), followed by sandy clay (0.33) and sandy loam (0.17). For soil drainage, well-drained soils received the highest rank (0.40), while moderately drained, excessively drained and imperfectly drained soils exhibited lower ranks. Regarding soil pH, the ranges of 7.1–7.5 and >7.5 had the highest rank (0.29), whereas lower pH ranges had equal but lower ranks (0.14). For OC (%), content >0.75 % were the most influential (0.50), followed by 0.5–0.75 % (0.33) and <0.50 % (0.17). In the case of SAR, the 0–10 meq/L range was the most significant (0.38), while higher SAR ranges were less influential, particularly values >26 meq/L (0.12). For residual sodium carbonate (RSC), values <1.25 meq/L had the highest rank (0.50), whereas higher values were assigned progressively lower ranks. Total iron (Fe, mg/L), the concentration of 1–2 mg/L was most influential (0.50), whereas lower concentrations (<0.3 and 0.3–1 mg/L) had lower ranks (0.25). Land use/land cover (LULC), waterbodies had a higher rank (0.67) than makhana cultivation (0.33), suggesting a stronger influence. Overall, variables with higher ranks are more critical, with texture, drainage, OC, RSC and LULC showing strong influences.

Fig. 5 and 6 present the pairwise comparison matrix for the selected parameters using AHP. The model exhibited acceptable consistency, with a CR of 0.064, which was below the acceptable threshold of 0.10. The maximum eigenvalue ($\lambda_{\max}$) was 9.685, with a consistency index (CI) of 0.098 and a random index (RI) of 1.450, resulting in a CR of 0.098, meeting Saaty's criterion. The priority

vector indicated slope (26.82 %) and soil texture (20.96 %) as most influential, while land use (2.44 %) had the least impact. Other factors like total Fe (4.91 %), SAR (5.70 %) and RSC (5.70 %) had lower weights, suggesting less influence on suitability. This ranking supports land-use planning and agricultural decision-making, prioritising key factors for makhana cultivation. Similar findings appear in previous studies using AHP in MCE-GIS frameworks for crop suitability, urban land evaluation and resource planning (52, 53).

Fig. 7 and 8 illustrate the spatial classification of land suitability for makhana cultivation in the Purnea East Block based on the AHP model. These suitability categories were derived by considering factors such as soil quality, topography and climate and water availability. Areas labelled as “highly suitable” offer optimal conditions for growing crops, requiring minimal inputs or interventions. Regions identified as “moderately suitable” have certain constraints that can be mitigated with moderate input or adjustments. “Marginally suitable” areas face significant obstacles that impede productivity or increase risk, often requiring more intensive management or the choice of less demanding crops. This classification supports land use planning, resource allocation and agricultural development strategies to boost productivity and sustainability. The results indicated that potential sites of makhana growing areas were identified after overlaying all nine parameters and the results showed that 1826 ha (7.24 %) occurred as makhana growing areas, covering most parts of Purnea East. The AHP-based suitability assessment revealed that 480.23 ha (26.30 %) of the makhana growing areas were highly suitable (S_1), 846.53 ha (46.36 %) were moderately suitable (S_2) and 422.90 ha (23.16 %) were marginally suitable (S_3), whereas 73.77 ha (4.04 %) and 2.556 ha (0.14 %) were classified as currently unsuitable (N_1) and permanently unsuitable (N_2) categories, respectively.

These findings indicate substantial potential for expanding makhana cultivation through appropriate land and water management practices. Similar results have been reported in studies that integrating fuzzy AHP and ordered weighted averaging

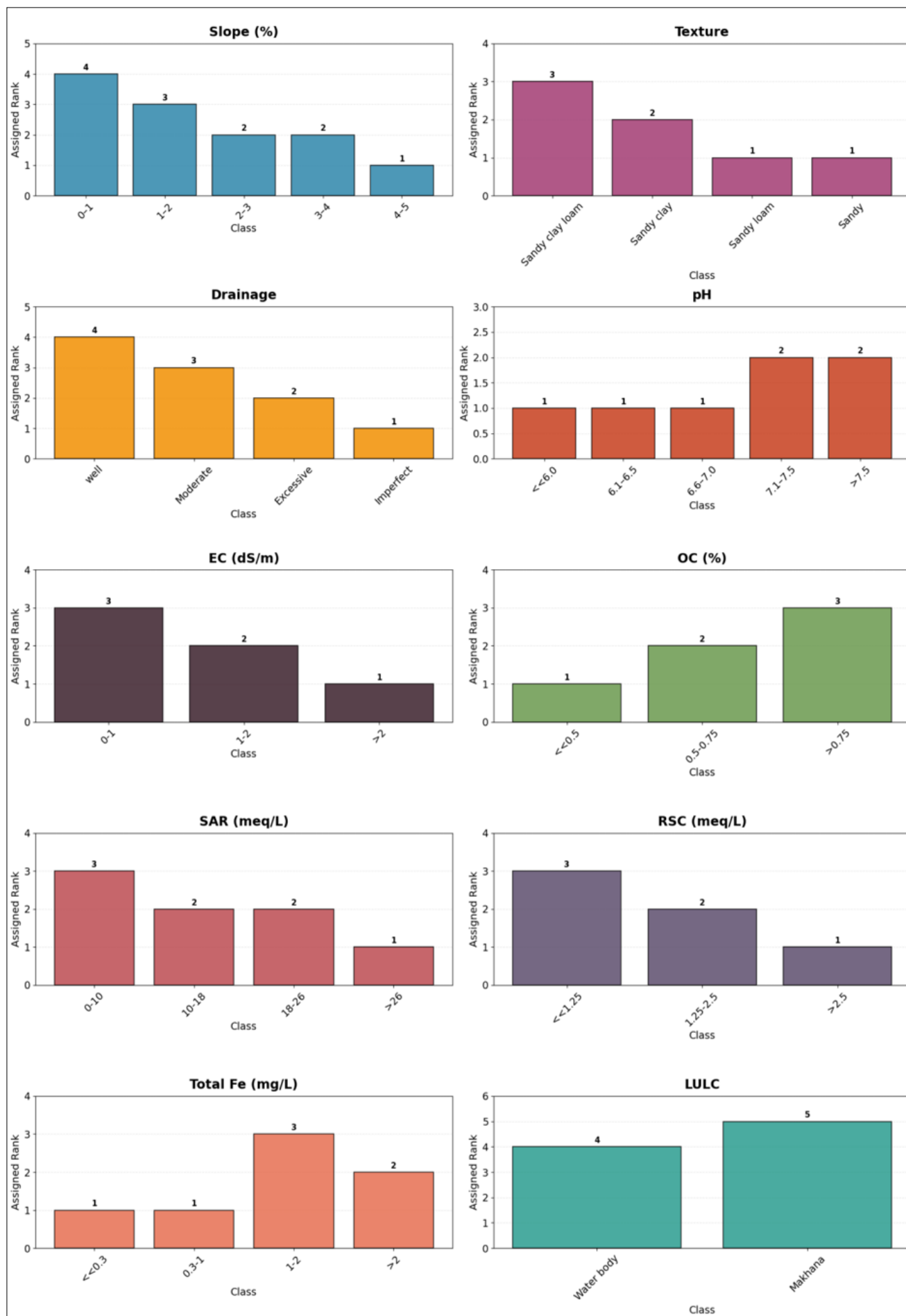


Fig. 4. Ranking of soil, water and land use/land cover for evaluate the soil suitability areas for makhana.

EC: electrical conductivity; OC: organic carbon; SAR: sodium adsorption ratio; RSC: residual sodium carbonate; total Fe: total iron; LULC: land use/land cover.

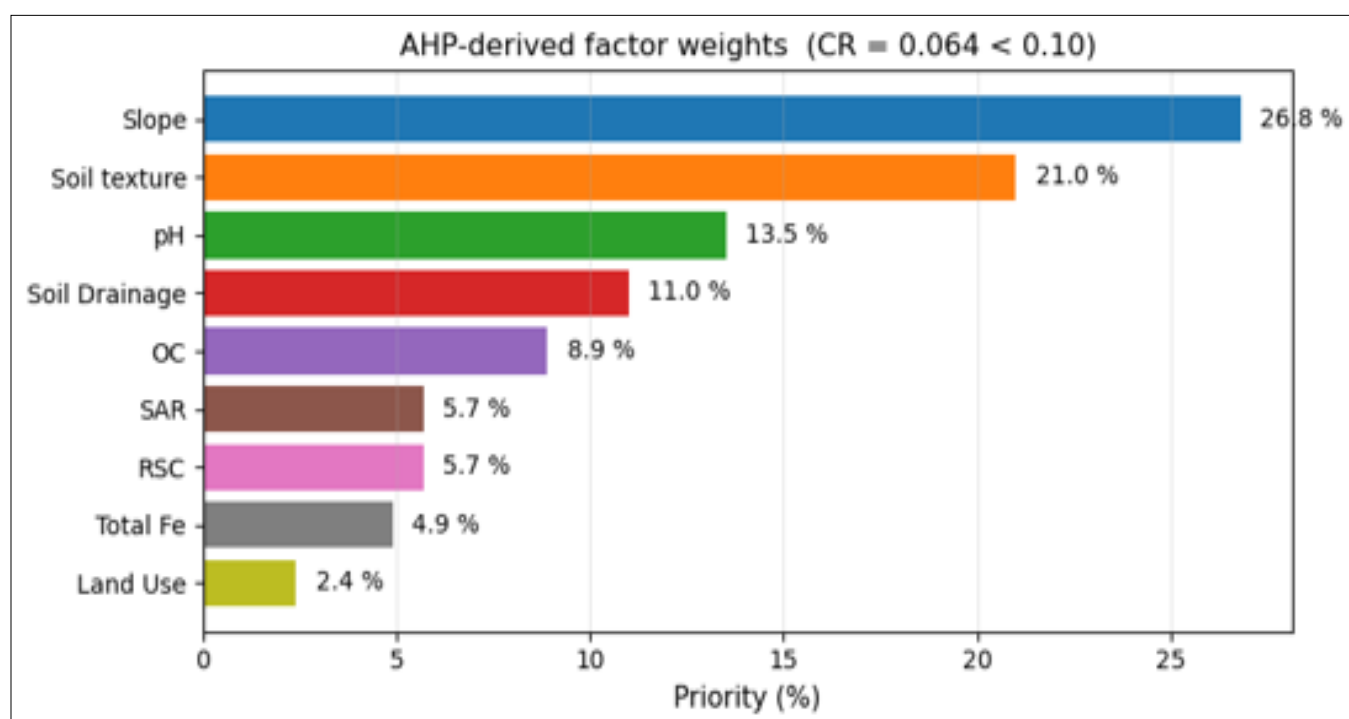
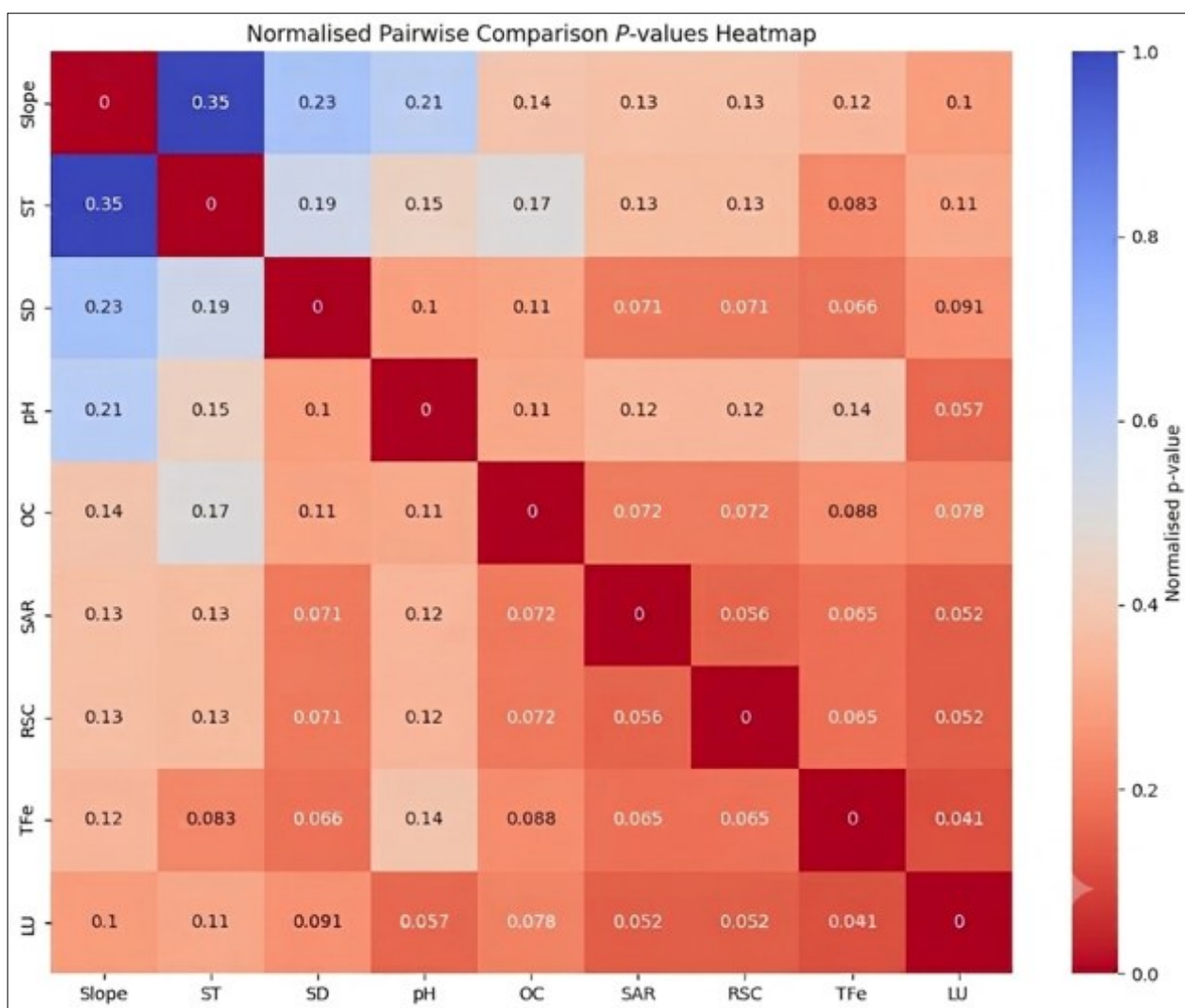


Fig. 5. Normalised pair-wise comparison and analytical hierarchy process derived factor to evaluate the soil suitability model of the test crop.

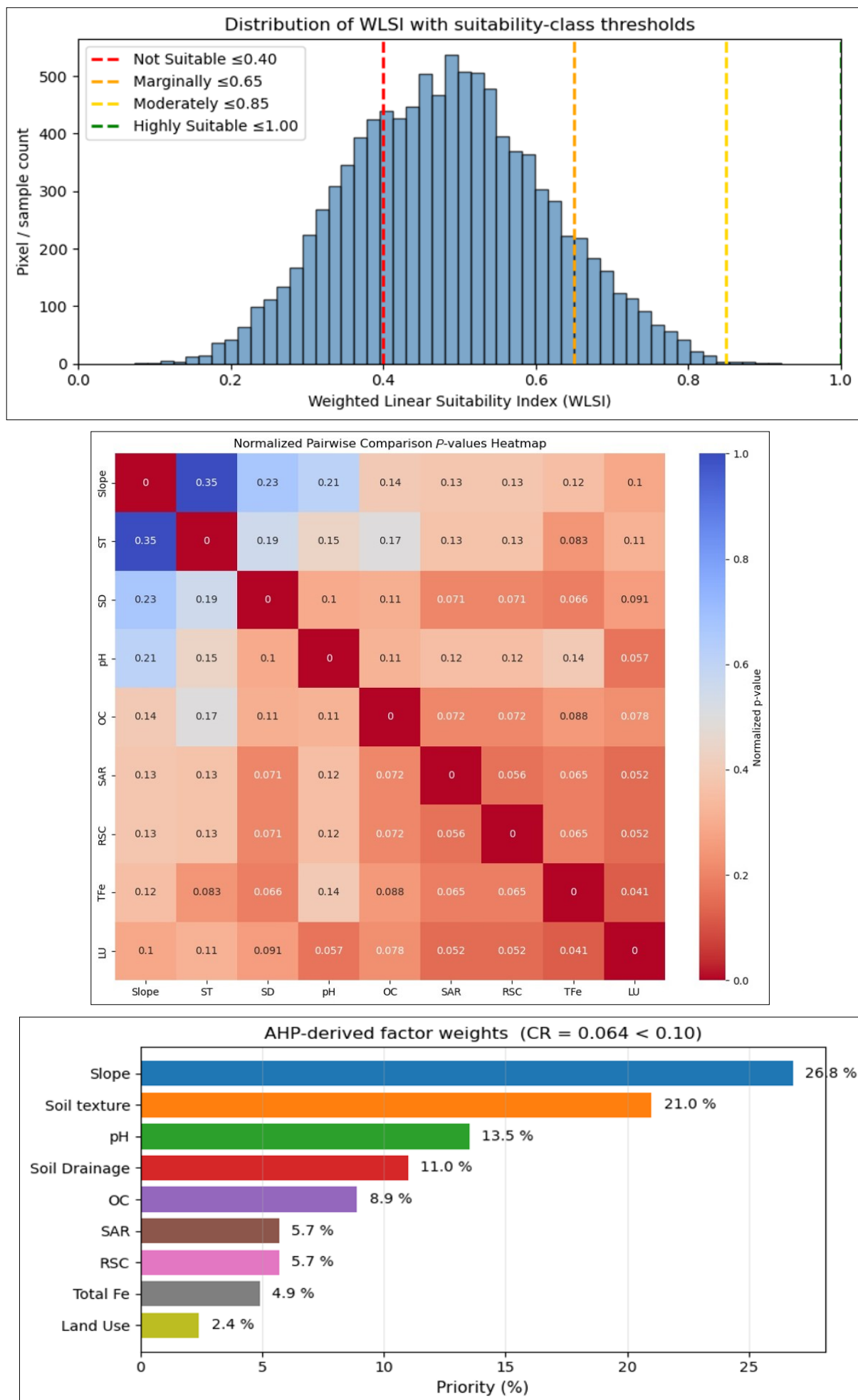


Fig. 6. Weighted linear suitability index to validate the soil suitability model.

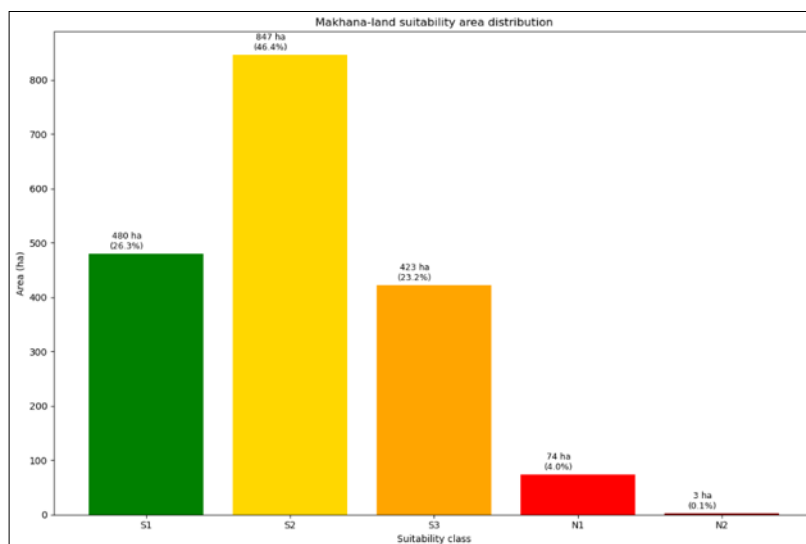


Fig. 7. Area wise distribution of soil suitability of makhana growing areas.

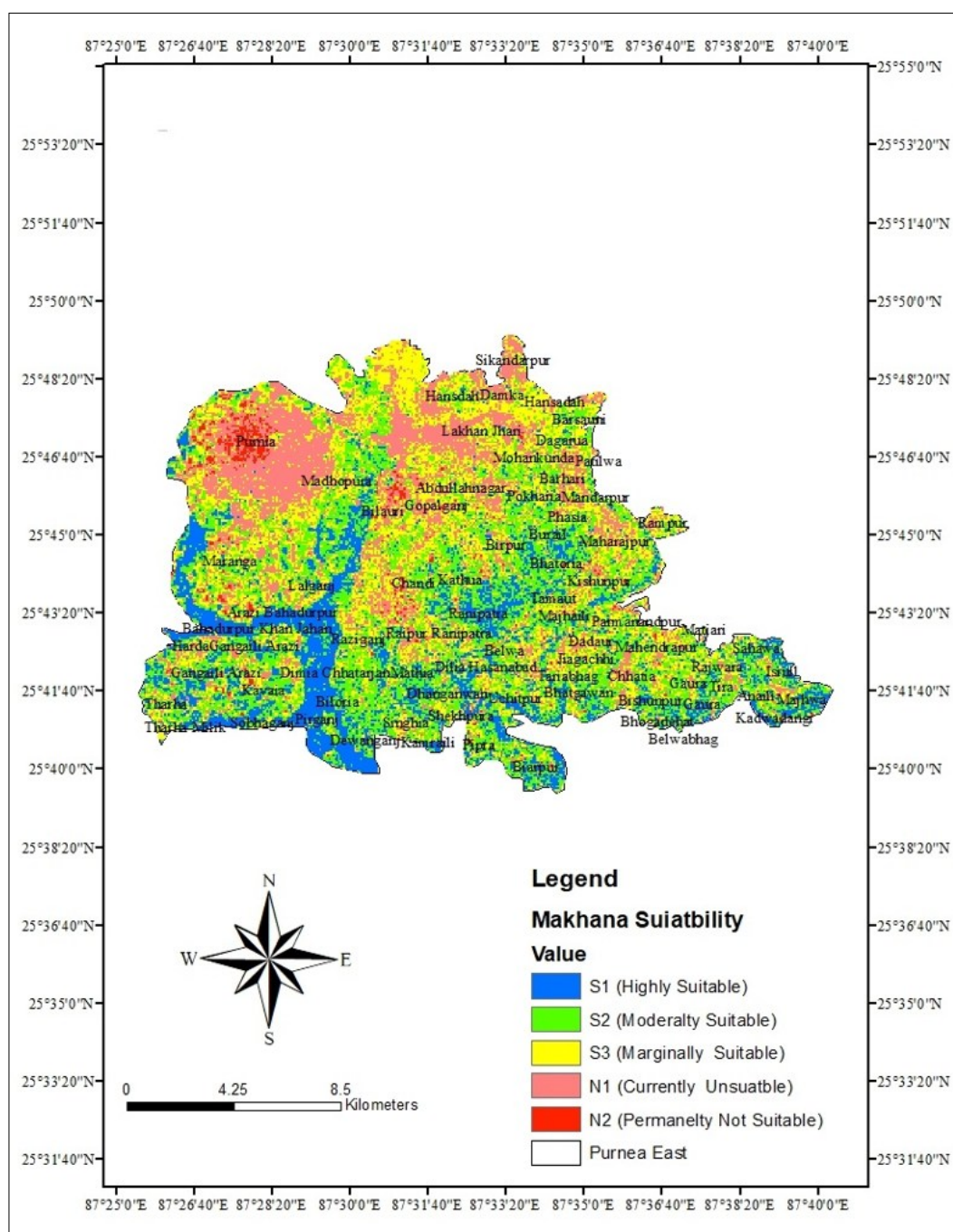


Fig. 8. Final suitability map of makhana growing areas of the study areas. [Source: Makhana Development Scheme, RKVY, Bihar, Government.]

(OWA) techniques to enhance decision-making processes (54–56). Overall, the majority of the study area was classified as moderately to highly suitable, with only a limited portion deemed unsuitable for makhana cultivation.

Limitations

Despite the robustness of the integrated MCE-GIS approach, certain limitations of this study should be acknowledged. The suitability assessment was based on a limited number of soil and groundwater samples, which, although spatially distributed, may not fully capture the micro-scale heterogeneity in soil and water quality across the study area. In addition, the analysis primarily relied on static environmental parameters and did not explicitly incorporate seasonal variability in hydrology, nutrient dynamics or water depth, all of which are important factors influencing makhana growth in wetland ecosystems.

The weighting of criteria using the AHP involves expert judgment, which may introduce a degree of subjectivity, despite acceptable CR. Furthermore, socioeconomic factors such as market accessibility, farmers' management practices and economic feasibility were not included in the suitability framework, although these factors may influence the practical adoption of makhana cultivation in the identified zones. Finally, the delineated suitability zones were not validated through field-based yield assessments; therefore, on-ground performance may vary under actual farming conditions.

Conclusion

This study highlights the critical role of soil and groundwater characteristics in determining the site suitability for makhana (*Euryale ferox* L.) cultivation in the Purnea East Block of Northern Bihar. Soil and water analyses revealed textures ranging from sandy loam to sandy clay loam, with pH levels from slightly acidic to alkaline, favourable for makhana growth. Groundwater quality varied, with iron levels exceeding limits in some samples, indicating a need for targeted irrigation strategies. Land use assessments showed that 7.24 % of the area was under makhana cultivation, with 42.56 % nearly level land, indicating expansion potential with proper management. Integrating soil, water, topographic and land use data using a geographic information systems (GIS)-based multi-criteria approach effectively identified potential cultivation zones. These GIS outputs inform recommendations by pinpointing areas for optimising makhana cultivation, thereby enabling stakeholders to prioritise resources and tailor interventions. Decision-support tools, such as the analytical hierarchy process (AHP), strengthen this framework by providing a systematic basis for site suitability and crop planning in wetland agriculture. The identified suitability zones can assist farmers, extension agencies and policymakers to enhance land-use efficiency, improve makhana productivity and sustainably manage flood-prone landscapes. By linking geospatial analysis with management practices, this study provides a practical framework for expanding makhana cultivation while addressing environmental constraints and supporting informed decision-making and optimised agricultural development in the region.

Future study

Furthermore, the methodological framework developed in this study can be extended to other aquatic and wetland crops with similar ecological requirements, thereby supporting regional

agricultural planning and sustainable land management. Future research should focus on the field-level validation of the identified suitability zones, assessment of crop performance under varying water and nutrient regimes and evaluation of climate change impacts, particularly altered rainfall patterns and flooding dynamics, on the long-term sustainability of makhana cultivation in Northern Bihar.

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Authors' contributions

SK designing of experiments, carried out the field experiment and drafted the manuscript. PKY, RK, AK¹, PN and RP conceptualisation of research and helpful for research work. KPS, JV and AK² analysis of the data and interpretation and preparation of the final manuscript. All authors have read and approved the final manuscript. [AK¹ - Anil Kumar and AK² - Anil Kumar.]

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During the preparation of this work the authors used Kimi ai used for code extraction using Python 3.14.4. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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