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Multi-Dimensional Yield Decline in Kerala's Kole Wetlands: Climate, Agronomy, and Governance Challenges

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Abstract: The Kole wetlands of Kerala constitute a vital agro-ecological system that supports a large share of the state's rice production but has experienced a persistent decline in productivity over the past decade. This study examined the multiple drivers of yield reduction through an integrated approach combining secondary datasets (2019–2024), structured farmer surveys, and field-level diagnostics. Annual rice yield, area sown, and rainfall records were compiled from official agricultural and meteorological agencies, while primary data documented farmers' perspectives on production constraints and management practices. Key limiting factors were erratic climatic patterns, delayed or inadequate drainage maintenance, sub-optimal agronomic practices, and gaps in the institutional delivery of inputs and technical support. The combined quantitative and qualitative evidence demonstrates that climate stressors, infrastructural limitations, and governance bottlenecks act synergistically to depress yields in this seasonally inundated landscape. The findings underscore the urgency of coordinated interventions focused on water-management governance, timely input supply, and locally responsive policy measures to enhance resilience and restore the long-term sustainability of rice cultivation in Kerala Kole wetlands.

Keywords: Agronomic constraints, Climate variability, Drainage infrastructure, Kole lands, Institutional governance, Paddy productivity, Wetland ecosystems.

1. INTRODUCTION

The Kole wetlands in Kerala, encompassing approximately 13,632 ha across Thrissur and Malappuram districts, form a crucial agro-ecological landscape that contributes significantly to the state's *Puncha* (dry-season) rice production. Their hydrology, characterized by an intricate system of bunds, sluices, and canals, supports both agriculture and key ecosystem services, including flood control and groundwater recharge (Sujana & Sivaperuman, 2008; Krishnankutty et al., 2013; Sunil et al., 2024). Despite these functions and a history of high productivity, paddy yields in this region have exhibited a sustained decline over the past decade (Prasad & Kuruvila, 2024).

This yield downturn reflects the interplay of climatic, agronomic, and institutional stressors. Climate projections for Kerala indicate rising temperatures and increasing rainfall variability during critical crop-growth stages, phenomena that disrupt flowering, induce heat stress, and prolong waterlogging—each of which adversely affects yield and crop duration (Aswathi et al., 2022; Riya & Ajithkumar, 2023). Erratic rainfall patterns have been shown to delay transplanting and impede fertilizer application, while high-intensity storms can damage bunds and drainage structures, exacerbating the effects of flooding and submergence. Agronomic constraints further reduce productivity. Soil salinity, continued use of obsolete rice varieties, and deterioration of field infrastructure contribute to declining yields (Krishnankutty et al., 2013; The Hindu, 2023). Limited seed replacement and overuse of nitrogenous fertilizers encourage pest outbreaks and nutrient imbalances, compounding the effects of climate stress. In several *padasekharams*, maintenance of drainage canals and sluice gates has lagged behind needs, decreasing the efficiency of water removal and increasing susceptibility to both flood and drought conditions. Institutional factors also play a decisive role. Weak coordination among local agencies, delays in input delivery, and non-compliance with bunding deadlines undermine field management and the collective action required to maintain the delicate hydrology of the wetlands. Such governance gaps reduce the capacity

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of farmers to respond to changing climatic conditions, creating a cycle of risk that further depresses yields (Prasad & Kuruvila, 2024).

Given the strategic importance of the Kole wetlands for Kerala's food security and the livelihoods of farming communities, there is an urgent need for an empirically grounded assessment of the drivers of yield decline. While previous studies have documented aspects of climate variability, agronomic stress, and institutional constraints, a comprehensive, multi-dimensional analysis integrating these factors remains limited.The present study addresses this gap by combining time-series data from 2019–2024 with structured farmer surveys, field diagnostics, and robust statistical modeling, including regression analysis. This approach aims to isolate the principal yield-limiting factors and provide actionable recommendations for scalable, context-specific interventions to restore productivity and enhance the sustainability of rice cultivation in this ecologically and economically vital wetland system.

2. MATERIALS AND METHODS

2.1 Study Area and Sampling Design

The investigation was conducted in the Thrissur–Ponnani Kole wetlands, India, situated between 10°20' and 10°40'N latitudes and 75°58' and 76°11'E longitudes. The Kole region covers about 13,632 ha of seasonally inundated lowlands distributed across Thrissur and Malappuram districts. The wetlands are characterized by clayey alluvial soils, prolonged monsoon flooding, and rich aquatic biodiversity that supports *Puncha* (dry-season) rice cultivation. The wetlands also perform crucial ecological functions such as flood attenuation, groundwater recharge, and habitat support for migratory birds and aquatic fauna. The rice fields are organized into cooperative farming units known locally as *padasekharams*, each administered by farmer committees (*Padasekharam samithis*) that coordinate activities under the jurisdiction of the grama and block panchayats (Vivek & Bonny, 2024).

For field investigation, twelve padasekharams (>50 ha each) were selected using a stratified sampling approach to capture variation in hydrology, drainage condition, and management intensity. These representative sites provided a cross-section of the region's agro-ecological and institutional diversity for subsequent data collection and analysis.

2.2. Data Sources and Collection

Both secondary and primary data streams were integrated to provide a comprehensive dataset. Secondary data covering the period 2019–2024 on annual paddy yield (kg ha^{-1}) and total sown area (ha) were compiled from the *Atlas of Kole Lands of Kerala, Volume 2* (Sunil et al., 2024). Temperature data (°C) for Thrissur and Malappuram were retrieved from the India Meteorological Department's Hydromet Web Portal (IMD, 2025) and cross-validated with satellite-derived gridded dataset available through NASA's POWER Data Access Viewer (NASA Langley Research Center, 2025).

Primary data were collected between December 2023 and March 2024 through structured interviews with 120 farmers proportionally distributed across the 12 sampled padasekharams. Respondents were identified using a snowball sampling technique to ensure adequate representation of experienced rice farmers within each farming unit. The semi-structured questionnaire elicited detailed information on drainage performance, bund and sluice conditions, fertilizer application rates and timing, seed replacement and varietal choice, pest and disease incidence, labour availability and cost, and awareness and uptake of government agricultural support schemes. To complement self-reported information, field-level observations were simultaneously undertaken using a standardized checklist to document canal siltation, weed burden, crop establishment success, and the physical integrity of bunds and sluice gates. This mixed-method approach ensured that both farmer perceptions and objective field diagnostics informed the analysis.

2.3. Analytical Variables

The dependent variable was paddy yield (kg ha^{-1}), obtained from official production records for the study period. Explanatory variables included maximum temperature during the flowering stage (°C), drainage status, sluice and bund maintenance, fertilizer application rate (kg ha^{-1}), seed type, visible salinity indicators, labour cost (₹ ha^{-1}), and participation in government support schemes.

Maximum temperature (°C) was treated as a continuous variable. Drainage status was assessed through field observations using a three-point ordinal scale (Good = 3, Moderate = 2, Poor = 1) based on channel openness, water stagnation, and drainage efficiency. Sluice and bund maintenance were recorded as a binary variable (Maintained = 1, Not maintained = 0) depending on structural condition and timely operation.

Fertilizer application rate (kg ha^{-1}) was estimated from farmer-reported nutrient inputs per hectare. Seed type was categorised as high-yielding variety (HYV = 1) or local landrace (0). Visible salinity indicators were recorded as a binary variable (Present = 1, Absent = 0) based on field signs such as salt crust formation and poor crop establishment. Labour cost (₹ ha^{-1}) was calculated as the total expenditure on hired and family labour per hectare for the cropping season. Participation in government support schemes was measured as a binary variable (Participated = 1, Did not participate = 0).

All economic figures were standardised to 2024 price levels using the Kerala Consumer Price Index to ensure comparability across years (Kerala State Planning Board, 2024b). Farmer-reported production constraints were prioritised using the Garrett ranking technique to identify the most critical challenges affecting paddy cultivation.

2.4. Statistical Analysis

Data were analysed using IBM SPSS version 28.0. Descriptive statistics were used to summarise temporal trends in yield, maximum temperature and cultivated area. Pearson's correlation coefficients were calculated to measure the strength and direction of relationships between maximum temperature and yield. An empirical simple linear regression model was employed to estimate the influence of maximum temperature during the flowering stage on yield variability. The model was specified as (Eq.1):

$$Y_i = \beta_0 + \beta_1 T_i + \varepsilon_i \quad (1)$$

where Y_i represents paddy yield (kg ha^{-1}), T_i denotes maximum temperature (°C), β_0 is the intercept, β_1 is the regression coefficient, and ε_i is the random error term. Model adequacy was evaluated using the coefficient of determination (R^2), and statistical significance was tested at the 5% probability level.

To evaluate productivity differences between well-managed and poorly managed *padasekharams*, a one-way analysis of variance was conducted. In addition, Chi-square tests were used to assess the association between farmers' awareness of government agricultural schemes and actual scheme uptake. Prior to analysis, assumptions of normality, linearity, and homogeneity of variance were verified to ensure the validity of statistical inferences.

3. RESULTS AND DISCUSSION

3.1. Yield trends and climatic variation

Padasekharam-level data for 2019–2023 show a coordinated decline in mean paddy yields concurrent with a rise in average maximum temperature (Tmax) during the reproductive (flowering) window. Specifically, reported values indicate mean Tmax at flowering increasing from 33.8 °C (2019) to 35.5 °C (2023), while mean yields dropped from 6,026 kg ha^{-1} to 4,112 kg ha^{-1} (Figure 1). Simple linear regression fitted to the five annual observations estimated a slope of aproximately –230 kg ha^{-1} $°C^{-1}$ (Yield = 12,800 – 230 × Tmax). Pearson's correlation analysis revealed a strong negative relationship between maximum temperature during the flowering stage and paddy yield ($r = -0.90$, $p < 0.05$). Simple linear regression further identified temperature as a major determinant of yield variability, explaining approximately 81% of the observed variation ($R^2 = 0.81$). The fitted model indicated that each 1°C increase in temperature was associated with an average yield decline of about 230 kg ha^{-1}. However, given the limited number of annual observations, the relationship should be interpreted as indicative rather than predictive.

The observed temperature–yield relationship is consistent

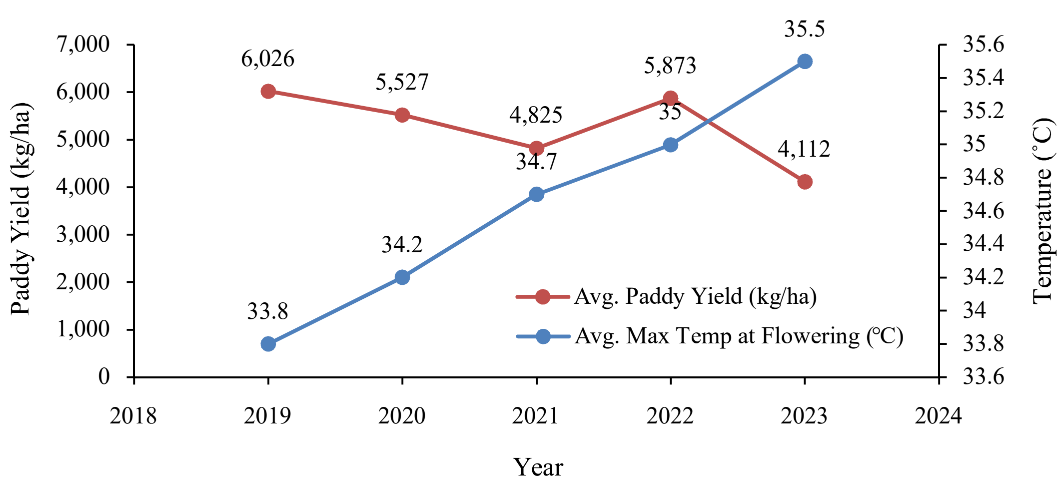

Figure 1. Average maximum temperature during flowering and corresponding paddy yield

with physiological and field evidence that reproductive-stage heat increases spikelet sterility and reduces grain set, thus sharply lowering yield (Peng et al., 2004; Jagadish et al., 2015; Krishnan et al., 2011). Peng et al. (2004) and Jagadish et al. (2015) document that both daytime maxima and elevated night temperatures at anthesis markedly reduce grain number and grain weight, while Krishnan et al. (2011) further highlight interactions among Tmax, vapor pressure deficit and water status that modulate realized damage in the field. Recent agronomic syntheses also demonstrate that modest reductions in spikelet fertility under high Tmax translate to large yield penalties at farm scale (Zhang et al., 2023). Given projected warming and increases in heat-extreme frequency in the region (state climate assessments and national projections), the observed sensitivity points to high exposure of Kole Puncha systems. Short-term adaptive measures include synchronizing planting dates to avoid peak anthesis heat, actively maintaining field water levels during flowering, and promoting heat-tolerant varieties (Jagadish et al., 2015; Zhang et al., 2023). Medium-term measures include strengthening the seed system for rapid deployment of tolerant cultivars and breeding programs targeting spikelet fertility under high T (Krishnan et al., 2011; Zhang et al., 2023).

3.2. Agronomic Drivers: Pests, Seed Systems and Soil Health

Garrett ranking of farmer responses places insect pest and disease outbreaks as the top agronomic constraint (Garrett mean = 79.6), followed by seed quality/varietal fatigue (74.3) and nutrient imbalance (69.8) (Table 1). Field diagnostics corroborate the survey: stem borer (*Scirpophaga incertulas*) and leaf folder (*Cnaphalocrocis medinalis*) dominated insect pressure in low, poorly drained fields, while bacterial leaf blight and sheath blight were more frequent in waterlogged and dense canopy conditions. These patterns reflect well-known pest–water–crop interactions: high humidity and delayed drainage favour fungal and bacterial pathogens and sustain vector populations (Savary et al., 2019).

Seed quality and varietal fatigue emerged as the second major constraint based on Garrett ranking (mean score = 74.3). Farmers reported the predominant and repeated use of the same local variety, indicating limited seed replacement and degeneration over time. This pattern may be due to dependence on farm-saved seed and inadequate access to certified seed systems, which can lead to reduced vigour and accumulation of seed-borne pathogens, as observed in similar smallholder systems (Jagadish et al., 2015; Vanlauwe et al., 2015).

Soil health and nutrient imbalance were ranked third to fourth. Field assessments and farmer responses indicated low surface soil organic carbon (often < 0.5%) and an over-reliance on nitrogenous fertilizers with limited use of phosphatic and organic amendments. Such nutrient imbalance may be responsible for declining soil fertility and reduced yield stability, consistent with findings reported by Vanlauwe et al. (2015).

Overall, these agronomic constraints—poor seed renewal and nutrient imbalance—may collectively increase vulnerability to climatic stress by lowering crop resilience and potential yield (Savary et al., 2019).

3.3. Infrastructure and Water-Management Constraints

Physical drainage infrastructure and operational synchronization emerged as key limiting factors influencing yield performance across years. Field inspections conducted between December 2023 and February 2024 revealed that a majority of padasekharams had partially blocked secondary drains (58%) due to siltation and weed growth, while 42% of sites had non-functional or poorly timed sluice operations (Table 2). Outer bund breaches were limited to one location (8.3%), but water-release and sowing mismatches occurred in nearly 67% of sites, causing transplanting delays of more than 10 days.

These drainage and scheduling deficiencies had a clear impact on productivity during 2019–2023. Padasekharams with blocked channels and delayed sowing consistently recorded lower mean yields (3,800 kg ha^{-1}) compared with well-maintained sites (6,750 kg ha^{-1}) (Table 4), indicating that prolonged submergence and late transplanting may be responsible for the observed year-to-year decline in yield. Similar associations between poor water control, disease incidence, and yield reduction in irrigated rice systems have been reported by Bouman et al. (2007) and Arouna et al. (2023).

Table 1. Ranking of agronomic constraints in Kole Padasekharams

Constraint	Garrett mean score	Rank
Pest and disease outbreaks	79.6	1
Poor seed quality and varietal fatigue	74.3	2
Nutrient imbalance	69.8	3
Decline in soil organic carbon	63.5	4
Lack of crop rotation	58.4	5
Inadequate extension services	52.7	6

Water-management literature further supports that timely desilting, synchronized sluice operation, and controlled water release are critical for maintaining crop health and uniform growth stages. The observed mismatches between canal-release schedules and farmer field readiness amplified inter-annual variation in yield by creating asynchronous planting and flowering periods across the padasekharam network. Operational lapses such as late bund closure or unsynchronized pumping schedules therefore translate directly into agronomic losses. Regular maintenance regimes, clear standard operating procedures (SOPs) for water release, and performance-linked maintenance funds may help reduce such variability, as evidenced in successful irrigation governance models elsewhere (Bouman et al., 2007; Meinzen-Dick, 2007).

3.4. Socio-economic Constraints: Labour, Land Fragmentation and Mechanization

The surveyed population shows an ageing farmer cohort (mean age ≈ 58 years) and high off-farm dependency (~53%) (Table 3). Labour shortages and rising wages (reported ~₹19,000 ha^{-1} $season^{-1}$) constrain time-sensitive farm operations (bunding, transplanting, weeding), while small, highly fragmented landholdings (~0.39 ha mean; 70% < 0.4 ha) limit mechanisation economies of scale and reduce uptake of custom-hire services. These demographic and structural patterns are consistent with regional studies documenting youth disengagement, rising agricultural wages, and area contraction for rice in Kerala (Kerala State Planning Board, 2024a).

Mechanisation can reduce labour bottlenecks if services are timely and appropriately localized; however, subsidy schemes and mechanisation programs often fail to reach smallholders without accompanying service-provision models (custom hiring centres) and capacity building (Regina et al., 2019). The net result in Kole is a reliance on contract labour and ad hoc machinery, which introduces timing uncertainty and inconsistent operational quality, further enlarging yield gaps between well-managed and poorly-managed padasekharams.

3.5. Yield Differentials by Management Intensity

The study indicates significant mean yield gap: 6,750 kg ha^{-1} in well-managed sites vs 3,800 kg ha^{-1} in poorly-managed sites (Table 4). The magnitude of this gap demonstrates large recoverable potential through improved management. One-way analysis of variance revealed a highly significant difference in paddy yield between well-managed and poorly managed padasekharams ($F(1,58)= 861.72$, $p < 0.001$), indicating that management quality is a major determinant of productivity. Empirical and experimental literature supports the idea that bundled management interventions (timely bunding, certified seed, synchronized transplanting and balanced fertilization) produce multiplicative benefits — i.e., the package effect often outperforms the sum of single interventions (Bouman et al., 2007; Vanlauwe et al., 2015). The implication for Kole is clear: targeted interventions that simultaneously address timing (water and operations), seed quality, and soil fertility are likely to yield the largest and most cost-effective recovery in productivity.

Table 2. Observed infrastructure and drainage constraints across Padasekharams

Parameter	Observed incidence (%)	Key observations
Blocked secondary channels	58	Channels obstructed by silt and vegetation; lack of systematic desilting
Non-operational sluices	42	Sluice malfunction or delayed closure; contributes to prolonged submergence
Outer bund breaches	8.3 (1 of 12)	Localized failure in structural integrity of outer bund in one location
Water release and sowing mismatch	67	Sowing delayed >10 days due to misaligned bund closure and irrigation

Table 3. Socio-economic characteristics of Kole Farmers (n = 120)

Parameter	Statistic	Observations
Average farmer age (years)	58.20	Majority over 55; youth disengagement evident
Average landholding size (ha)	0.39	70% hold < 0.4 ha; high fragmentation
Off-farm income dependency	53%	Reflects low return from monocrop rice
Labor cost (₹/ha/season)	19000	Increasing trend; impacts transplanting schedules
Machinery subsidy access	34%	Procedural hurdles and delayed disbursement

Table 4. Yield differentials between well-managed and poorly-managed Padasekharams

Management category	Mean yield (kg/ha)	Standard deviation	Remarks
Well-managed	6,750	412	Early bunding, timely sowing, certified inputs
Poorly-managed	3,800	365	Delayed transplanting, poor bund status, low input

3.6. Institutional and Policy Gaps

Despite multiple schemes (e.g., Kole Paddy Development Programme, mechanisation subsidies), effective uptake is low (38.3% of respondents accessed schemes successfully). Chi-square analysis revealed a highly significant association between farmer awareness and scheme uptake ($\chi^2(1) = 20.80$, $p < 0.001$), indicating that awareness plays a critical role in determining access to institutional support. Key institutional bottlenecks identified in interviews were limited outreach, complex procedures, delayed disbursements and weak field monitoring for compliance (bund construction, desilting timelines). Coordination among the Agriculture Department, Irrigation Department and Local Self-Government Institutions (LSGIs) was inconsistent; farmers in 7 of 12 padasekharams reported conflicting directives on sowing windows and bund timelines.

Institutional literature on irrigation and collective resource management emphasises that generic panaceas fall short; sustainable performance requires locally-fit arrangements, clear accountability, and farmer participation in monitoring and maintenance (Meinzen-Dick, 2007). In Kole, strengthening padasekharam-level institutions (formalizing padasekharam samithis, performance-linked maintenance funds, simple accountability mechanisms) and aligning departmental SOPs to the Puncha calendar would reduce operational delays and improve responsiveness.

3.7. Synthesis: Interacting Drivers and Priority Interventions

The evidence converges on a multi-causal and synergistic explanation for the observed yield decline. Rising Tmax at anthesis substantially increases biological vulnerability (spikelet sterility), but the degree of realized yield loss depends on the capacity of farmers and institutions to implement timely countermeasures — i.e., planting date shifting, precise water control and access to tolerant seed (Peng et al., 2004; Jagadish et al., 2015; Zhang et al., 2023). Agronomic deficits (seed, pests, soil fertility) amplify susceptibility; poor drainage converts episodic rainfall extremes into chronic waterlogging; and institutional/ operational failures prevent timely corrective actions.

Based on these empirical relationships, the study identifies four priority implications for enhancing productivity:

1. Climate-responsive crop management: The observed temperature–yield sensitivity suggests that aligning transplanting schedules to avoid peak anthesis heat and promoting access to regionally adapted, certified varieties may help mitigate yield loss under warming conditions (Jagadish et al., 2015; Zhang et al., 2023).

2. Drainage and operational synchronization: Field diagnostics confirmed that yield gaps were largest in padasekharams with poor drainage and delayed bund closure. Regular desilting, timely sluice operation, and better canal–field coordination may reduce inter-annual variability in yield (Bouman et al., 2007; Meinzen-Dick, 2007).

3. Soil fertility and pest balance: Soil organic carbon levels (<0.5%) and unbalanced fertilizer use were strongly associated with lower yields. Balanced nutrient management with organic amendments, combined with community pest monitoring, may enhance soil resilience (Vanlauwe et al., 2015; Savary et al., 2019).

4. Labour and mechanisation access: Reported labour shortages and low mechanisation access (34%) constrained timely transplanting. Expanding localized custom-hiring models could improve operational timeliness and reduce yield gaps (Regina et al., 2019).

Together, these findings suggest that improving timeliness of operations, drainage maintenance, and balanced input use at the padasekharam level offers the greatest potential to restore productivity in the Kole wetlands. Future interventions should therefore be sequenced to first strengthen water control and synchronization, followed by improvements in seed systems, soil fertility, and mechanisation support, consistent with the study's observed relationships.

4. CONCLUSION

The study analysed multi-year (2019–2024) data to identify the principal factors contributing to yield decline in Kerala's Kole wetlands. Each 1 °C rise in maximum temperature during flowering was associated with a measurable decline in paddy yield.. Padasekharams with efficient drainage, timely bund closure, and synchronized transplanting achieved maximum yields. Agronomic assessments revealed low seed replacement, nutrient imbalance, and frequent pest and disease incidence, supported by soil organic-carbon levels often below 0.5 %. Blocked drains and non-functional sluices were widespread, reducing the capacity for timely water control. Socio-economic observations showed high labour costs, small fragmented holdings and limited mechanisation access, all of which constrained timely operations. Institutional and policy analysis indicated low scheme uptake delayed disbursement of input subsidies, and weak coordination among agriculture, irrigation, and local-governance departments. These governance gaps limited the implementation of drainage maintenance and bunding schedules, thereby influencing field-level productivity. Overall, the findings indicate that yield performance in the Kole wetlands is influenced by multiple interacting factors including climatic stress, management quality, soil fertility, infrastructural condition, and institutional efficiency, with significant variability arising from the interaction of these factors across years.

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Credit authorship contribution statement

V.G. Sunil: Conceptualization, methodology, supervision, and manuscript review.

Asish Benny: Data collection, formal analysis, manuscript drafting, and editing.

V.S. Chinchu: Field investigation and data validation.

M.K. Jaliya: Statistical analysis and interpretation.

Suma Nair: Technical guidance and critical revision of the manuscript.

Amaljith V J: Literature review and data compilation.

All authors read and approved the final manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this manuscript.

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