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ORIGINAL RESEARCH ARTICLE

The impact of environmental, economic, and social sustainability under intensive agriculture

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ABSTRACT

BACKGROUND AND OBJECTIVES: Intensive agriculture has substantially increased agricultural productivity but is increasingly associated with environmental degradation, resource depletion, and socio-economic challenges. The study objectives were to evaluate the sustainability impacts of intensive agricultural practices across environmental, economic, and social dimensions in Namakkal district, Tamil Nadu, India, with particular emphasis on resource utilization, ecological stress, and the factors influencing sustainable agricultural development.

METHODS: Primary data were collected during 2025 from 663 eligible farmers selected through multistage stratified random sampling across eight taluks of Namakkal District using a structured questionnaire. Farms were classified as traditional or intensive based on cultivation practices. Relationships among the study variables were examined using correlation analysis, analysis of variance, regression analysis, and non-parametric statistical tests.

FINDINGS: The findings revealed a strong positive relationship between landholding size and family size (correlation coefficient = 0.7214), indicating close structural and demographic linkages within farming systems. Intensive agriculture was significantly associated with land expansion (correlation coefficient = 0.658), environmental pollution (correlation coefficient = 0.519), and declining health conditions among farming communities (correlation coefficient = 0.412). Approximately 63 percent of respondents reported land degradation, while 65 –78 percent reported salinity and nutrient depletion, reflecting perceived ecological stress. The regression model explained 7.1 percent of the variation in agricultural production (coefficient of determination = 0.071), indicating modest explanatory power. Questionnaire reliability was satisfactory (Cronbach's alpha = 0.824), supporting the internal consistency of the survey instrument.

CONCLUSION: Intensive agriculture is associated with higher short-term agricultural productivity but is also associated with environmental degradation, increases health risks, and places greater pressure on natural resources. These findings may inform strategies to improve the environmental, economic, and social dimensions of agricultural sustainability through sustainable soil management, balanced agrochemical application, efficient irrigation, and policy support. While the study is limited to a single district and cross-sectional data, it provides empirical evidence to inform future longitudinal and multi-regional investigations.

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INTRODUCTION

Agriculture plays a crucial role in driving the economic growth and overall prosperity of a nation, particularly in India where nearly two-thirds of the population depends on it for livelihood despite ongoing structural changes in the economy. The agricultural sector is a major contributor to gross domestic product (GDP) and employment while ensuring food security and supplying raw materials to agro-processing, textile, and other agro-based industries. Its role extends beyond production, as it sustains rural livelihoods, promotes regional development, and contributes to environmental, social, and economic sustainability (Bathaei and Štreimikienė, 2023). The concept of sustainable development itself has long been subject to critical scrutiny regarding its definition, scope, and operational boundaries (Lélé, 1991), and bibliometric evidence confirms a growing body of global research adopting the environmental, economic, and social sustainability (triple bottom line) framework to evaluate sustainability outcomes. Increasing population pressure has intensified food demand, challenging agriculture to increase productivity while minimizing environmental degradation. However, conventional farming has caused ecological stress through excessive chemical inputs, groundwater depletion, and soil degradation. Declining agricultural growth directly affects GDP, employment, and poverty, destabilizing the national economy (Kaur, 2014). Indian agriculture faces major challenges despite growth opportunities. Financial constraints, market uncertainty, and economic reforms have increased farmer vulnerability and distress, including suicides (Mariappan and Zhou, 2019). Environmental concerns linked to chemical-intensive farming practices have been widely documented, particularly the degradation caused by excessive fertilizer use and the need for region-specific sustainable alternatives (Rosas Baños and García Salazar, 2026). Sustainability research emphasizes balancing natural resource use with productivity growth through increased cropped area, cropping intensity, and efficiency (Mózner *et al.,* 2012). Broader reviews of agricultural sustainability concepts and assessment methods further reinforce the multidimensional and evolving nature of these frameworks (Lampridi *et al.,* 2019). Further studies highlight India's broader sustainability challenges, including fragmented landholdings, climate change, technological gaps, and policy inefficiencies (Kareemulla *et al.,* 2017; Das *et al.,* 2020). At the micro level, studies in the district show crop diversification driven by profitability and market conditions, with shifts from tapioca to sorghum and maize. Extension services improve productivity and land use, while sustainability assessments emphasize integrated farm planning and resource optimization (Ramasubramaniyan *et al.,* 2016). Policy research also highlights sustainable input distribution, particularly biofertilizers, for long-term agricultural viability. Most previous research has examined environmental, economic, and policy aspects independently, with limited integration across these dimensions. Limited research integrates socio-economic factors, production intensity, and environmental degradation using large-scale primary data at the district level (Mózner *et al.,* 2012). Few studies also examine how government support interacts with farming intensity or assess environmental, economic, and social sustainability within a unified framework. Accordingly, this study adopts the triple bottom line framework, evaluating environmental (soil quality, pollution, and resource use), economic (cultivated area, production, income, and input use), and social (household characteristics, family labour, health, and institutional support) dimensions using primary data from 663 farmers. A key contribution of this research is the combined assessment of socio-economic, environmental, and production-related aspects of intensive agriculture using a single analytical approach. Using multiple established statistical methods, the study examines relationships between agricultural

intensity and sustainability outcomes, providing empirical evidence to support balanced agricultural planning and policy development (Rockström *et al.,* 2017; Ologunde and Nunes, 2026). Unlike previous studies that addressed these dimensions separately, this research integrates them within a district-level assessment. The environmental concerns associated with intensive agriculture, including soil degradation and excessive fertilizer use, are well documented (Lampridi *et al.,* 2019; Das *et al.,* 2020). This integrated approach addresses the limited availability of comprehensive empirical evidence from intensively cultivated regions such as Namakkal District. Integrated strategies combining policy support, efficient resource management, and eco-friendly farming are essential for long-term agricultural sustainability. Accordingly, this study evaluates the environmental, economic, and social dimensions of agricultural sustainability using the triple bottom line framework. The aims of the study are as follows: i) to analyze the socio-economic characteristics of farmers and evaluate the role of government support and policy interventions in promoting sustainable agricultural practices; ii) to examine the relationship between intensive agricultural practices and agricultural productivity, with particular emphasis on fertilizer, pesticide, and irrigation use; and iii) to assess farmers' reported environmental conditions associated with intensive farming and identify potential strategies for improving agricultural sustainability. This study was carried out at SRM Institute of Science and Technology, Chennai, Tamil Nadu, India, during 2025.

MATERIALS AND METHODS

Study area and research design

The study was conducted in selected talukas of an intensive agricultural region with high input use and diversified cropping systems, making it suitable for assessing agricultural sustainability (Bathaei and Štreimikienė, 2023). A descriptive and analytical research design was adopted to evaluate the environmental, social, and economic dimensions of sustainability (Kaur, 2014). Primary data on farming practices, resource use, input management, and institutional support were analyzed to examine the relationship between agricultural intensification and sustainability outcomes.

Sampling design

A multistage stratified random sampling technique was used to select respondents from Namakkal District, Tamil Nadu (11°00′–11°36′ N, 77°28′–78°30′ E). The district has a semi-arid tropical climate, receiving approximately 850–900 mm of annual rainfall and an average annual temperature of 28–30 °C. Intensive cultivation of tapioca, maize, sorghum, groundnut, and other field crops, supported by canal, tank, and groundwater irrigation, provides a suitable setting for assessing intensive agricultural systems. A pilot survey involving 40 farmers (approximately 6% of the final sample) was conducted to validate the questionnaire. The final sample of 663 farmers was determined using the Slovin method. Sampling involved three stages: selection of eight taluks (Namakkal, Rasipuram, Tiruchengode, Paramathivelur, Kolli Hills, Sendamangalam, Kumarapalayam, and Mohanur), identification of farmers from 454 villages, and proportionate random selection of respondents. Only farmers actively engaged in cultivation and farm management were included, ensuring representative coverage across farm categories and geographical areas of the district (Etikan and Bala, 2017).

Data collection procedure

Primary data were collected through a structured questionnaire administered to farmers in the selected villages. A total of 700 farmers were approached during the survey, of whom 20 farmers declined participation and 17 responses were excluded due to incomplete information.

Finally, 663 valid responses were considered for analysis, resulting in a response rate of 94.7%. The sampling approach ensured adequate representation of both traditional and intensive cultivation systems, classified based on farming practices such as fertilizer and pesticide use, irrigation intensity, cropping frequency, and cultivation characteristics, thereby capturing variability in agricultural practices and sustainability outcomes across the study area (Goswami *et al.,* 2017; Kareemulla *et al.,* 2017). The questionnaire was administered through field surveys among farmers practicing diverse cropping and irrigation systems. Responses covered farming practices, input use, environmental perceptions, production activities, and government support. The survey was designed to ensure clear, complete, and locally relevant information for assessing the environmental, economic, and social dimensions of agricultural sustainability.

Data type and variables

Both general and specific categories of data were collected to ensure a holistic understanding of agricultural systems. General data included demographic characteristics of farmers, such as age, education, gender, family structure, farming system classification, cropping intensity, and environmental perceptions related to agriculture. These variables were used to assess the socio-economic and structural characteristics of farming households, including crop output, input costs, total production value, and net farm income. They also provided information on economic performance, productivity, and input–output relationships under intensive and traditional farming systems (Mariappan and Zhou, 2019; Bobitan *et al.,* 2023).

Data processing and presentation

After data collection, all responses were systematically coded, categorized, and organized for analysis. The data were structured into tables to facilitate classification and comparison across different variables of agricultural sustainability. In addition, bar charts were used to visually represent key agricultural indicators, enabling clear interpretation of trends in farming practices, Bar charts were used to visually present key agricultural indicators, enabling clear interpretation of trends in farming practices, input usage, and sustainability-related outcomes (Rani *et al.,* 2021). This structured presentation ensured effective summarization of complex datasets and supported further statistical analysis and interpretation of relationships among environmental, social, and economic variables.

Development of research instrument

A structured questionnaire was developed based on the research objectives and sustainability framework to collect primary data on agricultural practices. It covered crop cultivation, crop rotation, pest management, organic farming, soil and water management, fertilizer and pesticide use, biodiversity conservation, energy use, socio-economic characteristics, awareness, government support, farming constraints, and future farming intentions. It provided comprehensive coverage of the environmental, economic, and social dimensions of agricultural sustainability (Mariappan and Zhou, 2019).

Questionnaire development and validation

A structured questionnaire was developed based on the study objectives and the agricultural sustainability framework. The questionnaire collected primary data on socio-economic characteristics, farming practices, environmental impacts, institutional support, and production factors. It was developed based on relevant literature and adapted to the agricultural conditions of Namakkal District. Subject experts reviewed the instrument to ensure content validity and clarity. A pilot survey was conducted to assess and improve the wording and sequence of the questions. The final questionnaire covered the key dimensions of agricultural sustainability. Construct validity was established by aligning the

variables with the sustainability framework, and internal consistency was confirmed using Cronbach's alpha (α) before statistical analysis (Parihar *et al.,* 2015; Mariappan and Zhou, 2019; Scheper *et al.,* 2023).

Questionnaire structure

The structured questionnaire was developed to collect primary data on socio-economic, farm-level, environmental, institutional, and production-related aspects of agriculture in the study area, ensuring comprehensive coverage of sustainable farming dimensions.

Personal information

Variables such as gender, qualification, age, number of family members involved in cultivation, and status of employment level in the family were collected to understand the socio-economic characteristics of farmers (Mariappan and Zhou, 2019).

Environmental impact

Environmental variables included characteristics of air, water, and soil affected by cultivation, loss of health standards due to intensive cultivation, loss of productivity of cattle and biodiversity, harmful chemical impacts on land quality, human health, cattle and biodiversity, and substitutes for chemical fertilizers and pesticides (Parihar *et al.,* 2015).

Government and institutional support

Variables included fiscal incentives from government budg*et a*llocations and institutional support mechanisms to manage environmental impacts of intensive cultivation (Ramasubramaniyan *et al.,* 2016).

Production and innovation

The indicators included increased land productivity from intensive cultivation, willingness to pay compensation for pollution, adoption of bio-fertilizers and bio-pesticides, ability to maintain production using eco-friendly inputs, soil nutrient depletion, soil quality deterioration, and the younger generation's interest in technology-driven and innovative farming practices (Scheper *et al.,* 2023). Table 1 presents the questionnaire components structured based on the study framework, covering the key dimensions of personal information, farm characteristics, environmental impacts, government and institutional support, and production and innovation aspects of agricultural practices.

Measurement scale, coding procedure, and reliability assessment

Environmental impact, government and institutional support, production and innovation, and farmers' sustainability perceptions were assessed using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), where higher scores indicated stronger agreement. A pilot study involving 40 farmers from marginal, small, medium, and large farm categories was conducted to assess the clarity and suitability of the questionnaire. Responses were numerically coded before statistical analysis. Categorical variables (gender, education level, farming category, cultivation system, and irrigation pattern) were coded according to their response categories, whereas continuous variables (age, cultivated area, production, income, and input usage) were recorded in their original values. Likert-scale responses were coded from 1 to 5, and composite construct scores were calculated by averaging the corresponding item responses to ensure consistency across measures and facilitate subsequent statistical analysis and interpretation. The internal consistency and reliability of the measurement scale were assessed using the α coefficient. The overall reliability value (α = 0.824) indicated satisfactory internal consistency among the questionnaire items. Reliability was evaluated before statistical analysis to ensure the consistency and suitability of the measurement instrument for capturing the intended constructs and supporting subsequent empirical analysis of the study.

Table 1: Questionnaire components based on study framework

Section	Variables included (from study instrument)
Personal Information	Gender, qualification, age, number of family members involved in cultivation, status of employment level in the family.
Farm Characteristics	Total area of cultivation, type of land pattern, crop pattern (major and minor crops), irrigation pattern, traditional vs. intensive cultivation, annual income
Environmental Impact	Air, water, soil characteristics affected by cultivation, health impacts, livestock productivity loss, biodiversity loss, harmful chemical effects, substitutes for fertilizers and pesticides.
Government and Institutional Support	Fiscal incentives from government budget, institutional support for environmental management in intensive cultivation.
Production and Innovation	Increase in production, willingness to pay compensation for pollution, production using bio-fertilizers, willingness to switch to bio-inputs, soil nutrient depletion, youth technological adoption.

Sustainability challenges framework

The sustainability of the agricultural sector is shaped by interrelated environmental, social, and economic constraints that collectively influence farming systems and long-term productivity outcomes (Mariappan and Zhou, 2019; Scheper *et al.,* 2023). In this context, a structured framework of challenges has been developed to better understand the multidimensional pressures affecting agriculture in the study region, as presented in Table 2. Table 2 shows that environmental degradation in agriculture is mainly associated with soil erosion, resource depletion, and chemical pollution, reducing ecosystem health and agricultural productivity. Social challenges such as unemployment, migration, and labour shortages increase the vulnerability of farming communities. Economic challenges, including indebtedness, limited market access, and low livelihood security, reduce agricultural resilience. These findings highlight the need for integrated strategies that improve environmental, social, and economic sustainability.

Environmental assessment indicators

Environmental indicators were evaluated using farmers' perceptions and field observations collected through a structured questionnaire rather than laboratory or instrumental measurements. The survey captured farmers' perceptions of soil quality, land degradation, salinity, water quality, contamination, climatic variation, and the environmental effects of intensive farming. Particular emphasis was given to fertilizer use and its perceived effects on soil and water resources. These perception-based indicators were used to evaluate the environmental impacts of intensive agricultural practices within the study area (Ju *et al.,* 2007). The environmental indicators were derived from farmers' responses to the structured questionnaire. They reflect farmers' observations and perceptions rather than direct measurements of soil, water, or climatic conditions.

Analytical framework

The analytical framework was based on a cause–effect approach to examine how intensive agricultural practices, government support, farmers' awareness, and market price fluctuations influence agricultural sustainability. The study adopted the triple bottom line framework, incorporating environmental, economic, and social dimensions. Environmental sustainability comprised fertilizer application, soil and land quality, pollution, climatic conditions, and land-use patterns, reflecting farmers' perceptions of environmental pressures and resource conditions within the agricultural production system. Economic sustainability considered government support, cultivation area, production, fertilizer and pesticide use, irrigation practices, and marketable surplus. Social sustainability included farmers' socio-economic characteristics, family labour participation, and perceived health impacts of intensive cultivation. These dimensions were integrated to provide a comprehensive sustainability assessment (Lampridi *et al.,* 2019).

Table 2: Challenges for the sustainability of the agricultural sector in the current context

Environmental perspective	Social perspective	Economic perspective
Eutrophication, erosion, landslides, flooding, clogging of irrigation channels, crop failure, and deforestation.	Unemployment due to rainfall variability, water scarcity, and labour shortage.	Burden of loans and accumulation of bad debts.
Depletion of resources; pollution and greenhouse gas emissions from chemical fertilizers affecting water, soil, and air.	Marketable surplus issues and lack of stable markets.	Inability to meet basic livelihood requirements and lifestyle maintenance.
Insufficient irrigation and electricity resources.	Migration of farmers to urban areas.	Difficulty in supplying food for increasing population demand.

Ethical considerations

This study involved a questionnaire-based survey of farmers and did not include any clinical interventions or collection of sensitive personal information. Prior to data collection, all participants were informed about the objectives and purpose of the study, and informed consent was obtained before participation. Participation was voluntary, and respondents were assured of the confidentiality and anonymity of their responses. The collected data were used solely for research purposes in accordance with institutional and ethical guidelines.

Statistical analysis

The collected data were analyzed using multiple statistical techniques to evaluate agricultural sustainability. Analysis of variance (ANOVA) was used to examine relationships in intensive cultivation practices and test the research hypotheses. The assumptions of normality, homogeneity of variance, independence, linearity, and multicollinearity were assessed before analysis. The Mann–Whitney U test (Z-test) compared traditional and intensive farming systems, while the Kruskal–Wallis H test (H-test) assessed the relationship between agricultural production and environmental pollution. The % analysis examined the distribution of respondents across categories. Row-wise analysis, together with mean, standard deviation (SD), and Pearson correlation (r), was used to identify variable relationships. Regression analysis determined factors affecting agricultural production, and the Chi-square (χ^2) test evaluated the impact of government support on farming outcomes (James *et al.,* 2013). Collectively, these statistical tools enabled a comprehensive and multi-dimensional assessment of agricultural sustainability.

RESULTS AND DISCUSSION

Socio-economic and farm profile characteristics

The socio-economic and farm characteristics of respondents provide a foundation for understanding agricultural decision-making and sustainability in the study area. Household structure, demographic profile, education, and farm size influence farming practices, resource use, productivity, and adaptation strategies. Fig. 1 presents the % analysis of the distribution of respondents' responses across key socio-economic and farm profile variables. Gender composition (Fig. 1a) shows male dominance at 93% (617 individuals) and female participation at 7% (46 individuals). This distribution reflects unequal access to agricultural resources, land ownership, and decision-making roles, indicating structural gender disparity within farming systems. Female participation remains limited, suggesting constrained participation in formal agricultural activities and farm management processes (Goswami *et al.,* 2017). Age distribution (Fig. 1b) indicates concentration in older cohorts, with 40–50 years at 38% and above 50 years at 29.9%. The 21–30 years group accounts for 12.7%, while the 15–20 years category shows no representation. This pattern reflects an ageing farming population and limited youth involvement

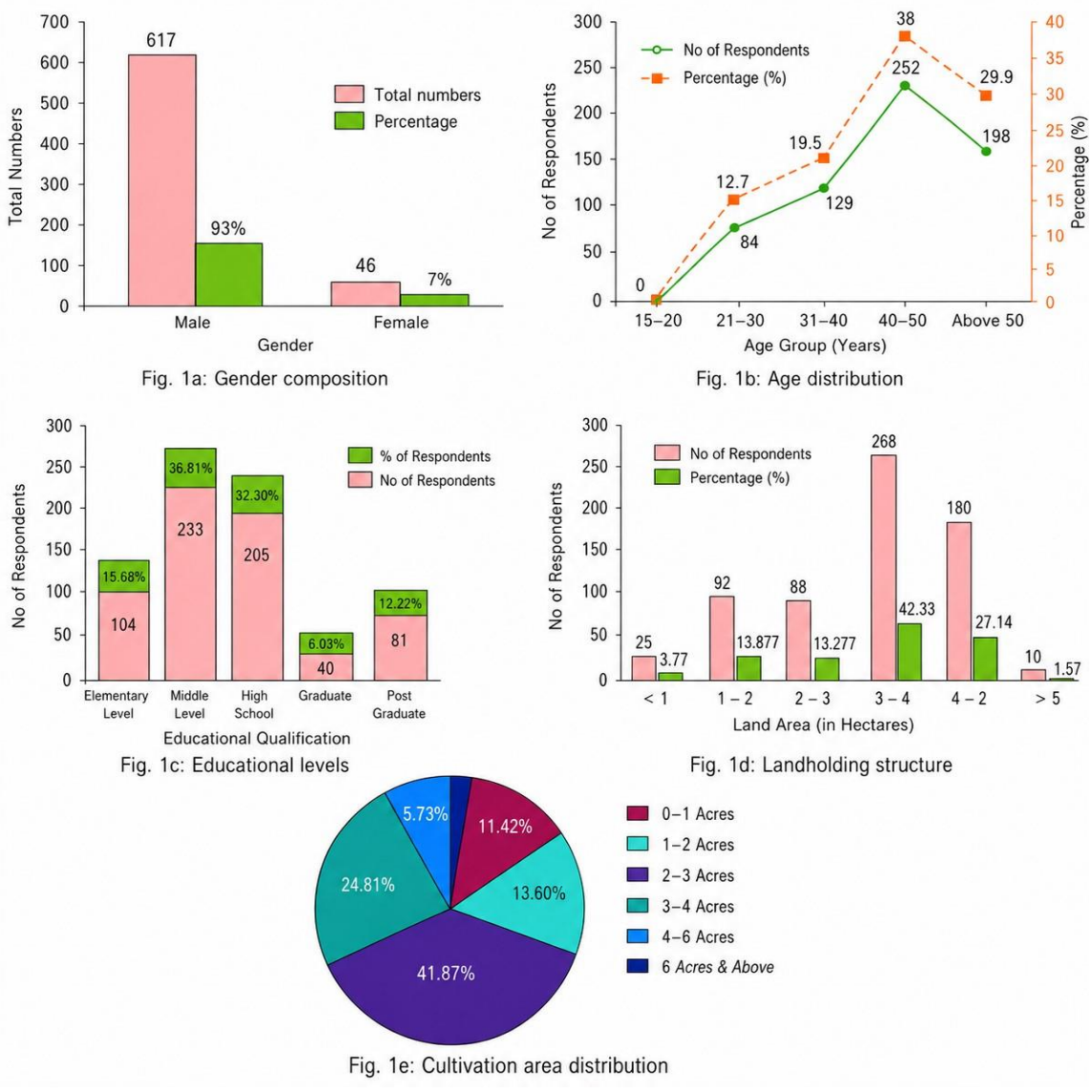

Fig. 1: The distribution % of respondents' responses

indicate potential challenges for labour continuity and innovation adoption in agriculture (Kareemulla *et al.,* 2017). Educational levels (Fig. 1c) are dominated by middle education at 35.11% and high school at 32.39%. Postgraduate qualification accounts for 12.22%, while graduates represent 6%. The distribution was dominated by respondents with basic education, while higher educational attainment remained limited, reflecting a mixed knowledge system combining experiential and formal agricultural understanding. Landholding structure (Fig. 1d) shows 3–4 hectares (ha) at 42.33% and 4–5 ha at 27.14%. Small holdings below 1 ha constitute 3.77%, while holdings above 5 ha account for 1.57%. The pattern indicates dominance of medium-scale farming units with relatively uniform operational capacity and similar resource requirements across respondents, reflecting strong dependence on landholding and livelihood

assets. Cultivation area distribution (Fig. 1e) shows dominance of 3–4 ha and above 4 ha categories. The 0–1 ha category accounted for the smallest proportion, whereas the 1–2 ha and 2–3 ha categories represented intermediate shares. The pattern indicates prevalence of medium to large-scale cultivation systems, suggesting higher operational capacity and dependence on household labour within semi-uniform farming structures. Fig. 1 shows that most respondents were male, middle-aged, and had moderate educational levels. Most farms ranged from 1–4 ha, with strong dependence on household labour. Limited participation of youth and women reflects the characteristics of smallholder farming systems and may influence sustainability outcomes across the study area.

Relationship between family size, income and area of cultivation

A cross-sectional analysis was conducted to examine the association between household demographic structure, income levels, and landholding patterns among the farming community.

Family size and area of cultivation:

Table 3 presents the distribution of family size across different categories of land area under cultivation in ha among the study respondents, highlighting the relationship between household composition and landholding structure within the agricultural system. Table 3 shows that 31% of landholdings were marginal farms below 3 ha, while 69% were small and medium farms of 3 ha and above. The average landholding size was approximately 3.3 ha, indicating the predominance of medium-scale farming. Family size showed a positive correlation with landholding size (r = 0.7214), suggesting that larger households generally managed larger farms. This relationship is likely associated with greater family labour availability but does not necessarily imply higher farm productivity or more efficient agricultural resource utilization.

Agricultural dependency

Table 4 presents the distribution of annual income across different categories of area under cultivation among the study respondents, illustrating the relationship between farm size and income levels within the agricultural system. From Table 4, it may be observed that the income pattern shows that 36% of farmers earn above United States Dollars (USD) 1,170 annually, while a substantial proportion remains within lower income categories, reflecting financial instability linked with inefficient cost management (Bobitan *et al.,* 2023). Higher income levels were generally associated with larger landholdings, whereas lower incomes were more common among small and marginal farmers. The income distribution indicates economic differences across farm categories, reflecting unequal resource availability. These findings highlight the need to strengthen market access and income opportunities for smaller farms.

Environmental sustainability and related factors

Environmental sustainability was assessed using indicators related to fertilizer application, soil quality, land quality, climatic conditions, pollution, and land-use patterns. The assessment was based on farmers' responses collected through a structured questionnaire instead of direct field or laboratory measurements. Therefore, the results represent farmers' perceptions of environmental changes associated with intensive agricultural practices. In the study area, respondents identified fertilizer application, land quality, and land-use patterns as the main factors affecting soil health, climatic conditions, and ecological stability. The following sections present the environmental assessment derived from responses from 663 farmers. These findings should be interpreted as perception-based observations rather than directly measured environmental parameters, providing context for locally perceived environmental pressures, degradation, and sustainability challenges in agricultural systems.

Table 3: Family size by landholding category in ha

Land area (ha)	Up to 2	3	≥ 4	Total
< 1	17	8	2	27
1 – 2	55	12	25	92
2 – 3	16	50	22	88
3 – 4	32	150	86	268
≥ 4	14	49	125	188
Total	134	269	260	663

Table 4: Distribution of annual income across different categories of area under cultivation

Annual income (USD)	Up to 2 ha	2 – 4 ha	Above 4 ha	Total
Up to 292	48	48	24	120
292–585	8	83	9	100
585–877	48	63	17	128
877–1,170	7	52	20	79
Above 1,170	6	110	120	236
Total	117	356	190	663

Note: Annual income categories were converted from Indian Rupees (₹) to United States Dollars (USD) using the average 2025 exchange rate (US$1 = ₹85.50) to facilitate international comparison.

Effect of fertilizer application on soil quality

Fig. 2 presents farmers' reported perceptions of soil salinity associated with different fertilizer types. Respondents most frequently associated ammonium sulphate with increased soil salinity (116 responses), followed by potassium fertilizer (98 responses). Urea was associated with 66 cases of nutrient deficiency and 62 cases of salinization, while phosphate fertilizer shows 30 salinization and 15 nutrient deficiency cases. Nitrogenous fertilizer records 15 salinization cases, and natural fertilizer shows 58 salinization and 12 deficiency cases. These results align with 24% soil organic carbon (SOC) reduction and 40% microbial biomass decline (Bonanomi *et al.,* 2011) and 25–75% carbon depletion (Lal, 2013), consistent with recent evidence that Intensive agricultural practices increasingly accelerate soil degradation (Al-Sammarraie and Kaplan, 2025) and that such degradation constitutes a pressing global environmental concern (Bünemann *et al.,* 2018). Present findings indicate 65–78% nutrient depletion and 63% land degradation, reflecting substantial soil deterioration. Farmers' perceptions indicated that prolonged intensive fertilizer application was associated with increased soil salinity, nutrient imbalance, and reduced soil quality.

Effect of fertilizer application on land quality and environmental conditions

Farmers' perceptions of land quality reflected the cumulative effects of agricultural inputs on soil, water, and surrounding environmental conditions. Fig. 3 shows contamination as the dominant impact with 519 out of 663 responses, followed by bad smell (62), turbidity (37), loss of biochemical oxygen demand (BOD) (26), and colour change (19), consistent with environmental pollution under high agrochemical usage (Mengel, 1993; Jwaideh and Dalin, 2025). Fertilizer-wise analysis showed that diammonium phosphate (DAP) recorded the highest contamination (147), followed by urea (130) and potassium fertilizer (118). Ammonium sulphate caused 36 contamination cases with turbidity and BOD impacts, while phosphate fertilizer caused 21 contamination and 19 bad-smell cases; nitrogenous fertilizer had minimal effects. These findings align with the ecological impacts observed under intensive farming systems (Mózner *et al.,* 2012). The study found a significant positive correlation between intensive farming and environmental pollution (r = 0.519), indicating that increased chemical fertilizer use is associated with soil salinization, land degradation, and environmental degradation.

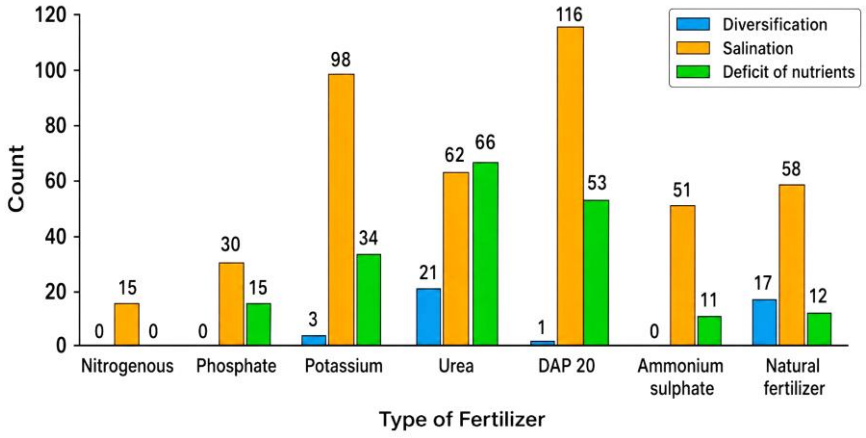

Fig. 2: Distribution of soil quality impacts of fertilizer application

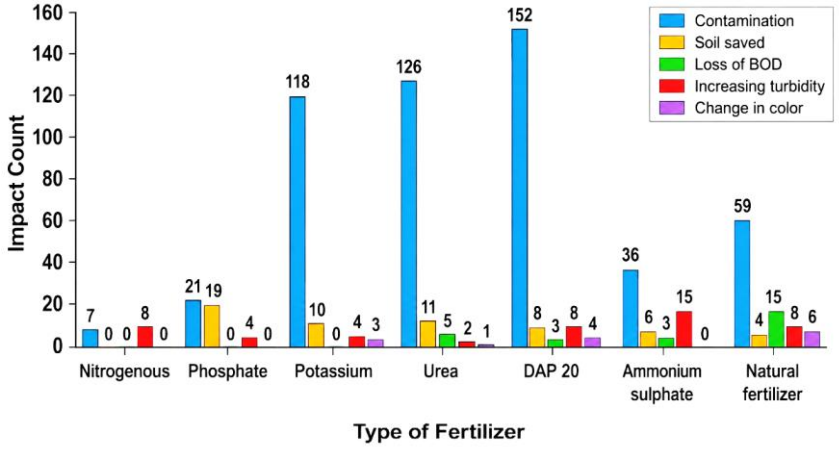

Fig. 3: Distribution of environmental and land quality impacts of fertilizer application

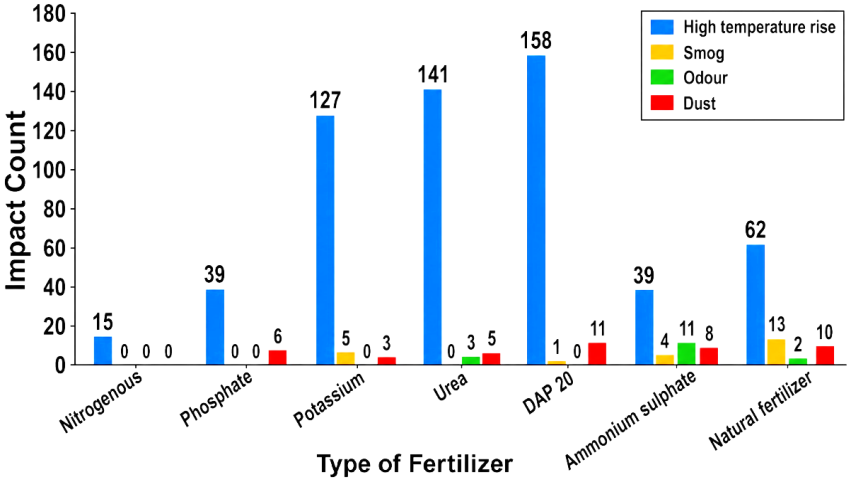

Fig. 4: Distribution of climatic impacts of fertilizer application

Effect of fertilizer application on climatic conditions

Climatic conditions in agricultural regions are increasingly associated with chemical input use, particularly fertilizers that affect temperature, air quality, and particulate emissions. Fig. 4 shows high temperature rise as the dominant effect with 581 out of 663 responses, followed by dust formation (43), smog occurrence (23), and odour impacts (16), consistent with climate impacts linked to soil carbon depletion of 25–75% (Lal, 2013; Imelda and Hidayat, 2024). Fertilizer-wise distribution showed that DAP recorded the highest number of temperatures rise cases (158), followed by urea (141) and potassium fertilizer (127). Ammonium sulphate showed combined effects on temperature, smog, odour, and dust, whereas natural fertilizer showed relatively moderate impacts. These findings are consistent with reports that abiotic stresses, such as salinity, reduce crop productivity (Parihar *et al.,* 2015). Farmers also perceived increased temperature and moisture stress under intensive farming. However, these results are based on farmers' perceptions and statistical analysis, not direct climatic measurements. Therefore, the present study does not establish a causal relationship between fertilizer use and temperature change.

Land pattern and area of cultivation

Land use patterns provide insight into environmental conditions, agricultural intensity, and resource distribution across the study region. Fig. 5 shows terrestrial barren land as the predominant land-use category with 356 out of 663 responses, followed by wet land (203), grassland (46), fallow land (37), and other land (21). Area-wise distribution indicates the highest concentration within the 2–4 ha category (356), followed by above 4 ha (190) and up to 2 ha (117), indicating predominance of medium-scale farming systems. This pattern reflects semi-arid conditions and land-use pressure, consistent with enhanced land-use utilization under intensive systems (Adhikari *et al.,* 2017) and irrigation-induced instability and land-use changes (Bosco and Simeoni, 2018; Ologunde and Nunes, 2026), while also indicating that expansion of cultivated area under intensive practices contributes to increased resource exploitation and ecological imbalance. The present findings revealed a strong positive correlation between intensive farming and cultivated land expansion (r = 0.658), consistent with increased land-use pressure and environmental stress associated with intensive agricultural systems (Adhikari *et al.,* 2017).

Farmers' perceptions of environmental impacts of intensive cultivation

Farmers' perceptions indicated that intensive agriculture was associated with environmental concerns. About 78% of respondents linked land contamination to chemical fertilizer use, while 65% associated soil degradation with salinization caused by intensive fertilizer application. In addition, 13% reported that natural fertilizers alone were insufficient for achieving satisfactory crop production. These findings suggest that excessive fertilizer use is perceived to adversely influence soil conditions in intensive farming systems (Ju *et al.,* 2007). Soil quality deterioration associated with continuous input-intensive agricultural practices has also been widely documented, highlighting its adverse effects on soil health and ecosystem functions (Bonanomi *et al.,* 2011; Bünemann *et al.,* 2018). The present findings indicate that intensive agriculture is associated with natural resource degradation through excessive input use. However, the current results are based on farmers' perceptions rather than direct soil or water measurements. They reflect perceived environmental stress and highlight the need for integrated nutrient management and sustainable intensification (Kaur, 2014; Rockström *et al.,* 2017).

Statistical analysis for integrated triple bottom line sustainability

A combination of statistical techniques was used to evaluate the environmental, economic, and

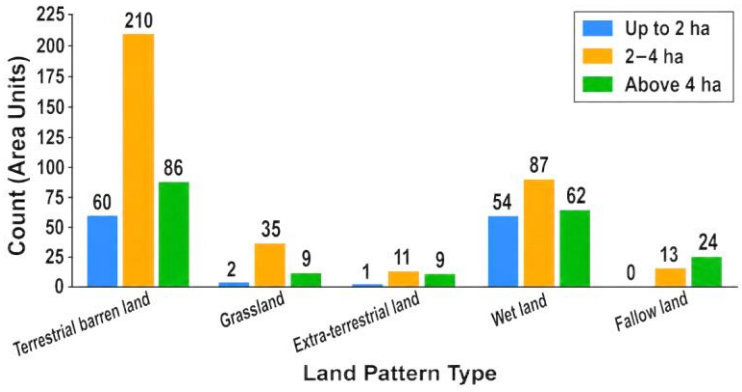

Fig. 5: Distribution of land patterns across different categories of area under cultivation

Table 5: Combined ANOVA results on agricultural sustainability variables

Source of variation	Sum of squares (SS)	Degrees of freedom (df)	Mean square (MS)	F-value	p-value	Effect size (η^2)
Government support and intensive cultivation						
Between Groups	35380.916	18	1965.606	8.998	< 0.001***	0.021
Within Groups	140680.65	644	218.448			
Total	176061.56	662				
Area of cultivation to intensive cultivation						
Between Groups	16144.933	6	2690.822	11.038	< 0.001***	0.092
Within Groups	159916.63	656	243.775			
Total	176061.56	662				
Health impact of intensive cultivation						
Between Groups	159.11	170	0.936	16.981	< 0.001***	0.854
Within Groups	27.119	492	0.0551			
Total	186.229	662				
Pollution due to intensive cultivation						
Between Groups	1661.255	170	9.772	15.619	< 0.001***	0.844
Within Groups	307.915	492	0.626			
Total	1969.17	662				

Note: Total degrees of freedom were calculated as $N - 1$ (N = 663); *p < 0.05; **p < 0.01; ***p < 0.001.

social dimensions of sustainability under intensive cultivation. The triple bottom line framework was adopted to examine relationships among agricultural practices, production, government support, environmental conditions, and social outcomes. ANOVA compared sustainability indicators across groups (Table 5). Pearson correlation (r) was used to assess relationships among continuous variables, and multiple regression was performed to evaluate the effects of fertilizer type, pesticide type, and irrigation pattern on agricultural production. The Z-test was applied to compare marketable surplus between traditional and intensive cultivation systems, while the χ^2 test and H-test examined associations among categorical variables and pollution-related responses, respectively.

ANOVA analysis

ANOVA was used to examine differences in key agricultural sustainability variables across intensive cultivation groups. Intensive cultivation categories were treated as grouping variables, while government support, area of cultivation, perceived health impacts, and perceived pollution were considered dependent variables. The analysis was based on 663 respondents with df = 662 (N − 1). It was used to determine whether differences among the variables were statistically significant within the study area. Table 5 shows

the combined ANOVA results, indicating significant differences among agricultural sustainability variables related to intensive cultivation.

Government support and intensive cultivation

It may be observed from Table 5 that the ANOVA results indicate a statistically significant relationship between government support measures and intensive cultivation, with an F-value of 8.998 and significance level of $p < 0.001$. The corresponding $\eta^2 = 0.201$ indicates a large practical effect, suggesting that government support explains approximately 20.1% of the variation in intensive cultivation practices. These findings are consistent with the role of policy interventions and institutional frameworks in influencing sustainability outcomes (Das *et al.,* 2020). The higher mean square (MS) between groups compared to the within-group mean square suggests that variations in government policies, subsidies, and institutional assistance significantly influence the adoption and intensity of cultivation practices, aligning with stakeholder-based governance approaches (Gillund *et al.,* 2016). This confirms that government support acts as a key determinant in shaping agricultural intensification patterns, with the present findings indicating a positive association between government support and the adoption of sustainable practices across respondent groups.

Area of cultivation and intensive cultivation

It may be observed from Table 5 that the analysis shows a significant impact of cultivated land area on intensive cultivation, with an F-value of 11.038 and $p < 0.001$. The corresponding effect size ($\eta^2 = 0.092$) indicates a moderate practical effect, suggesting that cultivated land area explains approximately 9.2% of the variation in intensive cultivation practices. These findings are consistent with the expansion of cultivated area under agricultural intensification (Adhikari *et al.,* 2017). The results indicate that farm size significantly influences agricultural intensification. Larger landholdings generally require greater inputs, labour, and management. The significant variation among groups suggests that cultivated area is an important factor influencing agricultural management practices and the level of intensification.

Social sustainability perceived health impacts of intensive cultivation

Social sustainability was examined through farmers' socio-economic characteristics, family labour participation, perceived health impacts, and institutional support. These indicators provide an understanding of how intensive agriculture influences farmers' livelihoods, well-being, and social conditions. It may be observed from Table 5 that the ANOVA results reveal a highly significant association between intensive cultivation categories and perceived health impacts, with an F-value of 16.981 and $p < 0.001$. The corresponding effect size ($\eta^2 = 0.854$) indicates a large practical effect, demonstrating that intensive cultivation explains approximately 85.4% of the variation in perceived health impacts. This finding is consistent with evidence linking pesticide exposure to chronic diseases, including cancer and neurological disorders (Horrigan *et al.,* 2002; Rani *et al.,* 2021). Perceived pollution responses were significantly associated with intensive cultivation categories ($F = 15.619$, $p < 0.001$). These results reflect farmers' perceptions rather than direct health or environmental measurements. Respondents consistently perceived that intensive cultivation, particularly the use of chemical inputs, was associated with adverse health and environmental effects. A moderate positive correlation ($r = 0.412$) was observed between intensive agricultural practices and perceived health impacts (Rani *et al.,* 2021).

Pollution due to intensive cultivation

It may be observed from Table 5 that the findings show a significant relationship between intensive cultivation and pollution levels, with an F-value of 15.619 and $p < 0.001$. The corresponding effect

size (η^2 = 0.844) indicates a large practical effect, suggesting that intensive cultivation accounts for approximately 84.4% of the variation in pollution levels. These findings are consistent with evidence of environmental contamination characterized by nutrient losses of up to −53 kilograms per hectare per year (kg/ha/y) and phosphorus surplus of up to 18.1 kg/ha/y (Muhammed *et al.,* 2018). The significant difference between the between-group and within-group variation indicates that perceived pollution varied with cultivation intensity. Farmers associated intensive agricultural practices with increased air, water, and soil pollution. A significant positive correlation (r = 0.519) further supports this relationship (Mengel, 1993). To further examine this relationship, the impact of government and institutional support on intensive cultivation is presented in the following section. Government and institutional financial support showed a significant positive association with intensive cultivation practices.

Economic sustainability and government support

Economic sustainability was evaluated using indicators related to government and institutional support, area of cultivation, agricultural production, fertilizer and pesticide use, irrigation practices, and productivity. These variables reflect the economic performance of intensive agriculture and the influence of agricultural inputs and policy support on agricultural output and resource use. Government and institutional support play an important role in influencing cultivation practices and the adoption of intensive farming methods, consistent with national policies promoting sustainable and climate-resilient agriculture (Keshyagol *et al.,* 2026). An analysis was carried out to examine the association of government and institutional support with key variables such as intensive cultivation, cattle and biodiversity, productivity, and environmental quality. Table 6 presents the impact of government and institutional support on intensive cultivation and related variables and Fig. 6 presents corresponding leverage plots illustrating these relationships. The results presented in Table 6 and Fig. 6 illustrate the relationship between government and institutional support and selected variables associated with intensive cultivation. Government and institutional support showed a significant positive association with intensive cultivation (Standardized regression coefficient (β) = 0.118888, p < 0.0001), indicating that policy support is significantly related to the adoption of intensive cultivation practices. However, the association with cattle and biodiversity was non-significant (p = 0.957), as were the associations with increase in productivity (p = 0.4085) and damage in environmental quality (p = 0.2489). The leverage plots in Fig. 6 show a strong relationship between government and institutional support and intensive cultivation, whereas the relationships with biodiversity, productivity, and environmental quality were weak. Accordingly, the null hypothesis was rejected for intensive cultivation and retained for cattle and biodiversity, increase in productivity, and environmental quality. The ANOVA results showed that government support, area of cultivation, health impact, and pollution were significantly associated with intensive cultivation (p < 0.001). However, government and institutional support had no significant direct effect on productivity or environmental degradation under the present study conditions.

Correlation analysis

Correlation analysis was performed to examine the relationship between land-use pattern and selected agricultural input variables. It helps identify the direction and strength of association between fertilizer use, pesticide use, and irrigation pattern with land-use dynamics. Table 7 shows the correlation between land pattern and the selected independent variables. The results indicate the strength and direction of the relationships. These findings represent statistical associations only and should not be interpreted as evidence of causal relationships.

Table 6: Government and institutional support and its impact on intensive cultivation

Term	Estimate	Standard error (SE)	t-value	p-value
Intercept (Government and institutional support)	1.943634	0.185725	10.47	< 0.0001***
Impact on the intensive cultivation	0.118888	0.021204	5.61	< 0.0001***
Cattle and biodiversity	0.020169	0.370876	0.054	0.957
Increase in productivity	-0.061935	0.074888	-0.83	0.4085
Damage in environment quality	-0.044279	0.038372	-1.15	0.2489

Note: *p < 0.05; **p < 0.01; ***p < 0.001.

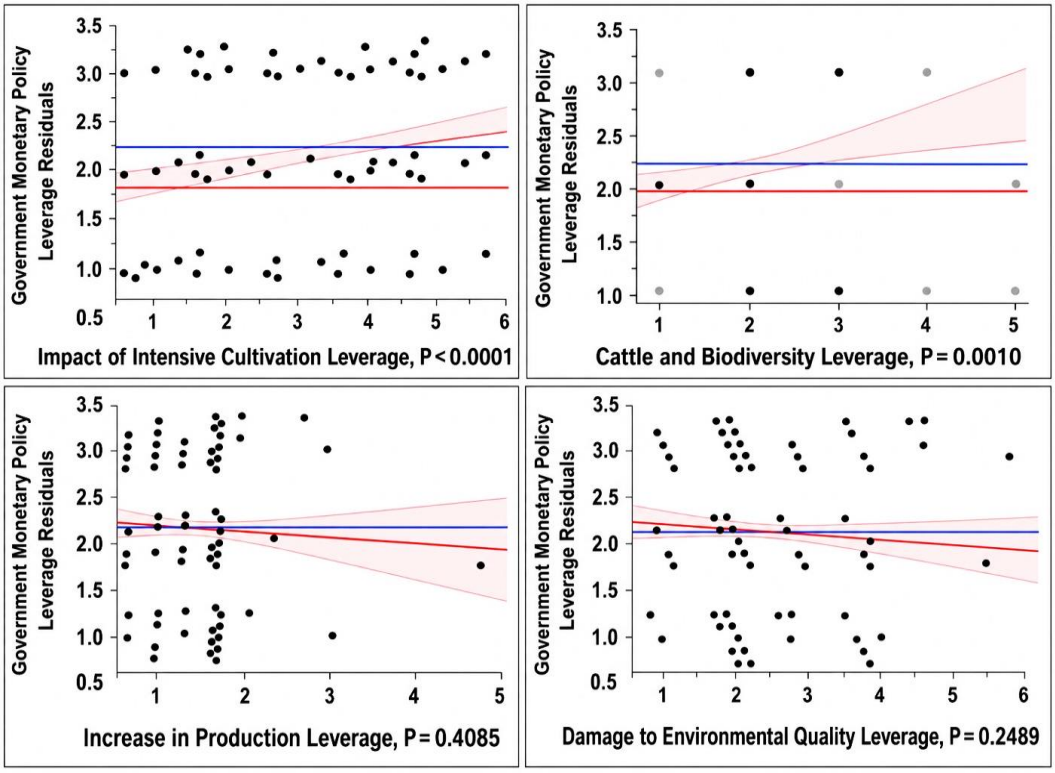

Fig. 6: Leverage plots

Land pattern and fertilizer use

It may be found from Table 7 that the correlation analysis shows a significant negative relationship between land-use pattern and fertilizer use (r = −0.105**). This finding indicates a limited inverse association between fertilizer use and land-use patterns. Although statistically significant, the very weak correlation suggests that fertilizer use should not be regarded as a primary determinant of land-use patterns. The negative direction suggests that intensification through fertilizer use may contribute to changes in traditional land management systems (Ju *et al.,* 2007).

Land pattern and pesticide use

It may be found from Table 7 that the relationship between land-use pattern and pesticide use is weak and not statistically significant (r = 0.045). This indicates that pesticide application does not have a meaningful impact on changes in land-use patterns within the study area. The weak and non-significant correlation suggests that the study did not detect a meaningful linear relationship between these variables, but does not establish their complete independence or absence of other potential relationships (Rani *et al.,* 2021).

Table 7: Correlation between dependent variable and independent variables

Variables	Mean	SD	N	r
Land pattern (last five years)	2.27	1.491	663	-
Fertilizer use	4.43	1.520	663	− 0.105**
Pesticide use	3.35	1.675	663	0.045
Irrigation pattern	2.80	1.927	663	− 0.158***

Note: *p < 0.05; **p < 0.01; ***p < 0.001 (2-tailed). N = sample size; r = Pearson correlation coefficient.

Land pattern and irrigation pattern

It may be found from Table 7 that land-use pattern shows significant negative correlations with fertilizer use (r = − 0.105**) and irrigation pattern (r = − 0.158***), indicating that changes in agricultural input and irrigation management are associated with variations in land-use configuration and cultivation patterns. In contrast, pesticide use showed a weak and non-significant relationship (r = 0.045), indicating little association with land-use dynamics. Fertilizer use and irrigation practices were more closely related to agricultural intensification and land management decisions. These findings are consistent with earlier studies on farming practices and irrigation-driven land-use change (Alhassan *et al.,* 2016; Keshyagol *et al.,* 2026). The observed relationships are further supported by the correlations with cultivated land expansion (r = 0.658), pollution (r = 0.519), and health impacts (r = 0.412), indicating interrelated sustainability outcomes under intensive agriculture.

Regression analysis

Multiple regression analysis was employed to assess the combined effect of key agricultural inputs on the increase in agricultural production**.** It was used to determine the extent to which fertilizer use, pesticide use, and irrigation pattern predict variations in agricultural productivity. Table 8 presents the multiple regression analysis for increase in agricultural production, showing the effect of key agricultural inputs on production. Table 8 presents the multiple linear regression analysis examining the effects of fertilizer use, pesticide use, and irrigation pattern on agricultural production. The regression model was statistically significant (F = 16.807, p < 0.001*). The R^2 value of 0.071 indicates that the model explained 7.1% of the variation in agricultural production, indicating modest explanatory power. This suggests that other factors, such as climatic conditions, soil properties, crop type, farm management, market conditions, and socio-economic characteristics, also influence production. Therefore, the results should be interpreted as statistical associations rather than causal relationships. The general form of the multiple linear regression model is given in Eq. 1 (James *et al.,* 2013):

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + e \quad (1)$$

Where: Y represents agricultural production, a is the intercept (constant), b_1, b_2, and b_3 are the regression coefficients, X_1 denotes fertilizer use, X_2 denotes pesticide use, X_3 denotes irrigation pattern, and e represents the random error term. Based on the estimated coefficients obtained in the present study, the fitted multiple linear regression, using Eq. 2 (Present study):

$$Y = 1.206 + 0.40X_1 + 0.38X_2 - 0.34X_3 \quad (2)$$

The intercept (1.206) was statistically significant (SE = 0.069, t = 17.398, p < 0.001*), indicating the baseline agricultural production. Fertilizer use showed a significant positive association with agricultural production (B = 0.40, β = 0.126, p = 0.002). Pesticide use also showed a significant positive relationship (B = 0.38, β = 0.132, p = 0.001), consistent with previous findings (Affandi *et al.,* 2026). In contrast, irrigation pattern showed a significant negative association with agricultural

Table 8: Multiple regression analysis for increase in production

Model component	Variable	Unstandardized regression coefficient (B)	SE	β	t-value	p-value
Model summary	Coefficient of determination (R^2)	0.071	—	—	—	< 0.001***
	F change	16.807	—	—	—	< 0.001***
	Numerator degrees of freedom (df1)	4	—	—	—	—
	Denominator degrees of freedom (df2)	659	—	—	—	—
Constant		1.206	0.069	—	17.398	< 0.001***
Independent variable	Type of fertilizer (X_1)	0.40	0.128	0.126	3.123	0.002**
	Type of pesticide (X_2)	0.38	0.117	0.132	3.255	0.001**
	Type of irrigation (X_3)	− 0.34	0.088	− 0.145	-3.852	< 0.001***

Note: *p < 0.05; **p < 0.01; ***p < 0.001.

production (B = −0.34, β = −0.145, p < 0.001*), indicating lower production at higher coded levels of the variable (Goswami *et al.,* 2017). Overall, fertilizer use, pesticide use, and irrigation pattern were significantly associated with agricultural production. These results represent statistical associations based on the coding of the predictor variables and should not be interpreted as causal effects (James *et al.,* 2013).

Non-parametric analysis of surplus, production, and environmental factors

Non-parametric tests were used because the analyzed variables did not satisfy the normality assumption required for parametric tests. These distribution-independent methods were applied to examine differences and associations among key variables. They were used to assess variations in marketable surplus, production, government support, and environmental factors under different cultivation practices. Table 9 presents the non-parametric test statistics, including the Z-test, χ^2 test, and H-test, for the selected variables. Table 9 shows that the Z-test identified significant differences in marketable and marketed surplus between traditional and intensive cultivation systems. The χ^2 test showed significant associations between increased production and willingness to pay (p < 0.001) and between government support and intensive cultivation (p < 0.001). The H-test indicated a significant difference in perceived pollution with increased production (p < 0.001), suggesting greater environmental stress under higher production. These findings are consistent with previous studies reporting improved profitability under alternative farming systems and sustainable agricultural management practices (Mariappan and Zhou, 2019).

Reliability assessment of the measurement instrument

The reliability of the questionnaire was evaluated using the corrected item–total correlation (CITC) and α if Item Deleted. The questionnaire included 10 constructs, each comprising five items, giving a total of 50 items. Fig. 7 presents the item-wise reliability results. The CITC values ranged from 0.651 to 0.781, exceeding the recommended threshold of 0.30, indicating satisfactory internal consistency. The highest CITC was observed for AS4 (0.781), followed by AS2 (0.772) and AS5 (0.763), while the lowest value was recorded for GS1 (0.651). The α if Item Deleted values ranged from 0.801 to 0.894, indicating that removing any item did not improve the overall reliability. Therefore, all questionnaire items were retained for further analysis, confirming their contribution to measuring agricultural sustainability across the study's key dimensions and ensuring adequate measurement consistency.

Table 9: Non-parametric test statistics (Z-test, χ^2 test, and H-test)

Test	Variables	Statistic	df	p-value
Z-test	Marketable surplus (Traditional vs. Intensive cultivation)	Z = −3.243	—	0.001**
Z-test	Marketed surplus (Traditional vs. Intensive cultivation)	Z = −5.104	—	< 0.001***
χ^2 test	Increase in production vs. Willingness to pay	χ^2 = 32.593	1	< 0.001***
χ^2 test	Government support vs. Impact on intensive cultivation	χ^2 = 657.679	17	< 0.001***
H-test	Pollution (air, water, and soil) vs. Increase in production	H = 50.737	1	< 0.001***

Note: *p < 0.05; **p < 0.01; ***p < 0.001.

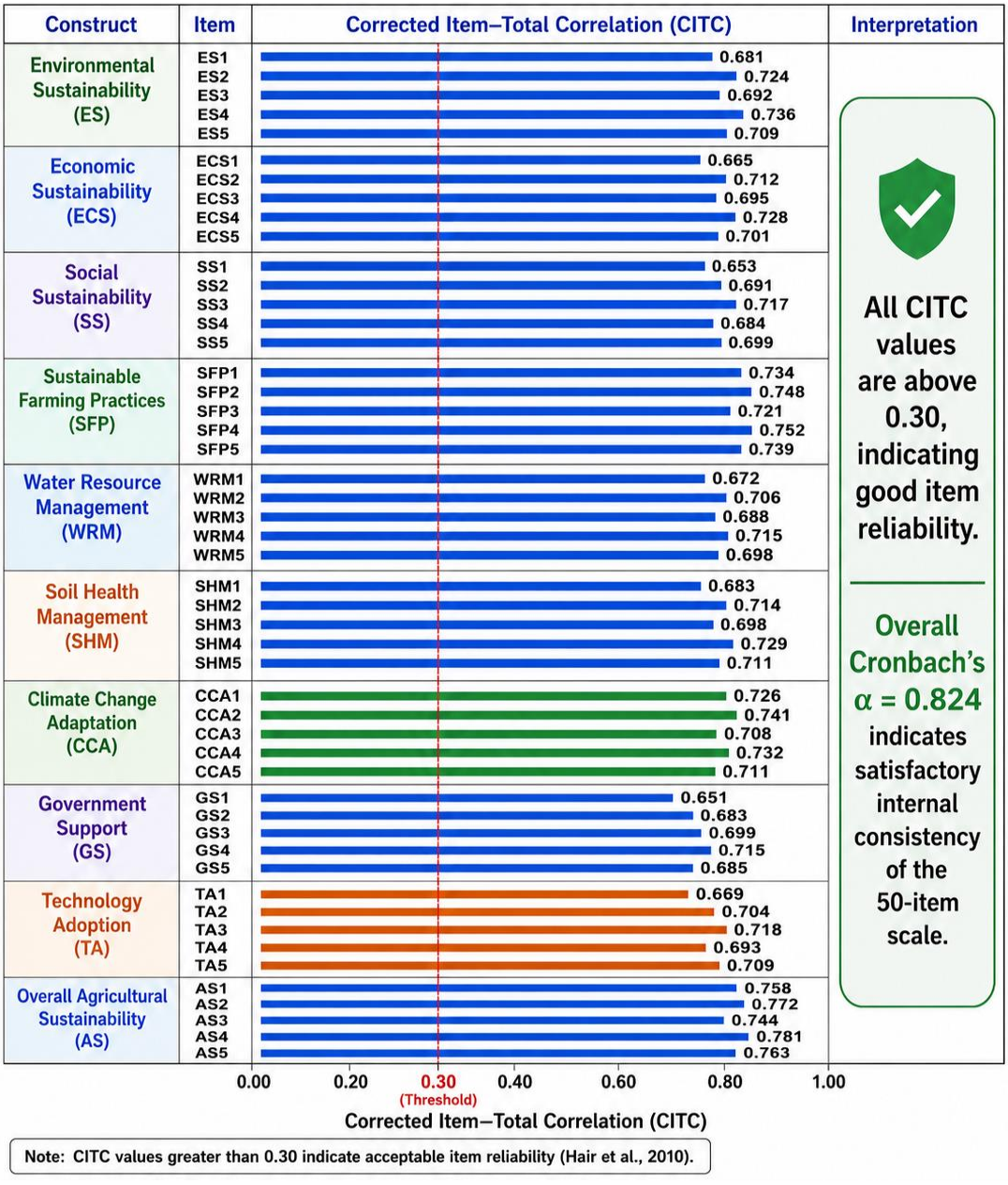

Fig. 7: Item-wise reliability assessment of the agricultural sustainability questionnaire

Validity assessment of measurement instrument

The quality of the measurement instrument was evaluated through internal consistency reliability, content validity, and construct validity to ensure the reliability, validity, and appropriateness of the questionnaire for statistical analysis.

Internal consistency reliability

The internal consistency of the measurement instrument was evaluated using the α coefficient. The overall questionnaire achieved an α value of 0.824, exceeding the recommended threshold of 0.70 and indicating satisfactory reliability. The α if Item Deleted values ranged from 0.801 to 0.894, indicating that removing any item would not substantially improve reliability. Therefore, all 50 questionnaire items were retained for subsequent statistical analyses.

Content validity

Content validity was established through an extensive review of previous agricultural sustainability studies and the study objectives. The questionnaire covered environmental, economic, social, institutional, technological, and resource management dimensions. A pilot study involving 40 farmers from marginal, small, medium, and large farm categories was conducted to assess the clarity, relevance, and applicability of the questionnaire. Feedback from the pilot survey was incorporated into the final questionnaire before the main data collection.

Construct validity

Construct validity was supported through the satisfactory performance of the corrected CITC values. The CITC values (0.651–0.781) indicate that all items were appropriately associated with their underlying constructs and adequately represented the intended dimensions of agricultural sustainability. The absence of low item-total correlation values demonstrates satisfactory coherence among the measurement items, confirming that the questionnaire reliably captured the multidimensional characteristics of agricultural sustainability.

Comparative evaluation of previous and present study results

A structured comparison of the impacts of intensive agriculture was performed using quantitatively measurable indicators derived from earlier studies and present field observations. Table 10 presents these indicators with corresponding values, enabling a systematic evaluation of the consistency and variation across studies. From Table 10, it could be noted that the earlier studies have reported significant environmental and socio-economic challenges associated with intensive agriculture, including a 24% reduction in SOC, 40% decline in microbial biomass, and 25–75% depletion of soil organic carbon, indicating deterioration of soil biological functions and carbon dynamics (Bonanomi *et al.,* 2011; Lal, 2013). In comparison, the present study reported 63% perceived land degradation and 65–78% perceived nutrient depletion, along with a 13% reduction in perceived organic fertilizer effectiveness, indicating concerns about declining soil quality and function. Although earlier studies used direct soil measurements, the present study reflects farmer perceptions; both highlight soil vulnerability under intensive cultivation. Previous investigations quantified nutrient imbalance through a nitrogen surplus of 4328 kg/ha/y, phosphorus surplus of 1337 kg/ha/y, and nitrogen losses of −53 kg/ha/y, demonstrating inefficient nutrient cycling in intensive farming systems (Ju *et al.,* 2007; Muhammed *et al.,* 2018). Similarly, the present study identified excessive fertilizer application and perceived soil fertility decline, suggesting that increased nutrient inputs may not always result in improved nutrient-use efficiency. Previous research has also documented environmental pollution associated with agrochemical-intensive agriculture (Mengel, 1993), while the present study observed a significant association between intensive

Table 10: Contextual evaluation of sustainability indicators under intensive agricultural systems

Sustainability indicator	Evidence from previous studies	Evidence from present study	Interpretation
Soil quality and carbon dynamics	SOC reduction (24%), microbial biomass decline (40%), and soil carbon depletion (25–75%) reported under intensive agriculture (Bonanomi *et al.,* 2011; Lal, 2013)	Farmers reported land degradation (63%), nutrient depletion (65–78%), and reduced organic fertilizer efficiency (13%)	Both studies indicate declining soil quality; however, previous studies used measured soil parameters, whereas the present study reflects farmer-level observations
Nutrient management	Nitrogen surplus (4328 kg/ha/y), phosphorus surplus (1337 kg/ha/y), and nitrogen losses (−53 kg/ha/y) reported under intensive agriculture (Ju *et al.,* 2007; Muhammed *et al.,* 2018)	Excess fertilizer application and declining soil fertility were reported by farmers	Indicates possible inefficiencies in nutrient management under intensive cultivation
Environmental pollution	Intensive agrochemical use associated with increased pollution risks (Mengel, 1993)	Significant association between intensive agriculture and pollution perception (r = 0.519)	Suggests farmer-perceived environmental stress associated with intensive practices
Land-use pressure	Intensive systems improve land-use efficiency but increase resource pressure (Adhikari *et al.,* 2017)	Significant association between intensive farming and land-use intensification (r = 0.658)	Indicates increasing cultivation pressure within the study region
Health concerns	Agricultural chemical exposure linked with potential health risks (Rani *et al.,* 2021)	Significant association between intensive cultivation and reported health impacts (r = 0.412)	Highlights farmer concerns regarding chemical exposure and health outcomes
Socio-economic dependence	Agricultural livelihoods associated with land ownership and household labour (Goswami *et al.,* 2017)	Landholding size showed a strong association with family size (r = 0.7214)	Indicates continued dependence on family labour in intensive farming systems

agricultural practices and environmental pollution (r = 0.519), along with farmer-reported concerns related to salinity, dust accumulation, and climatic stress indicators. Earlier studies reported that intensive agriculture improves land-use efficiency but increases pressure on agricultural resources (Adhikari *et al.,* 2017), which is comparable with the present finding of a significant relationship between intensive farming practices and land-use intensification (r = 0.658). Previous evidence has highlighted potential health risks associated with prolonged agricultural chemical exposure (Rani *et al.,* 2021), and the present study similarly identified a significant association between intensive agricultural practices and reported health impacts (r = 0.412). Furthermore, previous studies emphasized the dependence of farming livelihoods on household labour and land ownership (Goswami *et al.,* 2017), while the present study observed a strong relationship between landholding size and family size (r = 0.7214), indicating continued dependence on family labour in intensive farming systems. The present findings are generally consistent with earlier studies on soil degradation, nutrient imbalance, environmental stress, health impacts, and socio-economic dependence. However, these relationships indicate statistical associations rather than causal effects, as the study used cross-sectional survey data. Reported land degradation (63%) and nutrient depletion (65–78%) may reflect local soil conditions, climate, cropping intensity, irrigation, and management practices. Differences from previous studies may arise from farmers' perceptions rather than direct environmental measurements. Significant associations between intensive cultivation and pollution (r = 0.519), land-use intensification (r = 0.658), health impacts (r = 0.412), and landholding size and family size (r = 0.7214) are consistent with previous findings. These relationships should therefore be interpreted within the local agricultural context rather than as evidence of causality.

Recommendations

Sustainable agricultural development requires targeted policy and management interventions. Since government support, area of cultivation, health impact, and pollution were significantly associated with intensive cultivation ($p < 0.001$), strengthening financial assistance, crop insurance, and timely access to institutional credit should be prioritized. The regression analysis showed positive associations of fertilizer and pesticide use with agricultural production, while irrigation pattern showed a negative association, indicating the need to improve irrigation management practices. Awareness programmes on the efficient and safe use of agricultural inputs should also be strengthened to reduce environmental and health risks. Future research should further examine conservation agriculture and climate-smart technologies to support sustainable agricultural development (Caldara *et al.,* 2026). Overall, the findings support enhanced institutional support, efficient resource management, and evidence-based policy interventions to promote long-term agricultural sustainability (Ţopa *et al.,* 2025).

Contribution of the study

This study contributes to the understanding of agricultural sustainability by integrating environmental, economic, and social dimensions within a unified analytical framework. Government support, area of cultivation, health impact, and pollution were significantly associated with intensive cultivation ($F = 9.542$, 13.266, 17.115, and 15.739; $p < 0.001$). Regression analysis showed positive associations of fertilizer and pesticide use with agricultural production, whereas irrigation pattern showed a negative association. Non-parametric tests also indicated significant associations among marketable surplus, production, and environmental factors ($p < 0.001$). This integrated assessment provides comprehensive evidence to support sustainable agricultural management and evidence-based policy decisions for resilient and environmentally responsible farming systems.

Limitations of the study

The study was limited to a single district, which may restrict the generalizability of the findings. The analysis was based on primary survey data and may be subject to respondent bias. Although multiple statistical methods were applied, some models showed moderate explanatory power, suggesting that additional factors may influence the observed outcomes. Multiple statistical tests were conducted without formal adjustment for multiple comparisons, which may have increased the likelihood of Type I error. The hierarchical data structure was not explicitly considered, which may have affected SE precision. Finally, the significant relationships represent statistical associations rather than causal effects due to the cross-sectional design. Future longitudinal and experimental studies should examine causal mechanisms.

Scope for future research

Future research should include multiple districts and states to improve the generalizability of the findings. Longitudinal studies are needed to examine the long-term environmental and socio-economic impacts of intensive cultivation and to better assess causal relationships. F Future studies should incorporate direct soil, water, and environmental measurements alongside environmental, institutional, and socio-economic variables to improve model explanatory performance. They should also assess agricultural subsidies, organic farming, and sustainable resource management across diverse agroecological conditions.

CONCLUSION

The study demonstrates that intensive cultivation is associated with variations in the environmental, economic, and social dimensions of agricultural sustainability, highlighting the interactions among production practices, resource utilization, and farmer-level socio-economic conditions. The statistical analyses indicate that

agricultural intensification is related to both structural characteristics and institutional factors, with implications for sustainability outcomes. ANOVA results showed significant differences among intensive cultivation-related variables, including government support, cultivated area, pollution perception, and reported health impacts, indicating that intensification is associated with multiple sustainability concerns. Government financial support showed a significant positive association with intensive cultivation practices; however, its relationship with productivity-related and environmental indicators was limited, suggesting the need for improved alignment between policy support and sustainability objectives. Correlation analysis indicated significant relationships between land-use patterns and selected agricultural input variables, including fertilizer use and irrigation practices, whereas pesticide use showed no significant association. Regression analysis showed that fertilizer and pesticide use were positively associated with agricultural production, while irrigation practices showed a negative association, emphasizing the importance of efficient input and water management strategies. However, the regression model explained a relatively small proportion of the variation in agricultural production (R^2 = 0.071), indicating that additional environmental, managerial, and socio-economic factors not included in the model are also likely to influence production outcomes. Additional statistical analyses indicated significant relationships among production practices, institutional support, and sustainability-related indicators, suggesting that agricultural sustainability requires consideration of both productivity and resource management dimensions. The findings provide empirical insights for policymakers, agricultural planners, and extension agencies to develop strategies promoting efficient fertilizer management, improved irrigation practices, responsible input use, and sustainable cultivation approaches. However, the study is limited by its cross-sectional survey design, geographical focus on Namakkal District, reliance on farmers' self-reported responses, and the modest explanatory power of the regression model, which may restrict the generalizability of the findings beyond the sampled farming population. Although significant relationships were identified between intensive cultivation indicators and sustainability outcomes, these associations do not establish causal relationships. Future studies should incorporate longitudinal observations, multi-location assessments, and direct field measurements of soil, water, and environmental parameters to further evaluate long-term sustainability outcomes. Although the present study did not directly evaluate advanced digital technologies, future research may also examine the potential of remote sensing and geographic information system to improve sustainability assessment and support evidence-based agricultural planning. Sustainable agricultural development requires balancing production objectives with efficient resource utilization, improved management practices, institutional support, and farmer capacity development to enhance the resilience and sustainability of farming systems.

AUTHOR CONTRIBUTIONS

S. Chandran contributed to the conceptualization of the study, methodology development, data collection, formal analysis, investigation, environmental sustainability assessment, interpretation of the findings, visualization, and preparation of the original manuscript draft. T. Ramachandran contributed to study supervision, research design, methodology refinement, validation, manuscript review, and editing. D. Sivakumar contributed to conceptual guidance, critical review, technical editing, and final approval of the manuscript. A. Ambika contributed to data validation, visualization, manuscript review, language editing, and final approval of the manuscript. All authors read and approved the final manuscript and agree to be accountable for all aspects of the work.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding this manuscript. Ethical standards, including informed consent, originality, research integrity, and avoidance of fabrication, falsification, duplicate publication, and redundant submission, were strictly observed.

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POSITIVE AI STATEMENT

During the preparation of this manuscript, the authors used QuillBot to improve the clarity and readability of the text. Following the use of this tool, the authors critically reviewed and revised the manuscript as necessary and accept full responsibility for the accuracy, integrity, and content of the final publication.

ABBREVIATIONS

%	Percent
ANOVA	Analysis of Variance
B	Unstandardized regression coefficient
BOD	Biochemical oxygen demand
CITC	Corrected item–total correlation
DAP	Diammonium phosphate
df	Degrees of freedom
df_1	Numerator degrees of freedom
df_2	Denominator degrees of freedom
F-value	F-statistic
GDP	Gross domestic product
ha	Hectare(s)
H-test	Kruskal–Wallis H statistic
Kg/ha/y	Kilograms per hectare per year
MS	Mean square
N	Sample size
p-value	Probability (significance) value
r	Pearson correlation coefficient
R^2	Coefficient of determination
SD	Standard deviation
SE	Standard error
SOC	Soil organic carbon
SS	Sum of squares
t-value	t-statistic
US$	United States Dollars
Z-test	Mann–Whitney U statistic
α	Cronbach's alpha coefficient
η^2	Effect size
χ^2	Chi-square statistic
β	Standardized regression coefficient

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