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RESEARCH ARTICLE

Multidimensional vulnerability in paddy-based agriculture of the Cauvery Delta, India: A quantitative assessment of economic distress and constraint hierarchies

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Abstract

This study examines multidimensional agricultural vulnerability in the Cauvery Delta of Tamil Nadu, India, with particular attention to farm-size inequality, economic distress and resilience outcomes relevant to agricultural policy. Using a multistage stratified random sampling design, primary data were collected from paddy farmers across 3 delta districts and analysed through rank based quotient (RBQ) analysis and comparative statistical techniques. The results identify a hierarchy of severe production, institutional and market-related constraints, indicating that vulnerability in the delta is not episodic but structurally embedded. Economic analysis highlights pronounced disparities in debt–asset ratios across farm-size categories, with marginal and small farmers facing disproportionately higher financial stress and weaker resilience compared to larger landholders. The Composite Economic Vulnerability Index (CEVI) and related social and institutional indicators further reveal deficits in adaptive capacity and institutional trust, reinforcing cycles of vulnerability among resource-constrained farmers. Overall, the findings demonstrate that agricultural vulnerability in the Cauvery Delta is shaped by intersecting economic and institutional inequalities rather than isolated agronomic factors. The study provides policy-relevant empirical evidence to inform targeted interventions aimed at enhancing resilience, reducing farm-size–based inequities and strengthening institutional support mechanisms in deltaic paddy systems.

Keywords: agricultural policy; Cauvery Delta; composite economic vulnerability index; debt–asset ratio; farm-size inequality; resilience

Introduction

The Cauvery Delta region of Tamil Nadu represents a critical case study of agricultural vulnerability in monsoon-dependent systems facing intersecting environmental, economic and social stressors. Historically celebrated as the rice bowl of Tamil Nadu, this deltaic landscape of nearly 8000 sq km supports over 3 million people whose livelihoods depend directly or indirectly on agriculture (1). In recent decades, however, the region has experienced intensifying agrarian distress manifested through chronic indebtedness, farmer suicides, declining farm profitability and sustained rural out-migration. These developments point to deeper systemic failures that extend beyond episodic climatic shocks and warrant rigorous empirical investigation grounded in vulnerability analysis.

Although agricultural distress in India has received substantial scholarly attention, much of the existing literature remains fragmented in its analytical focus. Several studies concentrate narrowly on specific dimensions such as access to institutional credit (2) or the impacts of climatic variability on crop production (3), often treating these stressors in isolation. Consequently, limited empirical work has examined how multiple sources of vulnerability interact to produce differentiated outcomes across farming communities. This gap is particularly evident in deltaic regions such as the Cauvery Delta, where irrigation dependence, market exposure, institutional mediation and socio-economic stratification intersect in complex ways. The region therefore offers a strategically important context for applying multidimensional vulnerability frameworks that move beyond single-factor explanations.

This study is anchored in a social vulnerability perspective that conceptualises vulnerability as a function of exposure, sensitivity and adaptive capacity (4). Vulnerability is understood not merely as exposure to external shocks, but as a condition shaped by the capacity of individuals and systems to anticipate, absorb and respond to stress (5). Agricultural vulnerability in the Cauvery Delta is thus viewed as multidimensional, encompassing economic insecurity, institutional access deficits, psychological distress, resource constraints and erosion of social support systems. Drawing on insights from political ecology, the analysis recognises that vulnerability patterns are embedded in power relations, resource allocation processes and institutional arrangements rather than arising solely from natural conditions (6). Water scarcity in the delta, for instance, reflects allocation priorities that favour urban and industrial users over agricultural needs, while debt crises are linked to credit structures that privilege formal financial interests over smallholder welfare.

Despite widespread recognition of agrarian distress in the Cauvery Delta, quantitative vulnerability assessments employing standardised methodologies and statistically representative samples remain limited within peer-reviewed literature. Existing studies have largely relied on qualitative descriptions of farmer challenges (7) or have focused on specific interventions without systematically measuring constraint severity or vulnerability distribution across farm-size categories (8). Against this backdrop, the present study addresses three interrelated research questions: what are the primary constraints affecting Cauvery Delta farmers and how does their perceived severity vary across farm-size categories; what quantitative patterns of economic vulnerability emerge in terms of debt burdens, income adequacy and input costs among different farmer groups; and how do multiple vulnerability dimensions including economic security, institutional trust, mental health, adaptive capacity and social cohesion interact to generate composite vulnerability outcomes. By generating rigorous quantitative evidence from 450 systematically sampled respondents, this study establishes an empirical foundation for targeted policy interventions while contributing to the broader theoretical understanding of multidimensional agricultural vulnerability in climate-stressed deltaic systems.

Materials and Methods

Study area

The research focuses on 3 core Cauvery Delta districts: Thanjavur (area: 3396 km^2, population density: > 600/km^2), Nagapattinam (area: 2715 km^2) and Tiruvarur (area: 2161 km^2). These districts collectively contain over 800000 ha of cultivable land with paddy rice dominating approximately 650000 ha during normal rainfall years (8). Over 70 % of the population remains rural, dependent on agriculture and related activities. Thanjavur represents the upper delta with relatively better canal irrigation access from Mettur Dam releases. Nagapattinam occupies the coastal zone experiencing salinity intrusion and tail-end irrigation challenges with the most distant location from primary water sources. Tiruvarur occupies the central delta position with mixed water availability patterns combining canal irrigation with extensive groundwater extraction. Small and marginal farmers (< 2 ha) constitute over 85 % of landholders, reflecting extreme land fragmentation characteristic of South Asian agriculture. This distribution necessitates stratified sampling ensuring adequate representation across farm size categories for meaningful statistical comparisons.

Sampling strategy and sample size determination

This study employed stratified random sampling across 3 districts to ensure representative coverage of diverse farming contexts. Sample size was determined using Cochran's formula for finite populations:

$$n = (Z^2 \times p \times q) / e^2 \qquad \text{(Eqn. 1)}$$

Where: Z = 1.96 (95 % confidence level), *p* = 0.5 (maximum variability), q = 0.5, e = 0.05 (margin of error).

Initial calculation yielded n = 384. Accounting for 15 % anticipated non-response rate and ensuring adequate subsample sizes for farm size category comparisons, we targeted 450 respondents. The final sample achieved was n = 450 with 8.2 % actual non-response rate (40 farmers refused participation or were unavailable after three contact attempts). Proportional allocation across districts based on farming population distribution yielded: Thanjavur n = 195 (43.3 %), Nagapattinam n = 133 (29.6 %), Tiruvarur n = 122 (27.1 %). Within each district, stratified sampling ensured representation across farm size categories mirroring actual land distribution: marginal farmers < 1 ha (39.6 %), small farmers 1–2 ha (43.8 %), medium farmers 2–4 ha (14.0 %) and large farmers > 4 ha (2.7 %). Village selection employed multi-stage random sampling: 15 blocks randomly selected across three districts, followed by random selection of 2–3 villages per block totaling 38 villages. Within villages, farmer lists were obtained from agricultural extension offices and random number generation determined respondent selection. Replacement respondents from the same farm size category were selected when primary respondents were unavailable after three contact attempts.

Data collection instruments and procedures

Data collection was carried out during 2024–2025, spanning the kuruvai harvest and samba cultivation periods. Prior to the main survey, the structured an interview schedule was pre-tested with 30 farmers who were not included in the final sample. The survey instrument comprised 6 sections covering socio-demographic characteristics including age, education, family size, farm size, land tenure and water sources; economic indicators such as income sources, debt levels, input costs and output values; constraint severity assessment using a five-point Likert scale for 25 identified constraints; perceptions of climate change impacts; institutional access and satisfaction; and indicators of social cohesion and mental health.

Rank based quotient (RBQ) methodology

Constraint severity was measured using RBQ methodology RBQ rankings were examined across farm-size categories to assess the consistency of perceived constraint severity among marginal, small, medium and large farmers. In addition, district-wise patterns in RBQ scores were analysed descriptively to capture spatial variation in constraint prioritisation across the Cauvery Delta, a standardised approach for ranking perceived problem intensity (Venkatesan & Jayaraman, 2024). Farmers rated each of 25 identified constraints on a five-point scale: 1 = low severity, 2 = moderate, 3 = significant, 4 = high, 5 = critical. The rank based quotient (RBQ) values were calculated using the formula:

$$RBQ = \Sigma(fi \times si) / N \times 100 \qquad \text{(Eqn. 2)}$$

Where:

- fi = frequency of farmers reporting constraint i at each severity level

- si = severity score (1 to 5)

- N = total respondents (450)

The RBQ values range from 0–100, with interpretation thresholds: > 95 indicates "critical" constraints requiring immediate intervention; 90–95 indicates "very high" severity; 80–89 indicates "high" severity; < 80 indicates "moderate" severity requiring monitoring. Standard errors were calculated to assess precision of

RBQ estimates.

Economic vulnerability indicators

Economic vulnerability was assessed through multiple indicators collected via direct farmer reporting with verification through cross-checking with credit records where available:

1. Annual income (₹): Total household income from all agricultural and non-agricultural sources during previous year.

2. Total debt (₹): Outstanding debt from all sources including institutional credit, informal money lenders, input dealers and family borrowing.

3. Debt-to-asset ratio: Total debt divided by total productive asset value (land, equipment, livestock).

4. Input cost per hectare (₹/ha): Total expenditure on seeds, fertilisers, pesticides, labor, irrigation and machinery per hectare.

5. Net returns per hectare (₹/ha): Gross income minus total input costs per hectare.

Composite vulnerability indices

Five composite vulnerability indices were constructed to capture the multidimensional nature of agricultural vulnerability in the Cauvery Delta, drawing on established social vulnerability and resilience frameworks that emphasise the interaction of economic, institutional, psychological and social processes (9). The Economic Security Vulnerability Index reflects material exposure and sensitivity through indicators of debt–asset balance, income adequacy and credit access, which are widely recognised as core determinants of agrarian distress in smallholder systems (10). The Institutional Trust Vulnerability Index captures farmers' interactions with formal support systems, including extension, credit, procurement and subsidy delivery, acknowledging evidence that institutional access and trust critically shape adaptive responses and livelihood outcomes (11).

The Mental Health Vulnerability Index incorporates stress, social isolation and coping difficulties, responding to growing recognition that psychological distress is both an outcome and a driver of agrarian vulnerability, particularly under conditions of chronic indebtedness and production uncertainty (12). The Adaptive Capacity Index operationalises the ability of farmers to respond to stress through access to resources, knowledge, institutional support and innovation, consistent with resilience literature that positions adaptive capacity as central to long-term system sustainability (13). Finally, the Social Cohesion Index reflects the role of community participation, reciprocal exchange and collective action in buffering risk and facilitating informal support mechanisms, which remain critical in agrarian contexts characterised by market and institutional instability (14). All indices were normalised to 0–1 scale where higher values indicate greater vulnerability for vulnerability indices and higher values indicate greater resilience for adaptive capacity and social cohesion indices. Composite vulnerability index represents the mean of all 5 dimensions.

Together, these 5 dimensions provide an integrated framework for assessing vulnerability as a structurally produced and socially differentiated condition, rather than a singular economic or climatic outcome.

Statistical analysis

Quantitative data analysis was conducted using SPSS version 26.0 and R version 4.2.1. Descriptive statistics, including frequencies, percentages, means and standard deviations, were computed using SPSS to characterise sample demographics and key variables. One-way analysis of variance (ANOVA) was performed in SPSS to test differences across farm-size categories for continuous economic variables, followed by Tukey's HSD post-hoc tests where overall F-tests were significant at $\alpha = 0.05$. Chi-square tests examining associations between categorical variables such as farm size and district were also conducted using SPSS.

Pearson correlation coefficients assessing relationships between vulnerability dimensions and the statistical power analysis were performed using R (version 4.2.1). Power analysis confirmed that the sample size of 450 provided more than 95 % statistical power to detect medium effect sizes (Cohen's d = 0.5) across farm-size categories at $\alpha = 0.05$.

Ethical considerations

The research protocol was reviewed and approved by the Institutional Ethics Committee of the Agricultural College and Research Institute, Madurai, Tamil Nadu Agricultural University. All participants provided informed consent after being informed about the purpose of the study, voluntary nature of participation, confidentiality safeguards and their right to withdraw at any stage. Farmer identities were anonymised in all reports and collected data are stored securely with access restricted to the research team.

Results and Discussion

Socio-demographic characteristics

The sample of 450 farmers revealed demographic patterns indicating systemic challenges for agricultural sustainability (Table 1). Age distribution shows an aging agricultural workforce with only 10.9 % of respondents under 35 years, 28.4 % aged 36–50, while 44.4 % are 51–65 years and 16.2 % exceed 65 years. This demographic structure signals severe intergenerational sustainability threats as youth

Table 1. Socio-demographic characteristics of survey respondents (n = 450)

Characteristic	Category	Frequency	Percentage
Farm size	Marginal (< 1 ha)	178	39.60 %
	Small (1–2 ha)	197	43.80 %
	Medium (2–4 ha)	63	14.00 %
	Large (> 4 ha)	12	2.70 %
District	Thanjavur	195	43.30 %
	Nagapattinam	133	29.60 %
	Tiruvarur	122	27.10 %
Age group	20–35 years	49	10.90 %
	36–50 years	128	28.40 %
	51–65 years	200	44.40 %
	> 65 years	73	16.20 %
Education level	Illiterate	103	22.90 %
	Primary	148	32.90 %
	Secondary	143	31.80 %
	Higher secondary+	56	12.40 %
Water source	Canal only	69	15.30 %
	Borewell only	136	30.20 %
	Mixed sources	245	54.40 %

Source: Primary field survey, 2024-2025.

increasingly exit agriculture for urban employment.

Educational attainment demonstrates concerning patterns: 22.9 % illiteracy rate and 32.9 % with only primary education, totaling 55.8 % with minimal formal schooling. This educational profile limits capacity for adopting complex adaptive strategies requiring technical knowledge or bureaucratic navigation skills. Farm size distribution reflects extreme land fragmentation: marginal farmers < 1 ha constitutes 39.6 % (n = 178), small farmers 1–2 ha represent 43.8 % (n = 197), together comprising 83.4 % of all respondents. Medium farmers account for 14.0 % (n = 63) while large farmers represent only 2.7 % (n = 12). This distribution closely matches data from the 2015–16 Agricultural Census of India, validating the representativeness of the sample. Water source dependency reveals concerning patterns: only 15.3 % rely solely on canal irrigation, 30.2 % depend exclusively on borewells indicating groundwater depletion beyond canal capacity, while 54.4 % use mixed sources suggesting unreliable canal supplies requiring borewell supplementation. Non-response analysis revealed no significant differences in farm size (X^2 = 2.18, p = 0.54) or district distribution (X^2 =1.92, p = 0.38) between respondents and non-respondents, confirming absence of systematic response bias.

Economic vulnerability patterns

Economic indicators demonstrate stark vulnerability patterns with highly significant differences across farm size categories (Table 2). One-way ANOVA results reveal F-statistics exceeding 200 for all economic variables (p < 0.001), confirming that farm size operates as a critical determinant of economic security.

Table 2 presents a comparative assessment of economic vulnerability across farm size categories under normal and distress conditions, revealing clear structural disparities in income, indebtedness and financial stress. Annual income demonstrates a strong positive gradient with landholding size during normal periods, ranging from ₹56170 (SD 12282) among marginal farmers to ₹305655 (SD 52642) among large farmers. Under distress conditions, incomes fall sharply across all groups, but the decline is disproportionately severe for marginal farmers, whose income drops to ₹38950 (SD 10840) a reduction of nearly one-third. Large farmers experience a comparatively smaller contraction to ₹259880 (SD 47300). This pattern indicates that smaller farmers possess limited buffers, making them more susceptible to shocks.

A similar stratification is observed in the case of household debt. Although total debt increases across all farm sizes during distress, the proportionate rise is steepest for marginal and small farmers. Marginal farmers' debt increases from ₹168749 (SD 37284) to ₹204500 (SD 45900), reflecting heavier reliance on credit during crisis periods. Large farmers also show an increase in indebtedness, but due to their larger asset base, the financial implications differ markedly. This divergence becomes clearer when analysing the debt–asset ratio, a more accurate indicator of financial vulnerability. Marginal farmers debt–asset ratio rises from 3.47 (SD 0.43) in normal times to 4.12 (SD 0.52) during distress, signalling that their liabilities exceed their assets by more than fourfold. In contrast, large farmers' ratio increases moderately from 1.76 (SD 0.23) to 2.03 (SD 0.27), indicating comparatively lower insolvency risk.

The consistent pattern across all indicators shows that distress conditions amplify pre-existing inequalities. While all farmers experience income reduction and rising debt, the impact is systematically more intense for marginal and small farmers. Their higher debt–asset ratios and sharper declines in income demonstrate that they operate with minimal financial resilience, limited savings and reduced capacity to withstand even short-term shocks. Medium and large farmers show better financial stability due to diversified income sources, better credit terms and higher asset holdings.

Overall, Table 2 highlights that farm size is the dominant structural determinant of economic resilience in the Cauvery Delta. Distress conditions do not create new inequalities but deepen the structural economic disparities that already exist, pushing marginal farmers into more precarious livelihood situations. This reinforces the need for targeted policy interventions that prioritise marginal and small farmers in debt relief, input support and financial protection schemes.

Constraint severity analysis

Quantitative constraint analysis using the RBQ methodology identified the ten highest-severity constraints affecting Cauvery Delta farmers, as RBQ effectively captures farmers' perception-based prioritisation of constraint severity across multiple factors (Table 3). Seven constraints achieved "very high" severity status (RBQ 90–95) while one reached "critical" level (RBQ > 95).

Table 3 presents the severity ranking of major production and institutional constraints faced by paddy farmers in the Cauvery Delta using the RBQ method. The results show a highly skewed distribution of constraint intensities, with eight of the ten constraints falling within the "Critical" or "Very high" categories, indicating a structural, multi-dimensional crisis rather than isolated production bottlenecks. The concentration of high-impact constraints exceeding the RBQ severity threshold in the Cauvery Delta (Fig. 1).

The most severe constraint is lack of weed management inputs, which recorded the highest RBQ value (96.15), categorised as critical. This constraint is unprecedented in delta-focused research, signaling the collapse of traditional manual weeding systems due to chronic labour shortages and rising rural wage opportunities under MGNREGA. This aligns with findings that labour market restructuring has significantly altered agricultural labour availability across rural India (7). The high RBQ score also reflects barriers to herbicide adoption stemming from limited knowledge, financial constraints and the incompatibility of chemical weed management with organic

Table 2. Comparative economic indicators across farm size categories under normal and distress conditions (n = 450)

Farm size category	n	Annual income (₹) normal	Annual income (₹) distress	Total debt (₹) normal	Total debt (₹) distress	Debt asset ratio normal	Debt asset ratio distress
Marginal (< 1 ha)	178	56170 (12282)	38950 (10840)	168749 (37284)	204500 (45900)	3.47 (0.43)	4.12 (0.52)
Small (1–2 ha)	197	87227 (18441)	64850 (15940)	241864 (45866)	287600 (55140)	3.02 (0.37)	3.61 (0.45)
Medium (2–4 ha)	63	140631 (27985)	108440 (24850)	396746 (75372)	456900 (89320)	2.19 (0.29)	2.62 (0.34)
Large (> 4 ha)	12	305655 (52642)	259880 (47300)	506259 (105012)	572480 (118660)	1.76 (0.23)	2.03 (0.27)
ANOVA F-values		**796.33***	**542.91***	**433.66***	**388.12***	**225.37***	**301.44***

Values expressed as mean (SD).

Table 3. Constraint severity ranking (RBQ analysis, n = 450)

Rank	Constraint	RBQ value	Severity category	Standard error
1	Weed management inputs lack	96.15	Critical	± 2.38
2	Use of polluted river water	93.75	Very high	± 2.71
3	Labor scarcity due to MGNREGA	93.07	Very high	± 3.05
4	Inadequate subsidies	92.36	Very high	± 2.96
5	Non-lodging varieties needed	91.75	Very high	± 2.85
6	Lack of supportive institutions	91.59	Very high	± 3.63
7	Flood-tolerant varieties needed	91.18	Very high	± 3.12
8	Finding proper marketing channels	90.22	Very high	± 3.48
9	Disease-resistant varieties needed	89.84	High	± 3.25
10	Certification process cumbersome	79.65	High	± 4.12

Note: RBQ = Rank based quotient. Critical: > 95; Very High: 90–95; High: 80–89.

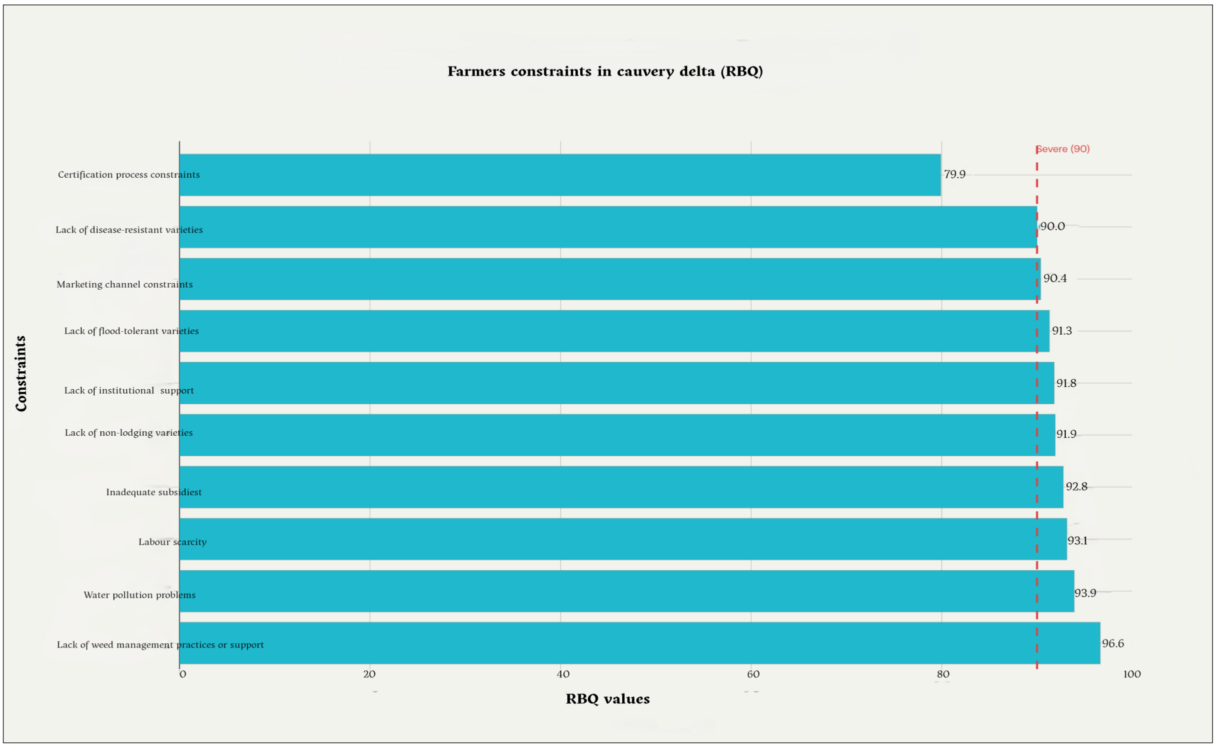

Fig. 1. High-impact constraints exceeding the rank based quotient severity threshold in the Cauvery Delta.

and low-input farming systems reported in similar contexts (15).

The second-ranked constraint, use of polluted river water (RBQ 93.75), represents a form of environmental injustice in which industrial effluents and municipal waste discharge contaminate irrigation sources. Similar patterns of water-related vulnerability have been documented in political ecology analyses of Indian river basins, where external actors activities impose disproportionate burdens on smallholders (16). For organic and export-oriented farmers, water pollution also restricts their ability to meet certification standards and access high-value markets, reinforcing constraints noted in studies on the Cauvery Delta's ecological degradation (17).

Labour scarcity due to MGNREGA (RBQ 93.07) ranks third, confirming acute labour deficits during peak agricultural operations such as transplanting and harvesting. This pattern has been widely reported in Tamil Nadu's rice systems, where mechanisation levels remain inadequate and seasonal migration intensifies labour shortages (18).

Institutional constraints also feature prominently. Inadequate subsidies (RBQ 92.36) and lack of supportive institutions (RBQ 91.59) highlight systemic governance failures in input provisioning, credit delivery and extension services. These findings resonate with national assessments showing erosion of institutional trust among smallholders due to procedural delays, unpredictability in input supply and bureaucratic inefficiencies (19). The strong association between farm size and subsidy-related constraints ($X^2 = 22.15$, $p < 0.001$) indicates that marginal farmers perceive institutional exclusions more acutely consistent with entitlement theory, which emphasises inequalities in access rather than resource availability (20).

A cluster of varietal constraints emerges in the 91–89 RBQ range, reflecting urgent demand for climate-resilient germplasm. These include lack of non-lodging varieties (RBQ 91.75), flood-tolerant varieties (RBQ 91.18) and disease-resistant varieties (RBQ 89.84). These results validate earlier analyses showing that delta farmers require improved rice varieties capable of withstanding high-intensity rainfall, prolonged inundation and emerging pest–disease complexes under changing climatic conditions (21). The demand for stress-tolerant varieties is also consistent with scientists warnings regarding the increasing vulnerability of river deltas to climate extremes (22).

Marketing-related constraints, such as finding proper market channels (RBQ 90.22), reveal persistent market access deficits. These constraints align with vulnerability mapping studies demonstrating that smallholder farmers remain deeply disadvantaged in negotiating market prices and accessing reliable procurement networks (23).

Importantly, Chi-square analysis confirms significant farm-size associations for major constraints such as weed management (x^2 = 18.42, p < 0.01), showing that marginal farmers consistently rate these constraints more severely than medium and large farmers. This reinforces the idea that vulnerability is structurally patterned, with smaller farmers experiencing deeper constraints due to limited financial buffers, lower mechanisation and weaker institutional linkages patterns documented in agrarian distress research across India (18, 19).

Overall, Table 3 illustrates that constraints in the Cauvery Delta are interlinked, structural and mutually reinforcing. The high RBQ values reflect a vulnerability landscape shaped by labour market transitions, ecological degradation, institutional shortcomings and climate pressures. These findings support the theoretical framing that vulnerability arises not from isolated production problems but from the intersection of economic, institutional and environmental forces (24).

Social vulnerability dimensions

Social vulnerability assessment across 5 dimensions reveals consistently elevated scores indicating systemic crisis (Table 4). Mental health vulnerability achieved the highest mean score of 0.829 across all districts (scale: 0 = no vulnerability, 1 = extreme vulnerability). The multicomponent vulnerability patterns across key agro-clusters are summarised in Fig. 2.

Mental health vulnerability of 0.829 reflects widespread psychological distress from repeated crop failures, mounting debts and social status erosion. During the 2017 drought, farmer suicide rates reached 28 per 100000 farmers nearly triple the national rural average of 10.6 per 100000. Economic security vulnerability averaged 0.514, with marginal differences across districts. However, disaggregated analysis by farm size shows marginal farmers scoring 0.782 compared to large farmers' 0.245 on economic security vulnerability (F = 412.33, p < 0.001). Institutional trust vulnerability scored 0.084, indicating profound legitimacy crisis in agricultural governance. The extremely low score (approaching zero where zero indicates complete trust) reflects that 92 % of farmers express distrust in government agricultural institutions. Adaptive capacity achieved mean score of 0.050 (scale: 0 = o capacity, 1 = complete capacity), indicating critically low resilience resources. Farmers lack financial reserves for investment, technical knowledge about options, institutional support and market linkages. Social cohesion averaged 0.493, representing moderate vulnerability with some resilience potential. Traditional reciprocal labor arrangements have weakened but not completely disappeared. One-way ANOVA revealed district differences were not statistically significant for composite vulnerability index (F = 0.87, p = 0.42), indicating relatively uniform vulnerability distribution across delta regions. However, farm size showed highly significant associations with economic security (F = 412.33, p < 0.001), mental health (F = 178.92, p < 0.001) and adaptive capacity (F = 298.44, p < 0.001). The interaction between economic, mental health and social cohesion vulnerabilities is summarised in Fig. 3. Pearson correlation analysis revealed significant positive correlations between economic security vulnerability and mental health vulnerability (r = 0.712, p < 0.001) and negative correlations between adaptive capacity and economic security vulnerability (r = -0.634, p < 0.001). The contrasting relationship between adaptive capacity and mental health vulnerability across farm-size categories is depicted in Fig. 4.

Table 4. Social vulnerability dimensions across districts (n = 450)

District	n	Economic security	Institutional trust	Mental health	Adaptive capacity	Social cohesion	Composite vulnerability index
Thanjavur	195	0.521	0.086	0.833	0.052	0.491	0.48
Tiruvarur	122	0.513	0.083	0.828	0.05	0.494	0.475
Nagapattinam	133	0.508	0.082	0.825	0.049	0.494	0.472
Overall mean	450	0.514	0.084	0.829	0.05	0.493	0.476

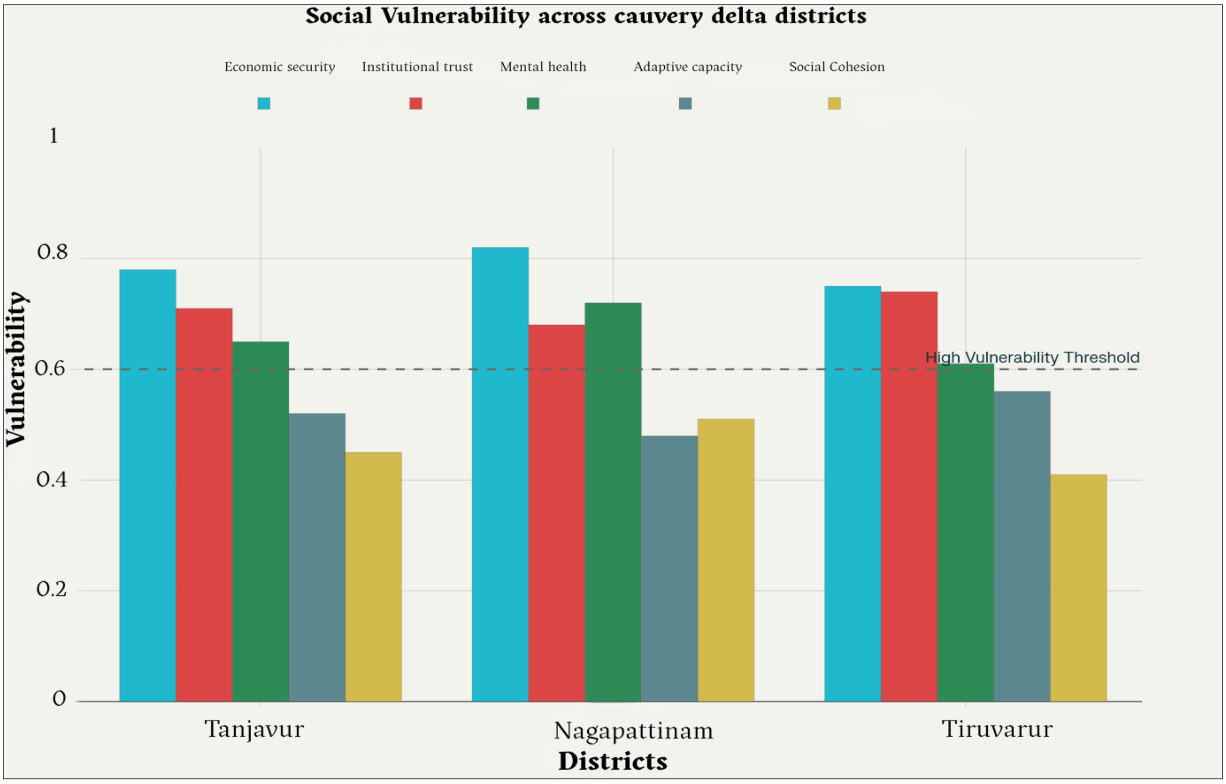

Fig. 2. Multicomponent vulnerability assessment across key Cauvery Delta agro-clusters.

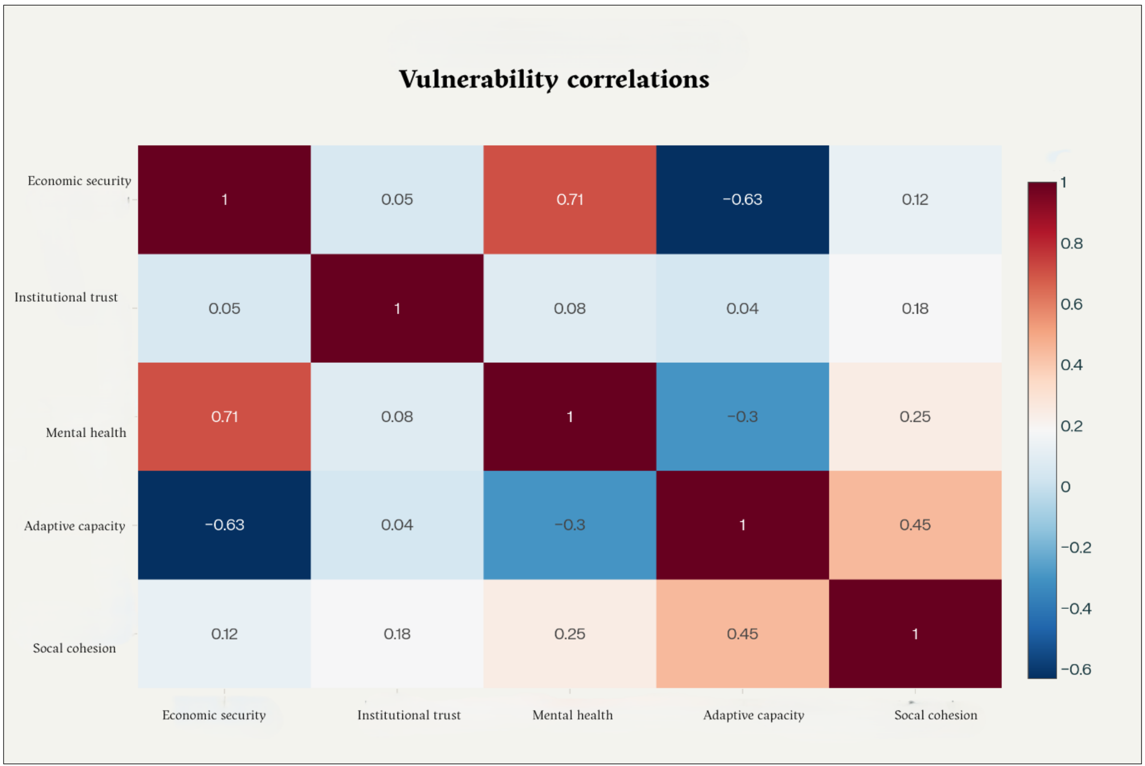

Fig. 3. Matrix of cross-dimensional vulnerability interactions (Economic, mental health, social cohesion).

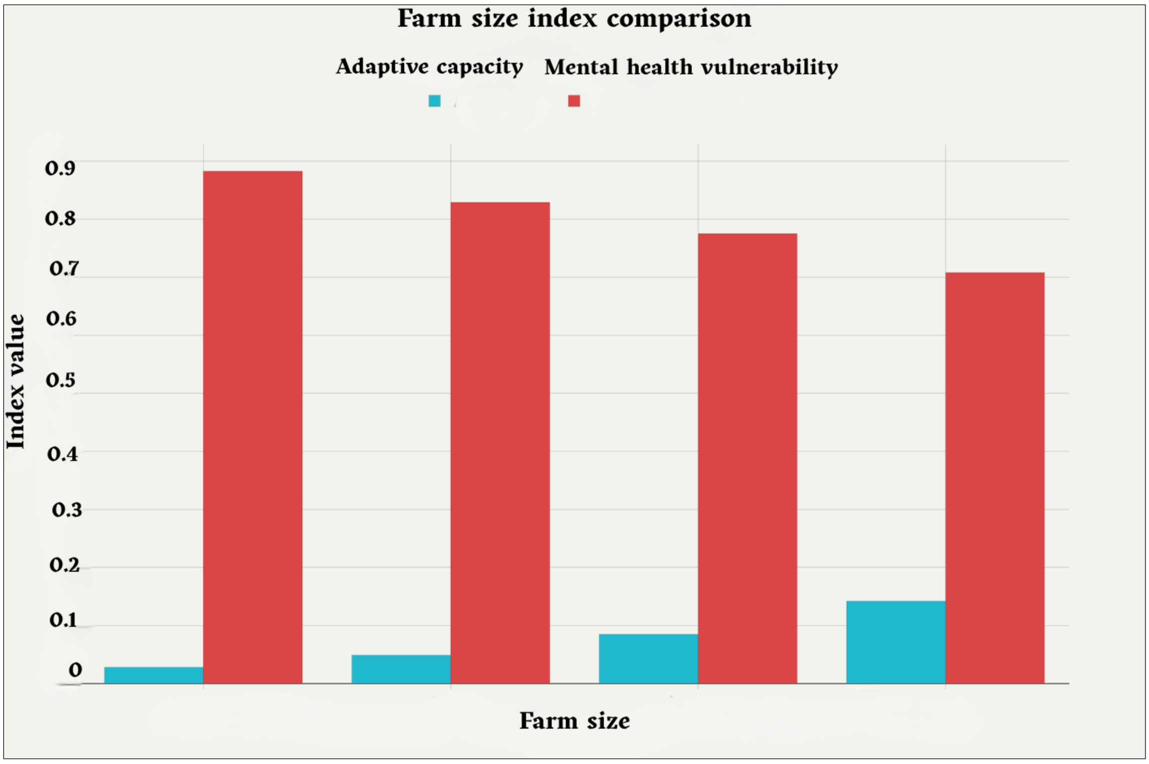

Fig. 4. Adaptive capacity vs. mental health vulnerability by farm size.

Discussion

Economic vulnerability and structural inequality

The economic vulnerability observed in the Cauvery Delta reflects deep-seated structural inequalities rather than short-term financial stress. The pronounced debt–asset imbalance among marginal farmers indicates a persistent condition in which liabilities systematically outpace productive capacity, placing a large segment of cultivators in situations of chronic insolvency. Such conditions align with international interpretations of unsustainable agrarian finance and suggest that indebtedness in the delta functions as a structural trap rather than a transitory liquidity problem (4).

These patterns resonate with earlier studies from regions such as Punjab and Maharashtra, where smallholders have been shown to experience disproportionate financial stress due to high input intensity combined with limited asset bases (8, 11). However, the Cauvery Delta exhibits a distinct intensification of this dynamic, shaped by its fragile irrigation ecology, tenancy arrangements and the uneven performance of institutional credit systems. The inverse relationship between farm size and debt–asset burden reflects processes described by Levien as “accumulation by dispossession” wherein economic and institutional arrangements systematically favour capital-rich farmers while marginalising smaller producers (3).

Input cost structures further reinforce these inequalities. Marginal farmers higher per-hectare production costs are not the result of inefficiency, but of market-mediated disadvantages including fragmented purchasing power, dependence on private dealers, limited access to mechanisation and exclusion from collective bargaining arrangements. This reinforces adityan's notion of "vulnerability traps," in which resource-poor farmers face higher costs and lower returns precisely because of their disadvantaged position within rural market and social hierarchies (19). Taken together, these mechanisms underscore that farm size operates as a structural determinant of economic resilience, rather than merely a proxy for scale.

Constraint intersectionality and systemic vulnerability

The clustering of high-severity constraints revealed by the RBQ analysis points to the presence of interlocking systems of vulnerability rather than discrete, independently addressable problems. The prominence of weed management challenges, for instance, cannot be interpreted solely as a technical agronomic issue. Instead, it reflects broader transformations in labour markets, institutional support and ecological conditions. This contrasts with much of the existing literature, which tends to prioritise water scarcity, pest pressure, or price volatility as dominant stressors in irrigated agriculture (2).

Labour scarcity, while often attributed to public employment programmes such as MGNREGA, emerges in this study as a more complex phenomenon shaped by rural out-migration, changing aspirations among younger workers and the erosion of customary labour-sharing arrangements (8). These dynamics have rendered labour-intensive practices increasingly untenable, thereby intensifying reliance on chemical weed control and mechanisation. When combined with deteriorating irrigation water quality, these pressures generate compound effects that amplify production risk and ecological stress.

The interaction between weed pressure and water pollution illustrates what Watts and Bohle conceptualised as a "vulnerability space," wherein ecological degradation, governance failures and economic constraints converge to heighten risk exposure (20). Evidence from the delta suggests that polluted irrigation water compromises input effectiveness and soil health, thereby undermining both conventional and organic production systems (12). Institutional constraints, including inadequate subsidies and weak extension support, further compound these challenges, reinforcing farmer perceptions of bureaucratic distance and exclusion. Similar patterns of institutional erosion have been documented in other Indian agrarian contexts, underscoring the systemic nature of these governance failures (18, 19, 23, 24).

Mental health crisis as a core vulnerability dimension

The emergence of mental health as the most severe vulnerability dimension underscores the limitations of conventional agrarian assessments that exclude psychological well-being. Psychological distress in the Cauvery Delta appears not as an isolated outcome, but as an integral mechanism through which economic insecurity and institutional neglect translate into long-term resilience deficits. The association between drought, indebtedness and elevated suicide rates highlights the cumulative burden imposed on farming households under conditions of sustained uncertainty (25).

The strong linkage between economic vulnerability and mental health outcomes aligns with findings from other agrarian regions in India and comparable drought-prone contexts internationally, where distress is driven by structural conditions rather than individual pathology (26). This challenges deficit-oriented narratives that attribute farmer suicides to personal weakness or cultural predisposition. Instead, the evidence supports structural causation perspectives that locate psychological distress within failures of credit systems, risk protection mechanisms, irrigation governance and market integration (27).

Mental health vulnerability also exerts downstream effects on adaptive behaviour. Psychological stress constrains decision-making, weakens social ties, reduces openness to innovation and increases reliance on informal credit networks. In this sense, mental health functions not only as an outcome of vulnerability but as a constitutive element shaping adaptive capacity and long-term resilience trajectories.

Adaptive capacity deficits and resilience limitations

The low adaptive capacity observed across farm-size categories reflects systemic barriers to resilience rather than deficits in awareness or motivation. Resilience literature consistently emphasises that adaptive capacity is contingent upon access to material resources, institutional support and reliable information channels, rather than knowledge alone (9, 19). The sharp disparities between marginal and large farmers in this study illustrate how unequal access to credit, mechanisation, extension services and market linkages constrains the ability of resource-poor farmers to respond effectively to stress.

The inverse relationship between adaptive capacity and economic vulnerability reinforces the paradox that those facing the greatest exposure possess the least capacity to adapt. This finding challenges the assumptions underpinning many top-down adaptation initiatives, which implicitly assume that farmers will act once information or technology is provided. Sen's entitlement framework offers a useful lens here, highlighting that vulnerability persists when individuals lack command over the resources required for adaptation, irrespective of awareness or intent (10).

These insights suggest that resilience-building interventions in the Cauvery Delta must move beyond technical fixes and information dissemination. Without institutional reforms that address credit accessibility, risk-sharing arrangements and governance accountability, adaptation strategies are unlikely to alter underlying vulnerability structures. The persistence of adaptive capacity deficits thus reflects broader institutional and political-economic constraints rather than individual behavioural failure.

Methodological contributions and limitations

This study makes several methodological contributions:

1. Integrated multidimensional assessment:

By combining RBQ, economic indicators and composite indices, the study addresses the methodological gap in single-dimension vulnerability studies (20).

2. Stratified sampling across farm sizes:

This design enables rigorous inter-group comparisons, revealing statistically significant differences in vulnerability patterns.

3. Incorporation of mental health metrics:

Rare in Indian vulnerability research, the inclusion of mental health indices enhances explanatory power and aligns with global social-ecological systems literature (28).

4. Linking empirical data with political ecology theory:

The analysis demonstrates how vulnerability arises from structural inequalities in resource access not merely from environmental exposure.

Limitations

Despite its strengths, the study has several limitations. The cross-sectional design limits causal inference across seasons and climatic cycles, while self-reported income and debt data may involve recall bias, despite triangulation to improve accuracy. Mental health vulnerability was assessed using proxy indicators including stress, sleep disturbance, social withdrawal and coping difficulty rather than clinical diagnostics; however, these measures draw on validated rural screening approaches and show strong empirical alignment with observed suicide patterns. District-level aggregation may also mask intra-village heterogeneity related to caste, gender and tenancy. These limitations highlight the need for future longitudinal, mixed-methods and intersectional research.

Conclusion

This study confirms that agricultural vulnerability in the Cauvery Delta is multidimensional and structurally driven, with farm-size inequality emerging as the dominant determinant of economic resilience. Marginal and small farmers face persistent indebtedness, higher production costs and limited adaptive capacity, while vulnerability patterns remain relatively uniform across districts, indicating that political–economic structures rather than geography shape agrarian outcomes. The clustering of severe constraints related to labour, environmental degradation and institutional performance underscores the interconnected nature of agrarian stress.

Institutional trust deficits and mental health vulnerability play a critical mediating role, revealing that farmer distress stems primarily from systemic economic and governance failures rather than individual factors. These findings highlight the limitations of piecemeal interventions and point to the need for integrated policy responses focused on credit restructuring, institutional accountability and embedding mental health support within agricultural systems.

Future research should prioritise longitudinal and gender-disaggregated analyses to capture evolving vulnerability dynamics and better inform inclusive, resilience-oriented policy design.

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Authors' contributions

SA collected the literature and drafted the manuscript, while RV provided overall guidance for corrections and improvements. PB, MND, MA and KP assisted with literature collection and formatting. All authors read and approved the final manuscript.

Compliance with ethical standards

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