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EDITED BY

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REVIEWED BY

Ashutosh Mall,
Indian Institute of Sugarcane Research (ICAR),
India
Juma Selemani,
Nelson Mandela African Institute of Science
and Technology Water Infrastructure and
Sustainable Energy Futures, Tanzania

*CORRESPONDENCE

Byung-Wook Yun
✉ bwyun@knu.ac.kr

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Rooted in crisis, growing solutions: economic impacts and adaptive pathways for Fiji's climate-threatened sugarcane industry

Shifadjic Khan¹ and Byung-Wook Yun^{1,2*}

¹The Graduate School, Department of Food Security and Agricultural Development, Kyungpook National University, Daegu, Republic of Korea, ²Laboratory of Molecular Pathology and Plant Functional Genomics, Department of Applied Biosciences, Kyungpook National University, Daegu, Republic of Korea

Small Island Developing States (SIDS) face accelerating climate hazards that undermine agricultural productivity. Fiji's sugarcane sector, which is central to rural incomes and foreign exchange earnings, is increasingly affected by floods, droughts, cyclones, irregular rainfall, and rising input costs. Assessing farm-level climate vulnerability is essential for guiding effective adaptation. A convergent mixed-methods design was applied, integrating surveys from 100 smallholder farmers, panel regression to estimate hazard-specific yield elasticities, and AI-assisted scenario modeling aligned with Asian Development Bank climate projections. Stratified sampling captured variation in farm size, location, and cooperative membership, and survey responses were cross-validated with production records to ensure reliability. Flood-related hazards showed the strongest negative association with multi-year yields ($\beta = -0.49$, $p < 0.001$), followed by irregular rainfall and drought effects. Flood impacts were most severe because water-logging, access disruption, and delayed harvesting weakened ratoons and reduced subsequent cycle yields. Socio-institutional constraints, including limited cooperative support, inadequate extension services, and low youth engagement, intensified vulnerability. Grassroots participation, modeled on South Korea's Saemaul Undong, can strengthen local coordination and adoption of adaptive practices. AI-assisted scenarios provided validated projections and identified priority adaptation pathways. The findings indicate a hydrology-first risk profile in Fiji's coastal sugarcane systems. Targeted water management and accelerated varietal upgrading are essential to sustaining productivity under increasing climatic extremes. Coordinated investments in drainage, stress-tolerant cultivars, and farmer-extension partnerships can narrow adaptation gaps and stabilize rural livelihoods. Although focused on Fiji, the analysis provides a transferable framework for estimating climate-induced yield elasticities and validating adaptation strategies in coastal smallholder cane systems across tropical Asia, Africa, and the Caribbean. The integrated empirical and AI-based methodology offers a replicable template for climate resilience assessment in tropical agriculture.

KEYWORDS

sugarcane (*Saccharum officinarum*), climate hazards, farmer vulnerability, agricultural adaptation, climate resilience, AI predictive modeling

1 Introduction

As a frontline nation in the climate crisis, the Fiji Islands, an archipelagic Small Island Developing State (SIDS) in the South Pacific, exemplify the profound challenges faced by nations that are disproportionately impacted by global climate change. Globally, sugarcane-producing regions, such as India, Thailand, and Brazil, face comparable hydrological stress (Gupta et al., 2017;

Marin et al., 2013; Pathak et al., 2019; Teixeira et al., 2016). Positioning Fiji as a critical microcosm for studying smallholder resilience in coastal agro-ecosystems, while being renowned for its rich cultural heritage, shaped by centuries of Indigenous Fijian traditions and Indo-Fijian influences (Lal, 2015). The country also has a deep history of agricultural development, shaped by its volcanic origins, fertile coastal plains, and tropical maritime climate (Foye, 1917; Macdonald and Foster, 2024). Among its primary agricultural products, sugarcane (*Saccharum officinarum* L.) is now under unprecedented and existential threat from escalating climate hazards. Since its introduction during British colonial rule in the late 1800s, sugarcane has profoundly influenced Fiji's population distribution, land tenure, and development (Moynagh, 2017; Pandey, 2023). Today, Fiji Sugar Corporation (FSC) manages the industry's milling and export operations, with over 80% of the country's sugar destined for international markets (McGree et al., 2020). Despite its historical significance, Fiji's sugarcane sector is becoming increasingly threatened by climate change. The Western Division of Viti Levu, particularly the Nadroga Navosa Province, faces floods, droughts, cyclones, and salinity intrusion patterns mirrored in other tropical smallholder sugarcane regions globally (Magee et al., 2016; PCRAFI, 2011). Climate hazards have increased in both frequency and severity. Cyclone Winston (2016) caused catastrophic damage to crops, infrastructure, and livelihoods. Erratic rainfall, including prolonged droughts and intense storms, further disrupts the sugarcane growing cycle. Between 1996 and 2022, sugarcane production fell by 64%, and planting areas contracted by 50% between 2018 and 2022 (FMS, 2023; FSC, 2023, 2024; Misra and Singh, 2024). These trends signal a critical inflection point for the industry and underscore the urgent need for Climate-Smart Agriculture and targeted adaptation strategies.

The economic and social impacts of these changes are profound, creating a vulnerability nexus. Sugarcane farming supports over 20,000 households and employs a significant share of Fiji's rural population (FSC, 2024; Raj, 2022) contributing substantially to Gross Domestic Product (GDP), foreign exchange earnings, and local commerce (Narayan and Prasad, 2005; Sugarcane Growers Council, 2020). Climate-induced yield losses, rising production costs, and market volatility gravely threaten the viability of smallholder farms. Farmers face increasing expenses for labor, irrigation, fertilizers, and pest control; however, unstable sugar prices and declining yields erode profitability and household income, leading to pervasive livelihood precarity (Chandra et al., 2018).

Fiji's archipelagic geography and low-lying coastal settlements increase its exposure to storms, erosion, and sea-level rise. Projected temperature rises of 1.6 °C–3.3 °C and sea-level increases of up to 1 m by 2,100 exacerbate vulnerability (Nunn, 2000; Nunn et al., 2016; Shiiba et al., 2023). Extreme weather, erratic rainfall, and higher temperatures significantly reduce sugarcane yields and increase pest and soil degradation risks (McNamara and Des Combes, 2015). Cyclones and floods have repeatedly caused infrastructure damage and economic losses (Christina et al., 2024; Kumar and Vennila, 2022; Kumar et al., 2013). Demographic trends, such as an aging farmer population and declining youth interest, compound these challenges (Medina Hidalgo et al., 2024). While government initiatives, including policies linked to the Climate Change Act 2021, aim to improve the climate-proofing of the sector, farmers report insufficient insurance, training, and extension service frameworks (Liligeto and Nakamura, 2022; Nand et al., 2024; Nsabiyeze et al., 2024; Raj, 2022). These constraints highlight the need for improved adaptation strategies and inclusive policy interventions that combine local knowledge with scientific evidence.

These mounting pressures have also led to severe social challenges, including food and water insecurity, economic displacement, youth disengagement from agriculture, and accelerated rural exodus to urban centers, threatening long-term food system resilience and intergenerational equity. Despite the recognition of these socio-economic challenges, few studies have quantified how specific climatic hazards affect smallholder sugarcane yields or examined socio-institutional constraints on adaptation. Previous research has generally focused on aggregate climate trends or descriptive vulnerability assessments without isolating hazard-specific yield responses or validating adaptation mechanisms through AI-assisted modeling. Consequently, a critical knowledge gap persists in quantifying how individual climate stressors translate into measurable yield elasticities and policy-relevant adaptation priorities in smallholder systems.

A critical empirical gap remains; few studies have quantified the localized, long-term impacts of specific weather hazards on smallholder sugarcane farmers. Evidence of the effectiveness of adaptation strategies and policies is limited. Most studies have not integrated quantitative yield and climate data into the qualitative insights from farmers and stakeholders. This study bridges this gap by providing an integrated vulnerability assessment that quantifies hazard-specific yield elasticities, evaluates socio-institutional constraints, and validates adaptation pathways using AI-assisted scenario modeling. These findings offer insights applicable to other SIDS and coastal smallholder systems worldwide.

2 Materials and methods

2.1 Study area and design

2.1.1 Study area

This study was conducted in the Maro sector of the Nadroga–Navosa Province, located within Fiji's Western Division. This settlement was selected because of its high dependence on sugarcane farming as a primary livelihood and its acute vulnerability to climate-related hazards, making it a critical area for assessing the impacts of climate variability on agricultural productivity.

2.1.2 Population and sample

Fiji has 17,019 active sugarcane growers, with approximately 1,171 located in the Western Division (Fiji Sugar Corporation, 2024; Sugarcane Growers Council, 2020). The study sample consisted of 100 registered sugarcane farmers, representing approximately 8.5% of the active growers in the division. Participants were selected through stratified purposive sampling to capture variations in farm size and cooperative membership, ensuring that diverse socio-economic conditions within the settlement were represented despite the single-location focus.

2.1.3 Selection criteria and verification

Eligible participants were active sugarcane farmers who were directly involved in both planting and harvesting activities, with at least 10 consecutive years of farming experience and valid land registration under the Fiji Sugar Corporation database. All participants were verified by the local growers' gang in charge to ensure the representativeness and authenticity of the data. Stratification by farm size and cooperative membership further reduced sampling bias and

ensured balanced representation across different socio-economic groups within the settlement.

2.1.4 Data reliability and rationale

Data reliability was strengthened through triangulation with Fiji Sugar Corporation production records and cross-validation of self-reported yields. Additionally, qualitative insights from key stakeholder interviews complemented the quantitative survey data. This approach provides a robust foundation for analyzing climate-induced impacts on sugarcane farming, combining empirical yield data with farmer perspectives to capture both the magnitude and contextual drivers of production variability (Figure 1).

2.2 Research questions and objectives

Based on the identified empirical and methodological gaps, this study aims to provide an integrated vulnerability assessment for Fiji's sugarcane sector. Specifically, this study is steered by the following research questions:

- 1 What are the localized, long-term impact estimates (quantified as β coefficients) of specific climate hazards (floods, irregular rainfall, droughts, and cyclones) on the multi-year sugarcane yield for smallholders in Nadroga–Navosa?
- 2 How do climate-induced production losses and rising costs intersect with socio-economic factors and institutional constraints (including youth engagement and access to support

systems) to shape farmer vulnerability and limit the uptake of adaptation practices?

- 3 Based on the empirical findings, how can a coordinated, field-ready adaptation and delivery model be formulated to address the primary climate risks (targeted water management and varietal upgrading) for Fiji's sugarcane sector and analogous SIDS?

2.3 Instruments and variables

Structured surveys were used to collect information on farm characteristics, sugarcane yields, management practices, and farmers' perceptions of climate hazards. The survey responses were cross-validated with official production trend records from Fiji Sugar Corporation's annual reports to guarantee data reliability. Additionally, key informant interviews with harvesting gang leaders and extension officers were conducted to capture the socio-institutional factors influencing adaptive capacity, complementing the quantitative data.

2.3.1 Variables

- A Dependent variable: Sugarcane yield (tons per hectare)
- B Independent variables: Frequency and severity of floods, droughts, cyclones, and rainfall variability
- C Socio-economic variables: Farm size, cooperative membership, access to extension services, and farmer demographics
- D Adaptation measures: Irrigation practices, varietal choices, and crop management interventions

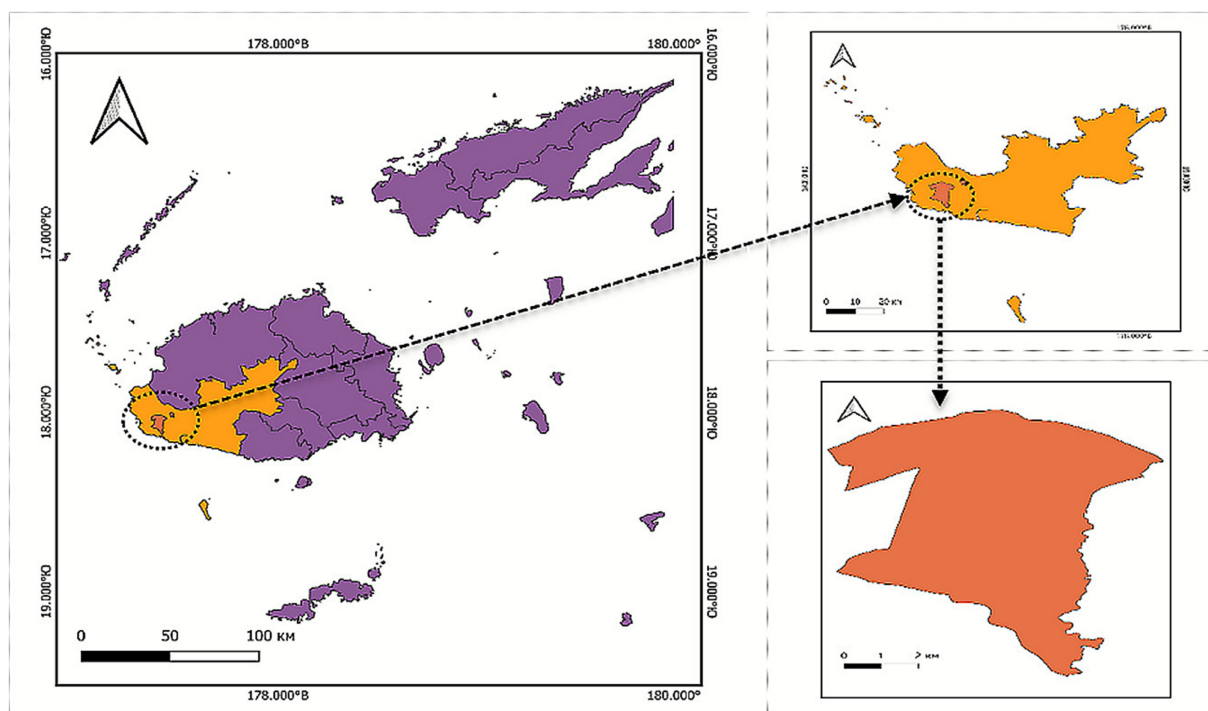


FIGURE 1
Study area map of Fiji showing the Western Division and Nadroga–Navosa Province (orange), with the Maro sector inset.

2.4 Statistical analysis

Descriptive statistics were used to summarize the key stressors, cost structures, and adaptive practices. To test for between-group differences (e.g., by farm size, experience, or cooperative membership), we employed one-way ANOVA and independent-samples *t*-tests, which are appropriate for comparing mean responses across groups (Field, 2017).

Associations between specific climate hazards and multi-year cane output were then estimated using ordinary least squares (OLS) regression with robust standard errors to account for heteroskedasticity, a method widely applied in agricultural and development economics (Wooldridge, 2016) (Equation 1):

$$Y_i = \beta_0 + \beta_1 \text{Flood}_i + \beta_2 \text{IrregRain}_i + \beta_3 \text{Cyclone}_i + \beta_4 \text{Drought}_i + \varepsilon_i \quad (1)$$

Where:

- Y_i = multi-year sugarcane output for farm *i*
- β_0 = constant term (intercept)
- $\beta_1, \beta_2, \beta_3$, and β_4 = estimated coefficients showing the marginal effect of each climate hazard
- $\text{Flood}_i, \text{Irregular Rain}_i, \text{Cyclone}_i, \text{Drought}_i$ = indicator or intensity measures of climate hazards faced by farm *i*
- ε_i = error term, capturing unobserved factors

Model fit was reported using the coefficient of determination (R^2) and its adjusted form, while overall significance was assessed using the standard ANOVA *F*-test (Field, 2017) (Equation 2):

$$F = \frac{\frac{SSR}{k}}{\frac{SSE}{(n-k-1)}} \quad (2)$$

Where:

- SSR = regression sum of squares
- SSE = error sum of squares
- k = number of predictors
- n = sample size

To assess multicollinearity, variance inflation factors (VIF) were computed for each predictor, a widely used diagnostic in regression modeling (Kutner et al., 2003) (Equation 3):

$$\text{VIF}_j = \frac{1}{(1 - R_j^2)} \quad (3)$$

Where:

- VIF_j = variance inflation factor for predictor *j*
- R_j^2 = coefficient of determination from regressing predictor *j* on all other predictors

All VIF values fell well below the conventional cut-off thresholds, indicating no serious multicollinearity. The study workflow, from problem definition and theoretical framing through institutional permissions, survey implementation, data integration, and synthesis of findings, is shown in Figure 2. This framework demonstrates how qualitative insights and quantitative modeling (SPSS-based robust

OLS with diagnostic checks) were braided to address the research questions.

2.5 AI-assisted scenario analysis (ChatGPT) and benchmarking against ADB projections

We complemented our empirical analysis with an AI-assisted scenario exercise using ChatGPT (OpenAI; accessed March 2025). The objective was not to produce physical climate forecasts but to synthesize plausible sector pathways for Fiji's sugarcane under alternative climate hazards and policy responses and to triangulate these pathways against published projections from the Asian Development Bank climate outlook for Fiji.

2.5.1 Procedure

We provided structured prompts summarizing (i) study area and baseline sector features; (ii) hazard profiles (drought, flood, irregular rainfall, and cyclones); and (iii) candidate adaptations (water management, cultivar choice, risk finance, and extension). We requested hazard-specific directional effects on yield/costs and qualitative uncertainty labels. We then compared the outputs to the ADB report's weather projections for Fiji and our empirical patterns (Sections 3–4). The outputs were treated as scenario narratives (not model predictions). We documented prompts, timestamps, and post-processing steps and reported them in the [Supplementary information](#). All interpretations were verified using our data and published sources.

2.5.2 Analytical value and integration

The AI-assisted scenario exercise strengthened the analytical depth of this study by integrating an expert-like synthesis with empirical validation. The outputs provided a structured comparison of hazard-specific risks and adaptive responses, complementing statistical trends with plausible sectoral trajectories. This hybrid approach enhanced interpretive confidence by linking observed patterns to forward-looking possibilities under varying climate and policy conditions. Importantly, the exercise demonstrated how generative AI can function as an adaptive research instrument, supporting hypothesis testing, sensitivity exploration, and data triangulation in resource-limited contexts. While not a substitute for physical or econometric models, it served as a rapid foresight tool, offering narrative-based benchmarks that improved the contextual understanding of Fiji's sugarcane adaptation pathways within broader regional projections.

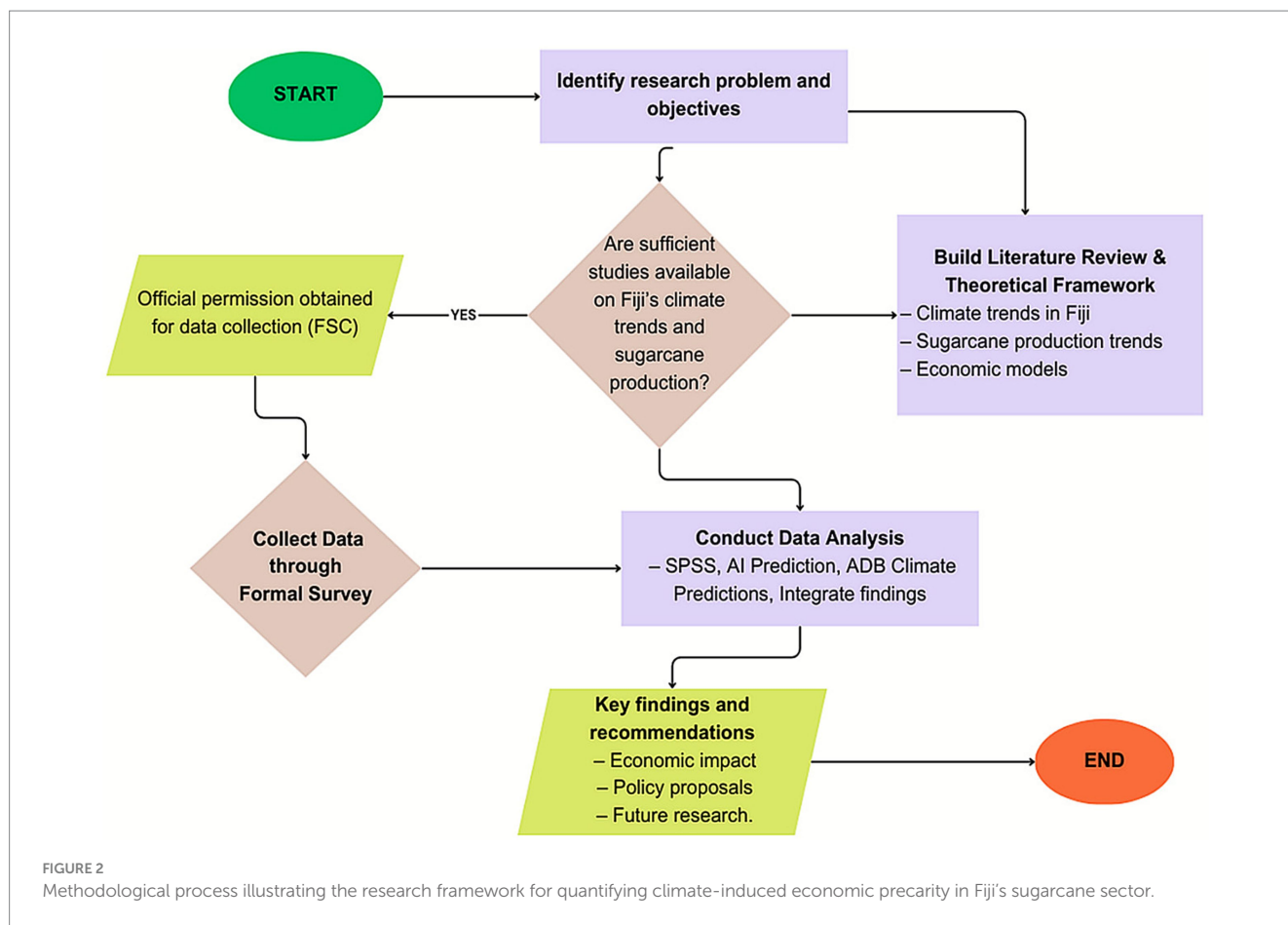
2.6 Ethics and reproducibility

Participation was voluntary, informed consent was obtained, and responses were anonymized. Institutional and community approvals preceded fieldwork.

3 Results

3.1 Farmer characteristics and production

Respondents averaged approximately 53 years of age with about 17.5 years of cane-growing experience, farming on an average landholding of 4.74 ha. Institutional access and financial exposure



further illustrate their vulnerability: three-quarters reported taking loans in response to climate-related losses, 77% received some form of financial assistance or subsidy, and half were cooperative members (Table 1). The multi-year output trend during 2014–2024, shown in Figure 3, exhibits significant variability and a sharp decline in 2016, reflecting differential exposure and adaptive capacity across farms.

The sugarcane yield trend shown in Figure 3 highlights the sector's acute vulnerability to extreme weather events. The dramatic dip in the average yield in 2016 is particularly pronounced and coincides with the passage of Tropical Cyclone Winston, a Category 5 storm that caused widespread damage across Fiji. While yields generally recovered and stabilized in subsequent years, the overall variability and depth of the 2016 loss underscored the significant economic shock climate extremes imposed on the smallholder system.

3.2 Reported climate stressors and economic consequences

Farmers reported intensifying extremes consistent with a hydrology-first risk profile: droughts and floods were the most frequently cited, alongside irregular rainfall, rising temperatures, perceived soil fertility decline, and increased pest and disease pressure. These hazards reflect both acute shocks and timing-related water stress that disrupt crop establishment and harvest logistics. In parallel, 75% of respondents reported rising production costs, with the largest shares attributed to land preparation (17.3%), labor (15.5%), and

TABLE 1 Sample characteristics of surveyed sugarcane farmers in Nadroga–Navosa Province.

Measure	Value
Age (years), mean	≈ 53
Experience (years), mean	≈ 17.5
Farm size (ha), mean	≈ 4.74
Loans due to climate losses, % Yes	75%
Financial assistance/subsidy received, % Yes	77%
Cooperative membership, % Yes	50%

fertilizer (13.7%), followed by irrigation, transport, and other inputs. Together, these findings demonstrate how climate hazards and cost pressures compound to erode farm viability (Figures 4A,B).

The survey data demonstrated that droughts, floods, and rainfall irregularities were the dominant stressors, corresponding to the largest yield reductions observed in the regression analysis (Section 3.3). Rising production costs for land preparation (17.3%), labor (15.5%), and fertilizer (13.7%) act as compounding financial stressors, reinforcing livelihood vulnerability.

In response to escalating climate hazards, farmers have reported adopting a range of primarily incremental adaptation strategies. The most common practice was adjusting planting and harvesting schedules, cited by 32% of the respondents. Nearly one-third (28%) undertook land preparation during the dry season to minimize

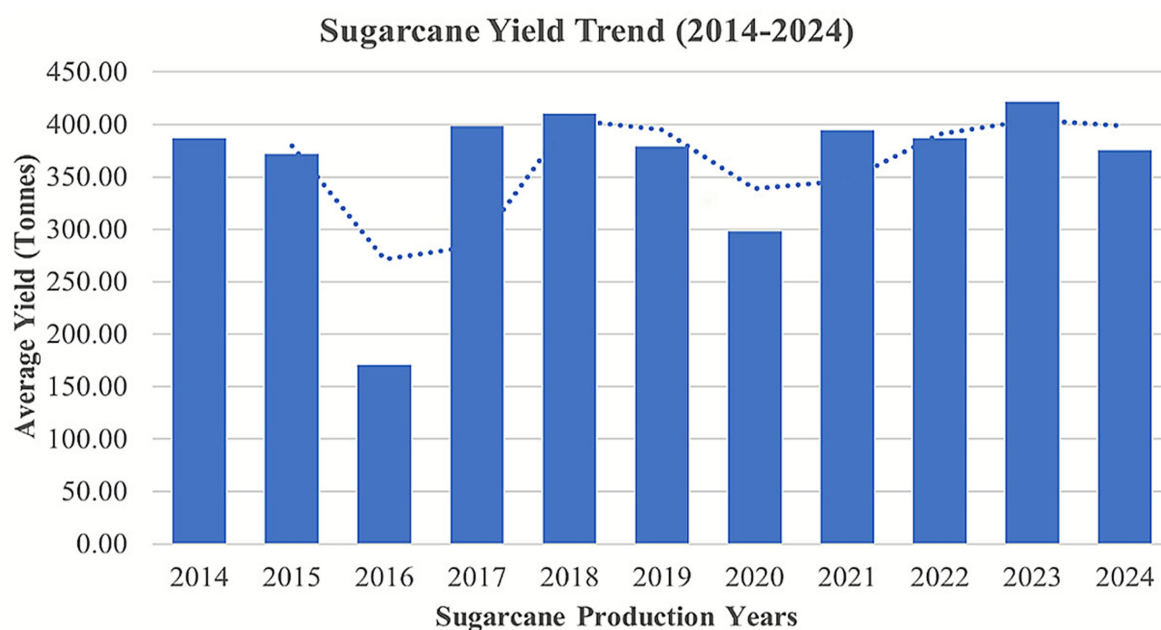


FIGURE 3

Sugarcane production trend for surveyed farms, 2014–2024; the 2016 low coincides with Tropical Cyclone Winston.

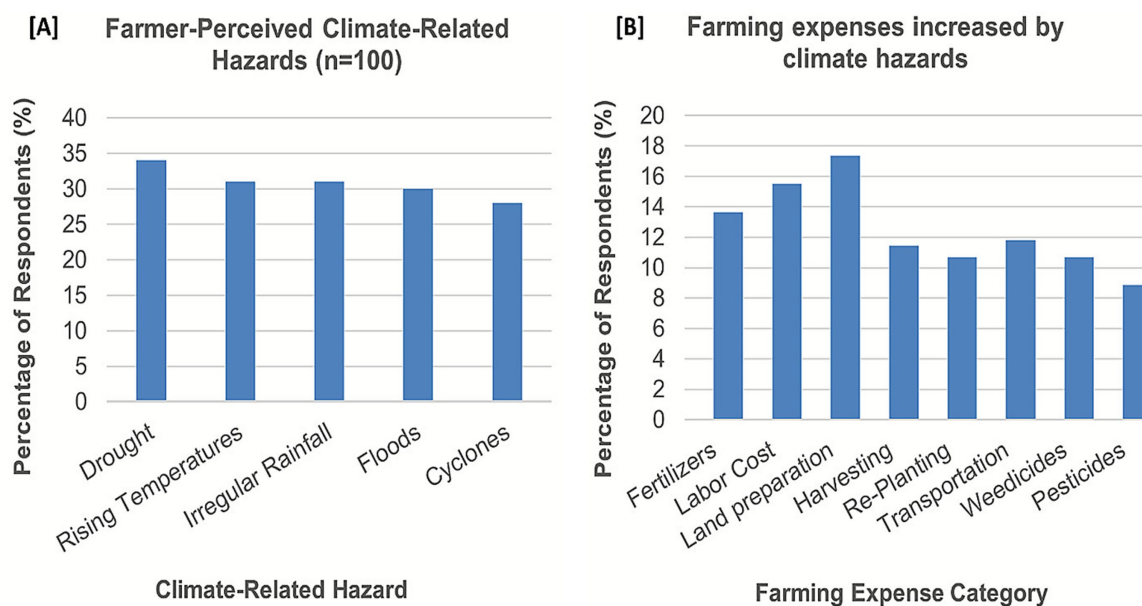


FIGURE 4

(A) Farming expense categories were reported to have increased due to climate hazards (% of respondents). (B) Farmer-perceived climate-related hazards (n = 100; % of respondents; multiple responses were allowed).

flood-related risks, whereas 24% installed or maintained drainage systems to manage excess water. More technologically advanced measures remained limited, with only approximately 12% adopting drought-tolerant sugarcane varieties. These findings highlight that while adaptive practices are being implemented, they are largely short-term and incremental, reflecting financial and institutional constraints (Table 2).

3.2.1 Youth engagement and intergenerational perspective

Survey responses revealed that a significant proportion of farmers perceived declining youth interest in sugarcane cultivation. Specifically, 62% of the respondents reported that their children or younger household members were not interested in continuing sugarcane farming, citing low profitability, high labor demands, and limited

innovation as key deterrents (Figure 5A). Despite this challenge to generational renewal, most farmers (63%) expressed cautious optimism that the industry could survive climate change, whereas 37% did not share this belief (Figure 5B). This declining youth engagement represents a structural risk to adaptive capacity, suggesting that generational renewal in Fiji's sugarcane sector is becoming increasingly constrained.

3.3 Regression: estimated effects of hazards on output

Floods exhibited the highest negative impact ($\beta = -0.496$, $p < 0.001$), followed by irregular rainfall ($\beta = -0.243$, $p < 0.001$), cyclones ($\beta = -0.143$, $p = 0.019$), and drought ($\beta = -0.155$, $p = 0.020$). These hazard-specific elasticities quantify the relative risk contributions of each climate factor to sugarcane yield losses, highlighting priority areas for targeted interventions. Effect sizes and uncertainty are visualized in the coefficient plot (Figure 6), and the detailed regression coefficients are presented in Table 3.

These hazard-specific elasticities quantify the relative risk contributions of each climatic factor to sugarcane yield losses. Figure 6 visually displays these effect sizes and their confidence intervals, highlighting the dominant-negative impacts of floods. This provides clear evidence-based guidance for targeting interventions where they will be most effective.

3.4 Benchmarking AI scenarios with ADB climate projections for Fiji

The AI-assisted scenarios were directionally consistent with the ADB projections that emphasize more intense rainfall extremes and coastal flood risk, with drought risk varying by season and locality. The AI outputs similarly ranked flooding and irregular rainfall as the dominant channels of production loss, followed by drought and cyclones, matching our regression ordering and hotspot mapping. Where divergence occurred, AI narratives added market/behavioral channels (input price shocks, youth exit), often not quantified in the ADB outlook but visible in our survey.

Across hazards, the AI scenarios and ADB projections show directional agreement and consistent rank ordering. Both sources emphasize heavier rainfall extremes and stronger high wind/cyclone events by the mid-century, with temperature extremes also rising (ADB, 2013). This ordering matches our empirical loss patterns. The hotspot analysis results are shown in Figure 5. Differences are expected where indicators are not directly comparable (AI rainfall variability % vs. ADB 99th-percentile rainfall); therefore, we report ordinal rather than numeric concordance. AI scenarios additionally identify economic

and behavioral channels, including price shocks and youth exits, which are not captured in the ADB projections. This integration provides a practical framework for prioritizing field-level adaptation interventions.

3.5 Climate-risk hotspots and economic losses

The rank of loss channels in the AI scenarios, rainfall/waterlogging, cyclones, and drought/heat is consistent with ADB's emphasis on heavier rainfall and high-wind extremes and with our regression/hotspot results. To illustrate sector trajectories under stress, Figure 7 shows projected output paths from a 2023 baseline under moderate (-3% yr.⁻¹) and severe (-5% yr.⁻¹) decline scenarios, used for stress testing and aligned with the hazard ordering in Table 4.

Projected sugarcane production per farm in Fiji under moderate (-3% yr.⁻¹) and severe (-5% yr.⁻¹) decline scenarios, 2023–2035. Lines apply the compound annual decline from a 2023 baseline ($\approx 4,000$ t/farm), yielding $\approx 2,780$ t (-30%) under -3% and $\approx 2,160$ t (-46%) under -5% by 2035. Scenario narratives for stress testing, not calibrated forecasts; see Methods (Section 2.4).

The decline paths are consistent with the risk ranking in Table 4: heavier rainfall/waterlogging and timing disruptions dominate losses, followed by droughts and secondary cyclones. Hotspot effects are concentrated in flood-prone coastal zones and river basins (Table 5), reinforcing priorities in drainage/flood work and on-farm water management. Hotspot mapping indicated that the coastal and river basin areas experienced disproportionate economic losses, emphasizing the need for targeted drainage, flood control, and water management interventions (Table 5; Figure 7). These findings can be used to inform spatially differentiated adaptive planning strategies.

The descriptive and inferential results presented above outline the empirical patterns of climate impacts, costs, and adaptive responses. Interpretive implications and theoretical synthesis are discussed in Section 4 to maintain analytical clarity and avoid overlap between the findings and interpretation.

4 Discussion

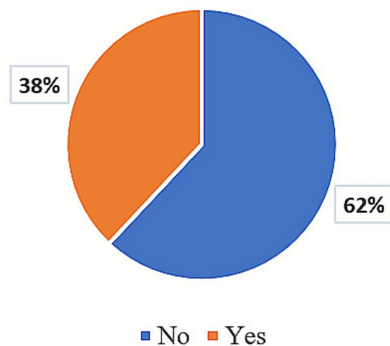
4.1 Principal findings and interpretation

This study robustly demonstrates that smallholder sugarcane farmers in Nadroga Navosa Province, Fiji, are experiencing profound and accelerating vulnerability to a complex array of climate hazards, including intensified droughts, recurrent floods, increasingly irregular rainfall, and a surge in pest and disease outbreaks. As shown in Figure 4, an overwhelming majority (73%) of the surveyed farmers reported more frequent droughts and floods, while an equal proportion noted increased pest and disease occurrences. These on-the-ground observations strongly corroborate macro-level projections and empirical studies, which consistently highlight the increasing unpredictability and severity of weather hazards across the Small Island Developing States (SIDS) in the Pacific region. Together, the pattern indicates that hydro-climatic extremes, notably excess water and rainfall timing, are the dominant risk channels for cane production in this setting. The regression results support these observations, showing that floods and irregular rainfall are the

TABLE 2 Adoption of adaptation practices among surveyed farmers.

Practice	Share of respondents (%)
Scheduling changes (e.g., planting/harvest shifts)	32
Dry-season land preparation	28
Drainage installation/maintenance	24
Drought-tolerant cane varieties	~12

[A] Interest of Younger Generations in Continuing Sugarcane Farming



[B] Can Fiji's sugarcane industry survive climate change?

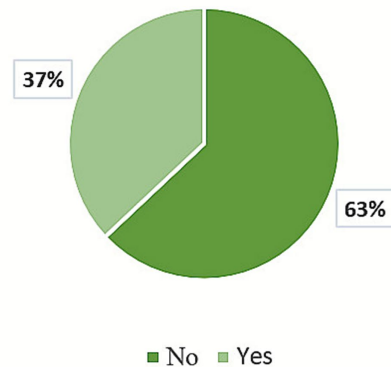


FIGURE 5

Youth interest in sugarcane farming and perceived industry resilience. (A) 62% of youth are uninterested in continuing farming, while (B) 63% of respondents believe the industry cannot survive climate change.

Climate Hazards and Sugarcane Production (β , 95% CI)

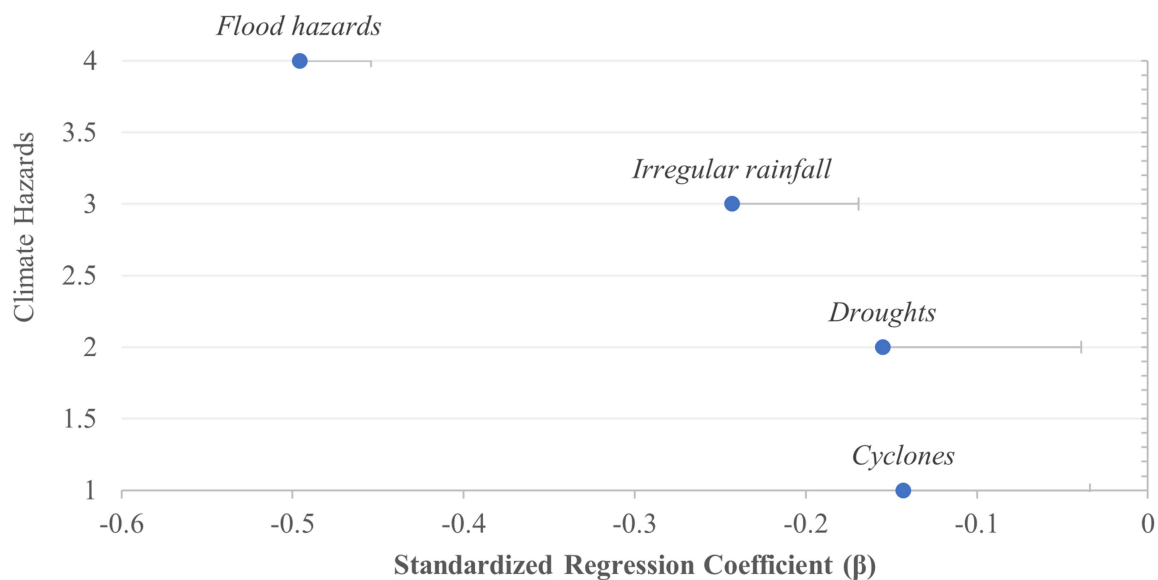


FIGURE 6

Standardized regression coefficients (β) with 95% confidence intervals for climate hazards predicting sugarcane production.

TABLE 3 Ordinary least squares regression results for the effects of climate hazards on multi-year sugarcane output.

Predictor	B	Std. Error	β (std.)	t	p	95% CI (Lower)	95% CI (Upper)
Constant	8683.566	213.970	—	40.583	<0.001	8258.783	9108.349
Floods	-718.974	91.284	-0.496	-7.876	<0.001	-900.197	-537.752
Irregular rainfall	-351.703	92.038	-0.243	-3.821	<0.001	-534.422	-168.984
Cyclones	-203.972	85.410	-0.143	-2.388	0.019	-373.532	-34.412
Droughts	-238.219	100.570	-0.155	-2.369	0.020	-437.875	-38.563

Model fit: $R = 0.924$; $R^2 = 0.854$; adjusted $R^2 = 0.848$; $F(4,95) = 139.43$, $p < 0.001$; SEE = 700.37. VIF range: 2.34–2.79 (no serious multicollinearity).

Forecasted Sugarcane Production per Farm in Fiji under Moderate and Severe Decline Scenarios (2023–2035)

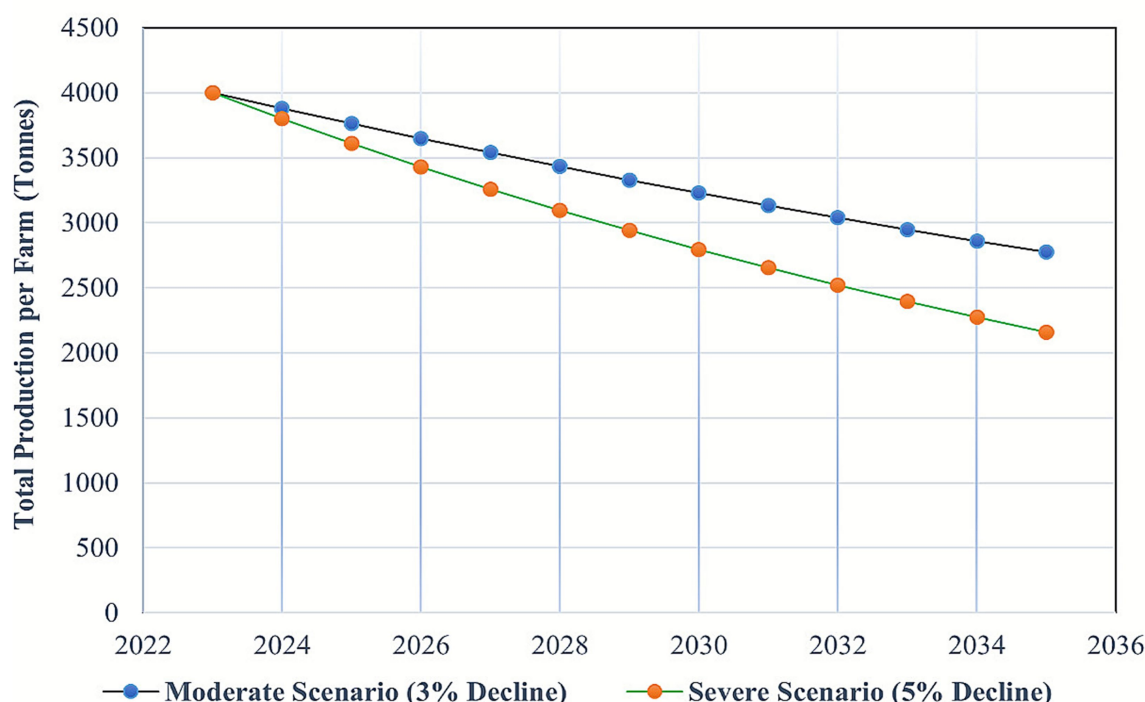


FIGURE 7

Artificial Intelligence (AI) predicted sugarcane production per farm in Fiji under moderate (-3% yr $^{-1}$) and severe (-5% yr $^{-1}$) decline scenarios, 2023–2035.

TABLE 4 Concordance between AI predictions and Asian Development Bank (ADB) climate risk classifications.

Hazard dimension	AI scenario (2030/2050/2100)	ADB projection (mid/late-century)	Concordance	Notes
1. Heavy/Extreme rainfall	Variability $\pm 15/\pm 25/\pm 40 \rightarrow \uparrow$ risk of waterlogging and timing shocks	99th-percentile rainfall increases over western Viti Levu and nearby islands	High	Same direction and same priority hazard; aligns with hotspots (Table 5)
2. Cyclone/high-wind severity	Cat 4–5 + 10% / +20% / +35%	More intense wind/cyclone extremes by mid/late-century	High	Direction and escalation match
3. Temperature extremes	+1.2 / +2.0 / +3.5 °C	Higher extreme max temperature percentiles	High	Different metrics, same direction
4. Drought	Yield loss channel present, but secondary	Mixed signal; varies by season/locality	Partial	ADB emphasizes wet extremes; drought remains context-specific

dominant yield-reducing hazards. Droughts and cyclones are secondary but still significant. This hazard-specific quantification strengthens our understanding of adaptive priorities at the farm scale.

The economic ramifications of these climatic shocks are not merely substantial but existential. Approximately 75% of farmers experienced alarming increases in production costs, particularly for labor, fertilizers, and land preparation (Figure 4), alongside widespread yield and income losses. Such financial pressures, often leading to reliance on loans and external support, align with previous findings that climate shocks destabilize agricultural supply chains and severely undermine farmers' profitability in Fiji. Cost inflation, therefore, acts as a shock amplifier, tightening cash flow constraints and limiting the ability to invest in preventative adaptation.

In response to escalating climate threats, farmers have reported adopting a range of mostly incremental adaptation strategies. The most frequently cited included adjusting planting and harvesting schedules (32%), land preparation during the dry season (28%), and installing drainage systems around cane farms (24%). Additionally, crop residue management techniques, such as leaving cane trash post-harvest to suppress weeds and improve soil quality, were reported by 16% of the respondents. However, the uptake of more technologically advanced or transformative adaptation measures remains notably limited. For instance, only 12% of farmers reported using drought-tolerant sugarcane varieties (e.g., Mana and Viwa), whereas engineered water management practices were largely absent. These results unequivocally suggest that current adaptation efforts are limited in

TABLE 5 Identified climate risk hotspots for sugarcane farming in Nadroga–Navosa Province.

Region	Key climate risk	Projected impact (2030–2050)	Economic loss (FJ\$)
Nadroga coastal zones	Sea-level rise, cyclones	18% arable-land loss	21 million/year
Sigatoka River Basin	Floods, soil degradation	15% sucrose-content decline	14 million/year
Western Division	Labor shortages	40% skilled-labor decline	8 million/year

Loss values are indicative of the annual totals for the period stated in current FJ\$. The methods/assumptions are presented in Section 2.

both scale and sophistication and are constrained by barriers related to access to appropriate technology, critical information, and financial resources. This constitutes a widening adaptation gap in the high-exposure zones of the cane belt.

4.2 Integrating AI scenarios with published climate projections

Our empirical findings, AI scenarios, and ADB outlook jointly indicate a hydrology-first risk profile: heavier rainfall and waterlogging dominate the observed losses, with cyclones intensifying damage and drought as secondary but important constraints. The AI exercise contributes to operational clarity by linking climate drivers to farm-level levers (drainage retrofits, efficient irrigation, certified seeds for stress-tolerant cultivars, risk-layered finance, and farmer-centered extension), which our survey and hotspot mapping also support. We, therefore, treat the AI scenarios as concordant narratives rather than forecasts used to frame mechanisms and delivery priorities. This analysis unequivocally demonstrates that without urgent and accelerated adaptation, Fiji's sugarcane sector faces a steep and unavoidable production decline, threatening both rural livelihoods and vital national export earnings, thereby compounding Fiji's climate development trap. Although scenario magnitudes depend on assumptions, the direction and relative ranking of risks (flooding, irregular rainfall, drought, and cyclones) are consistent with agronomic pathways observed locally.

4.3 Mechanisms and consistency with prior work

Sugarcane performance is tightly linked to water balance at critical growth stages. Short water deficits during formative and grand growth reduce tillering and internode elongation. Conversely, waterlogging suppresses root aeration and photosynthesis and increases lodging and disease pressure effects amplified in heavier, poorly drained soils typical of Fiji's cane lands. Our regression coefficients corroborate these physiological mechanisms, indicating that flood- and rainfall-timing disruptions had the largest negative impact on yield. Evidence from comparable tropical cane systems reinforces the notion that drainage and field access are critical first-line defenses.

4.4 Literature synthesis and comparative insights

The observed increase in pest and disease outbreaks under extreme weather conditions (Figure 4) is corroborated by (Kumar and

Vennila, 2022; Nega, 2025), who highlighted the vulnerability of sugarcane crops to heightened pest pressures under warmer and more humid climatic conditions. Similar findings have been reported across tropical agricultural systems, where erratic rainfall and rising temperatures have disrupted pest life cycles, increased reproductive rates, and reduced the effectiveness of conventional pest management strategies (Msomba et al., 2024; SRIE, 2014; Subedi et al., 2023). These patterns underscore that pest and disease management will become an increasingly complex challenge in the context of climate change, necessitating integrated climate-responsive agroecological approaches. In practical terms, this points to pairing drainage/soil-health measures (e.g., trash blanketing, traffic control) with integrated pest management calibrated to extreme-weather windows.

The survey results indicated a decline in youth participation in sugarcane farming. 62% of respondents reported that younger family members are uninterested in continuing cultivation, reflecting an intergenerational gap and future labor risk (Figure 5A). Regarding the industry's resilience, 63% believed Fiji's sugarcane sector can survive climate change with adaptive reforms, while 37% were pessimistic (Figure 5B). These results reveal cautious optimism amid persistent vulnerability. Similarly, Medina Hidalgo et al., 2024 reported declining youth participation in the Fijian sugar sector, citing limited economic prospects, high labor demands, and a lack of innovation and mechanization as key deterrents. This is consistent with studies from other Small Island Developing States (SIDS), which reveal that younger generations often perceive agriculture as economically unattractive and socially undesirable (Dean, 2022). This demographic shift presents a profound structural threat to long-term sector sustainability, as aging farmer populations may be less inclined or able to adopt innovative or labor-intensive adaptation strategies, posing a risk to the sector's adaptive capacity. Targeted youth pathways (field schools, certification, incubators, and micro-grants) therefore become a resilience lever, not just a workforce policy.

Moreover, findings from this study critically underscore the suboptimal uptake of advanced adaptation practices, aligning with prior literature that emphasizes not only economic and technical constraints but also significant behavioral and informational barriers. For instance, (Prasad et al., 2021; Singh, 2020) observed that many farmers in Fiji demonstrate a fatalistic view toward climate impacts, often perceiving them as inevitable and beyond human control. This sense of resignation hampers the willingness to engage with available adaptation options, especially in the absence of clear, long-term economic benefits and actionable, user-friendly guidance. These insights support the argument that adaptation strategies must go beyond infrastructure and technology to include behavioral change interventions, capacity building, and the co-production of locally relevant knowledge. Collectively, the study's findings reinforce the broader scholarly consensus that addressing climate change in the

agricultural sector requires an integrated approach that combines technical, institutional, and socio-cultural dimensions to enhance resilience and secure future agricultural productivity. Accordingly, a co-produced, farmer-centered extension is essential to translate climate risk into practical, economically viable farm decisions.

The methodological innovation of this study lies in operationalizing an AI-assisted validation of econometric hazard models. This dual-layered approach generates the first quantified dataset of hazard-specific yield elasticities for Pacific Small Island Developing States while demonstrating how generative AI scenario narratives can complement traditional regression analysis. This synthesis provides a replicable framework for integrating empirical data with predictive foresight to inform adaptive planning in other tropical agricultural economies.

4.5 Policy and institutional gaps

Although institutions are expected to play a crucial role in supporting farmer adaptation, their limited presence and ineffective implementation significantly exacerbate vulnerability. Only 28% of respondents acknowledged government programs (Figure 8), whereas 72% reported no access to institutional support, meaning that they were either unaware of existing programs or did not receive timely updates. This gap is particularly concerning given the changing climate patterns, which intensify floods, droughts, and irregular rainfall, directly threatening sugarcane productivity.

Institutional fragmentation, unclear agency mandates, and weak coordination prevent farmers from obtaining timely guidance and resources. Existing programs often fail to align with smallholder realities, socio-economic constraints, and traditional practices, thus reducing their relevance and uptake. As Fiji's sugarcane economy stands at a crossroads, balancing climatic risks with economic sustainability, strengthening institutional capacity, and delivering context-specific, actionable interventions is critical to enhance resilience and secure the sector's future.

4.5.1 The financial and risk coverage failure

The institutional system is failing to provide essential financial and risk-layering support, severely exacerbating the economic vulnerability of smallholders. A vast majority of the respondents (77%) reported receiving no financial assistance or subsidies for climate adaptation (Figure 8). Access to formal risk management tools is also critically low, with less than one-third (26%) reporting practical access to crop insurance. This systemic coverage failure leaves the remaining 74% fully exposed to climate-related losses. This limited access to finance and insurance directly contributes to the finding that three-quarters of farmers must resort to taking loans after climate shocks, creating an acute debt vulnerability (Liligeto and Nakamura, 2022; Nand et al., 2024). Without targeted financial and risk management interventions, smallholders remain trapped in a cycle of climate-induced economic instability (Figure 9).

4.5.2 Capacity deficits and policy perception

The absence of proactive extension services and structured training underscores a critical failure in building the adaptive capacity of smallholder farmers. A substantial 74% of the respondents reported

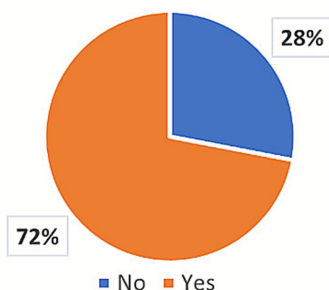
receiving no formal training on climate adaptation strategies, indicating a significant knowledge and skill deficit that limits their ability to respond effectively to increasing climate hazards. This shortfall is reflected in the low overall perception of government initiatives, with 74% of farmers rating current policies addressing climate risks as "not effective" (Figure 8). While some farmers, approximately half, noted limited assistance from cooperatives, this local-level support remains insufficient to compensate for the fragmented and largely ineffective national-level institutional framework. The lack of coordinated extension services and training opportunities not only reduces farmers' awareness of adaptation measures but also diminishes their capacity to implement them efficiently. These findings highlight the urgent need for inclusive farmer-centered adaptation strategies, stronger institutional coordination, and targeted knowledge transfer programs that bridge the gap between policy design and implementation. Strengthening these mechanisms is essential to ensure that adaptation support reaches smallholders, enabling them to build resilience against climate-induced shocks and safeguard the long-term sustainability of Fiji's sugarcane sector.

The economic and climate vulnerabilities experienced by smallholders are compounded by significant deficiencies in institutional support and policy implementation. Farmer responses regarding access to government programs, risk financing mechanisms, and climate-specific training reveal a profound gap between the formal policy landscape and practical support at the farm level, as shown in Figure 8.

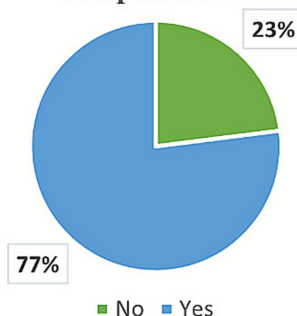
Operationally, the Integrated Coordination Committee (ICC) outlined in the recommendations (Figure 6) provides a delivery spine that links the Sugar Research Institute of Fiji (SRIF)–Fiji Sugar Corporation (FSC) R&D/seed systems, Ministry of Agriculture (MoA) infrastructure targeting, Sugar Cane Growers Fund (SCGF) risk finance, and Ministry of Education (MOE) vocational training with cooperatives and farmer representatives. The ICC's quarterly cycle, public delivery plan, and KPI dashboard institutionalize top-down policy/finance with bottom-up feedback on adoption, improving accountability and speed to scale. Given this study's evidence of exposure, costs, and adoption barriers, a coordinated platform is necessary to close the adaptation gap identified above.

In addition to institutional limitations, this study identified salient behavioral and informational barriers that further constrain the adaptive capacity of sugarcane farmers. A significant proportion of respondents demonstrated limited awareness of the underlying drivers of their vulnerabilities, indicating a cognitive disconnection between lived experiences and the broader climate risk context. This lack of self-recognition impedes timely and informed adaptive decision-making. Furthermore, adaptation strategies are seldom communicated with a clear articulation of their long-term economic benefits, reducing their perceived utility among farmers, who are focused on immediate survival and cost minimization. A pervasive sense of resignation, characterized by sentiments such as "*we just have to live with it*," reflects a deeper psychological barrier to change, a pattern also noted in findings from the Sugar Research Institute of Fiji (SRIF, 2014). Compounding these challenges is the absence of accessible and user-friendly informational resources; current materials are often overly technical, lacking localization and practical relevance. Collectively, these constraints underscore the importance of integrating behavioral insights and participatory communication strategies into policy.

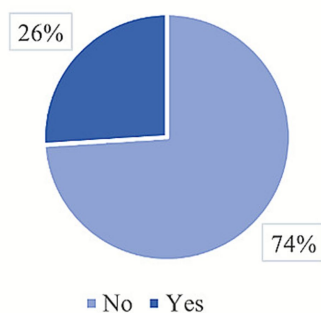
Are any government programs that support farmers in coping with climate hazards



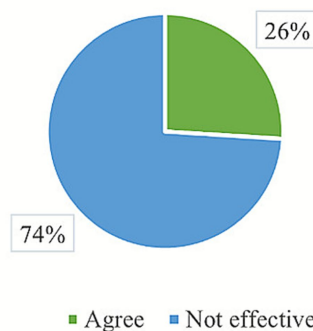
Have you received financial assistance or subsidies for climate adaptation ?



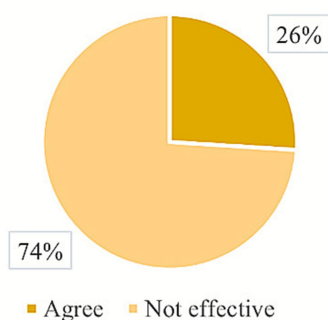
Do you have access to crop insurance for climate-related losses?



Are current policies effective to address climate challenges in sugarcane farming?



Have you received training on climate adaptation strategies?



Are cooperatives assisting sugarcane farmers deal with climate challenges

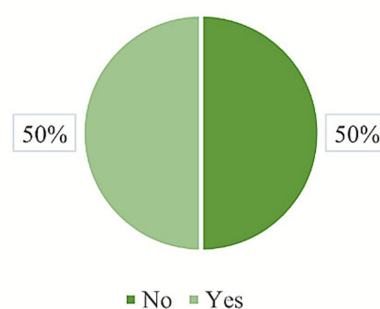


FIGURE 8
Institutional and policy support for climate adaptation among sugarcane farmers (%).

5 Conclusion

Fiji's sugarcane sector stands at the frontline of climate change, facing compound threats from floods, droughts, irregular rainfall, rising temperatures, and escalating production costs. This study integrated multi-year farmer surveys, regression-based quantification of climate hazards, and AI-assisted scenario modeling to reveal floods

and rainfall irregularities as the dominant drivers of yield losses ($\beta = -0.496, p < 0.001$; $\beta = -0.243, p < 0.001$), whereas cyclones and droughts acted as secondary but significant constraints. The AI-assisted projections, benchmarked against the Asian Development Bank climate outlooks, confirmed these hazard rankings and delineated priority hotspots in coastal and river basin areas, generating actionable guidance for site-specific adaptation. However, farm-level responses

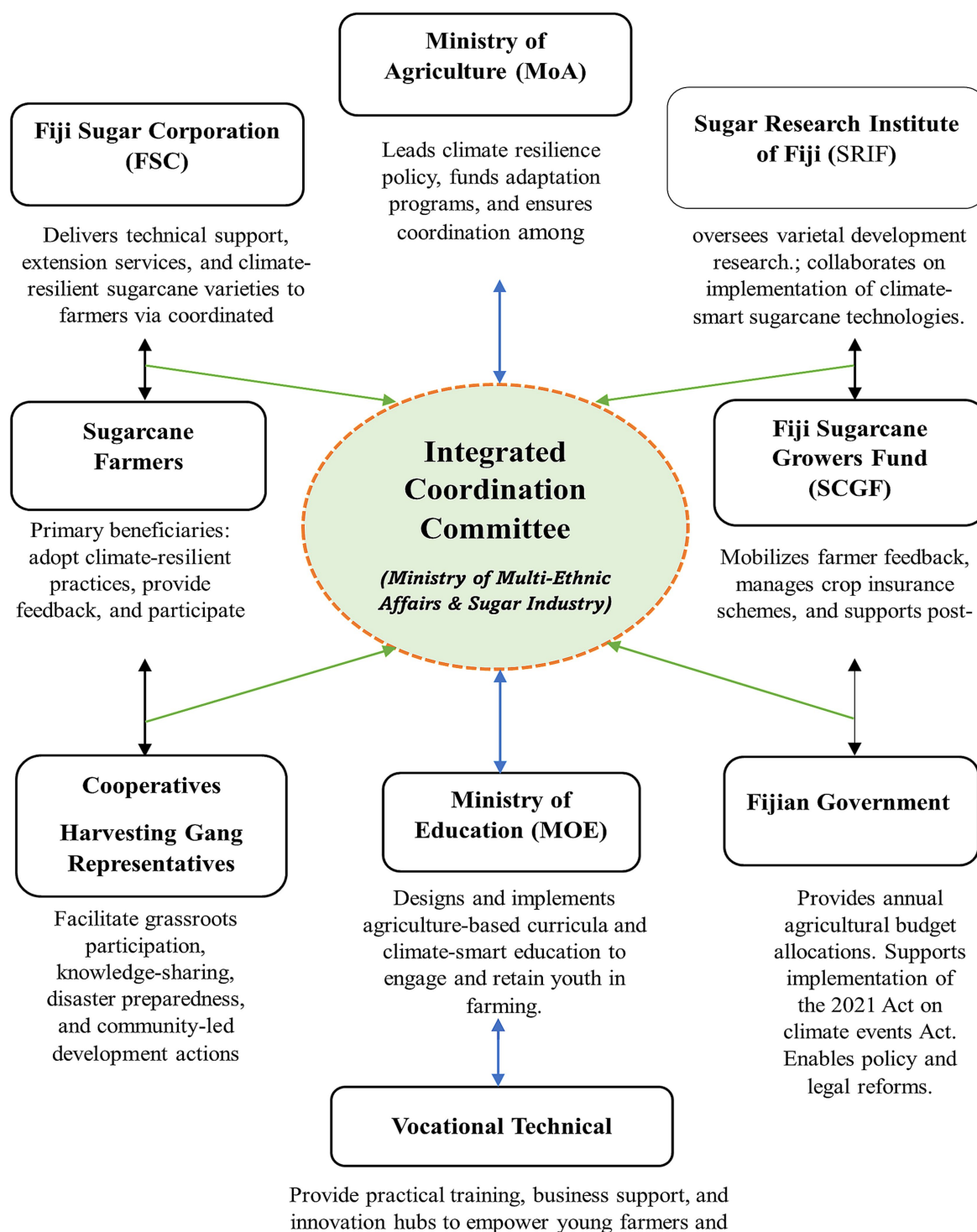


FIGURE 9

Adaptation framework: Integrated Coordination Committee (ICC) model linking policy, research, extension, finance, and farmer feedback.

remain largely incremental, and the adoption of transformative technologies is minimal. Financial and institutional weaknesses are compounded by behavioral barriers, such as low-risk awareness, which intensify vulnerability and impede proactive adaptation.

Therefore, a climate-resilient transformation of Fiji's sugarcane industry demands an integrated framework built upon two foundational pillars: targeted water management and the accelerated

upgrading of climate-resilient sugarcane varieties. These core technical interventions must be enabled and amplified by robust support systems, including participatory extension, risk-layered finance, youth engagement, and institutional coordination. Embedding these priorities within an Integrated Coordination Committee (ICC) model offers a pragmatic pathway to bridge research, policy, and practice. Ultimately, Fiji's experience provides both a cautionary lesson and a transferable

framework for other Small Island Developing States (SIDS) and tropical agricultural economies. This underscores the universal imperative for confronting escalating climate risks; strengthening water management infrastructure and advancing climate-resilient cultivars are the cornerstones of securing agricultural productivity, rural livelihoods, and climate preparedness in an era of intensifying environmental stress.

5.1 Strategic recommendations for climate-resilient sugarcane farming

A holistic and integrated approach is required to sustain Fiji's sugarcane industry. This must combine infrastructure, institutional reform, innovative finance, and grassroots actions. This study shows that climate change drives extreme events, rising input costs, and declining youth engagement. Technology alone is not sufficient. Long-term sustainability needs aligned policy, practice, and partnerships consistent with Fiji's Paris and SDG commitments.

1 Targeted infrastructure and large-scale investment

- Upgrade irrigation systems, drainage, flood protection, farm roads, sugar mills, and farm implements to enhance efficiency and reduce losses.
- Focus on micro-catchments and high-risk zones to stabilize yields and minimize climate shocks.
- Expand farmer training programs on farm management, weather monitoring, and preparedness.

2 Cultivar innovation and agro-ecological resilience

- Accelerate the adoption of climate-resilient sugarcane varieties [drought-tolerant Ea-DREB2B (Dean, 2025; Kumar et al., 2024; Chaudhary, 2025), flood-resistant lines, Beqa, Galoa; (SRIF, 2024)].
- Coordinate SRIF-FSC for certified seeds, varietal mapping, farmer training, and subsidies.
- Promote agro-ecological diversification with mixed cropping and high-value crops to buffer climate shocks.

3 Extension, participatory engagement, and stakeholder networks

- Re-tool extension services for farm-specific guidance, co-produced adaptation plans, and hands-on support.
- Establish farmer networks connecting FSC, cooperatives, and stakeholders for early warning updates and climate preparedness.
- Integrating behavioral insights to overcome resignation, low awareness, and adoption barriers.

4 Policy, research, and institutional strengthening

- Fund varietal trials, AI-assisted climate forecasting, and long-term monitoring.
- Strengthen inter-ministerial coordination, ensure farmer representation, and implement the Climate Change Act of 2021.
- Embed an Integrated Coordination Committee (ICC) to align policy, R&D, extension, finance, and farmer feedback, with quarterly monitoring and KPI dashboards.

5 Youth engagement and capacity building

- Embed climate-smart agronomy and agribusiness in curricula.
- Establishing field schools, mentorship programs, micro-grants, and digital tools for training, markets, and peer learning.
- Foster youth participation through the successful Saemaul Undong model of South Korea to secure intergenerational continuity in the sugarcane sector.

5.2 Study limitations and future research directions

The study focuses on 100 farmers in the Maro settlement (Nadroga-Navosa), so the findings may not be generalizable nationally. Self-reported data collected via Google Forms are subject to recall and selection bias and offer limited qualitative depth. Resource and time constraints restricted the sample size and prevented a longitudinal design, thus limiting causal inference on adaptation efficacy.

Build panel datasets linking mill-verified yields, costs, and plot-level management to independent climate reanalysis/remote sensing; evaluate infrastructure and risk-finance interventions using quasi-experimental designs; run varietal and technology choice experiments that incorporate risk and cash-flow constraints; and establish multi-country variety checks (standardized multi-environment trials across the Pacific Islands and comparator cane regions) to assess stress-tolerant cultivars for yield stability, sugar recovery, and adoption speed.

The AI component is non-physical and non-deterministic; outputs depend on prompts and are used only for scenario synthesis and triangulation with ADB projections. Future studies should couple these narratives with mechanistic crop-climate models and multi-country variety checks (standardized METs) to quantify robustness across ecologies.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding author/s.

Ethics statement

The studies involving humans were approved by International Development Cooperation, Kyungpook National University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

SK: Investigation, Writing – original draft, Conceptualization, Writing – review & editing. B-WY: Writing – review & editing, Conceptualization, Validation, Investigation, Software, Formal analysis, Supervision, Methodology, Resources, Data curation,

Funding acquisition, Writing – original draft, Project administration, Visualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Generative AI statement

The authors declare that Gen AI was used in the creation of this manuscript. The author(s) verify and take full responsibility for the use of generative AI in this manuscript. Generative AI tools were employed exclusively to support predictive modeling of climate impacts and projections for sugarcane production in Fiji. All underlying data, statistical analyses, and interpretations were conducted and validated by the author(s).

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fclim.2025.1690723/full#supplementary-material>

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