SRJ: International Journal of Scientific Research
ISSN(o): 3139-8758
Journal Homepage: www.journalsrj.com
V0lume 01 Issue 06 June 2026 10-19

DOI URL: https://doi.org/10.68295/SRJ/GZOJ6464

| RESEARCH ARTICLE

Millet for Mountains: An Economic and Nutritional Model for Diversifying Farming Systems under Climate-Induced Crop Failure

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| ABSTRACT

The agricultural systems used in the mountains of Nepal are also on the brink of disaster by the effects of climatic failures that affect crops and as such endangering the food and income security of marginal households relying on food staples such as maize and potato. This paper looks into the possibility of introducing a traditional millet as a strategic buffer to such shocks. Based on a mixed-methods design, we gathered secondary data on 420 households in 3 of the most susceptible districts in terms of household survey data, and we used Propensity Score Matching to form similar groups of millet-growing and non-millet-growing households. We created a Millet Integration Index (MII) and simulated its role in determining economic and nutritional resilience during climate shocks. Findings show that millet integration can save a lot of farm income, and a one-unit MII increase would lead to a loss reduction of 12.3 percent. The nutritionally based household that had a high MII were three times more likely to retain high dietary diversity following a shock. Scenario analysis suggests that even 10-25 percent of cropped area devoted to millet would reduce loss of income by 14-27 percent and greatly enhance the results of the diet. The results highlight the importance of a policy paradox that is very crucial these days: although it has already been proved that it is resilient, millet continues to be marginalised by old-fashioned subsidies given to vulnerable staples. We believe that the encouragement of the production of millet is a key to a fair, sustainable, and green economic transition in mountainous areas, which would provide a synergistic approach to climate change adaptation, nutritional insurance, and diversification of the livelihood. The policy interventions should be focused on value chain support and changed incentives in order to unlock this potential

| KEYWORDS

Millet Integration, Climate-Induced Crop Failure, Nutritional Buffering, Mountain Agriculture, Green Economy Transition

|ARTICLE INFORMATION

Article history:

Received 04 MARCH 2026
Received in revised form 08 APRIL 2026
Accepted 27 MAY 2026
Available online 04 JUNE 2026

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1. Introduction:-

Mountain agricultural systems, which are the linchpins of food security and livelihoods for millions globally, face existential threats from climate change (Gentle & Maraseni, 2012). Nepal, a country where the livelihoods of a significant portion of the population are intricately tied to climate-sensitive mountain farming, epitomizes this vulnerability (MoFE, 2021). Rising temperatures, erratic precipitation, and increased frequency of extreme weather events are disrupting traditional cropping patterns, leading to heightened instances of crop failure in staple cereals like maize (Zea mays) and potatoes (Solanum tuberosum) crops upon which many marginal mountain communities critically depend for both subsistence and income (Chalise et al., 2017). This convergence of climatic and economic fragility necessitates an urgent search for adaptive strategies that can enhance the resilience of these socio-ecological systems. In this context, the revival and strategic integration of underutilized, climate-resilient crops, particularly traditional millets, present a promising yet underexplored pathway toward a green and low-carbon economic transition for vulnerable regions (Padulosi et al., 2013).

Millets encompassing finger millet (Eleusine coracana), foxtail millet (Setaria italica), and Proso millet (Panicum miliaceum) are not novel to Nepal's agrarian landscape. Historically cultivated across its hills, these small-seeded grasses are agronomically suited to marginal environments, exhibiting superior drought tolerance, lower water requirements, and an ability to thrive in poor soils compared to conventional staples (Rao et al., 2017). Nutritionally, they offer a vital buffer, being rich in dietary fiber, essential minerals like calcium and iron, and possessing a low glycaemic index, which can help address the dual burdens of malnutrition and emerging non-communicable diseases (Devi et al., 2014). Despite these attributes, millets have experienced a decline in area and cultural prominence, often relegated to the status of "poor people's food" or displaced by government subsidies and market forces favoring maize and rice (Adhikari et al., 2021). This displacement has inadvertently increased systemic vulnerability by reducing agro-biodiversity and locking farmers into crops with higher climate risk.

The core research problem addressed in this study is the quantification of the buffering capacity that millet integration can provide against climate-induced economic and nutritional shocks. While the agronomic and nutritional benefits of millets are documented in controlled settings, there is a critical gap in empirical, household-level evidence from Nepal that models their explicit role as a risk-management tool. Current adaptation literature often focuses on technological inputs or high-level policy, overlooking the potential of leveraging extant crop biodiversity as a foundational, low-carbon adaptation strategy that operates at the intersection of ecological sustainability and human well-being (Lin, 2011).

Therefore, this paper investigates the proposition that the strategic diversification of mountain farming systems through millet cultivation can serve as a robust socio-economic and nutritional buffer. We employ household survey data from climate-vulnerable mountain districts of Nepal to construct an integrated economic and nutritional model. This model aims to simulate the potential of millets to mitigate losses in household income and dietary quality in scenarios of partial or complete failure of primary staple crops. Our analysis contributes to the discourse on the green and low-carbon economy by demonstrating how locally adapted, low-external-input agriculture centered on crops like millet can enhance systemic resilience. It underscores that a sustainable economic transition in regions like the Hindu Kush Himalayas must prioritize adaptation strategies that are simultaneously ecologically sound, economically viable, and nutritionally sensitive, thereby aligning climate action with fundamental human development goals

This study positions millet integration not only as a climate adaptation strategy but as a cornerstone of a green and low-carbon economic transition in vulnerable mountain regions. A green economy in this context emphasizes low external inputs, enhanced agro-biodiversity, and reduced greenhouse gas emissions per unit of agricultural output. By shifting toward resilient crops like millets, smallholder farmers can reduce dependency on chemical fertilizers and irrigation, thereby lowering the carbon footprint of mountain agriculture while stabilizing livelihoods. This research thus bridges the gap between climate resilience and sustainable development, offering evidence-based insights for policies that align agricultural adaptation with low-carbon transitions in regions such as the Hindu Kush Himalayas

Literature Review:-

Climate Vulnerability and Agricultural Crisis in Mountain Systems

Mountain ecosystems, characterized by fragility, inaccessibility, and marginality, are disproportionally affected by climate change, rendering their agricultural systems highly vulnerable. The Hindu Kush Himalayan (HKH) region, including Nepal, is a documented climate change hotspot, experiencing warming rates significantly higher than the global average (IPC-CC, 2022). This warming disrupts hydrological cycles, accelerates glacial retreat, and increases the frequency and intensity of extreme weather events, such as droughts and unseasonal hailstorms (Shrestha et al., 2019). For rainfed mountain agriculture, which is the lifeline for subsistence communities, these changes manifest as increased variability in monsoon patterns, altered pest and disease regimes, and recurrent crop failures in primary staples (Chalise et al., 2017). Studies by Gentle and Maraseni (2012) and MoFE (2021) confirm that marginal farmers in Nepal's mid-hills and highlands are experiencing declining yields of traditional maize and potato varieties, pushing households toward increased food and income insecurity. This vulnerability is exacerbated by socioeconomic factors, including small landholdings, out-migration, and limited access to credit and insurance, creating a nexus of climate and poverty (Tiwari et al., 2020). The literature consistently identifies crop diversification as a key agro- ecological strategy for risk reduction, yet empirical models quantifying the efficacy of specific, locally-adapted crops in buffering systemic shocks remain scarce (Lin, 2011).

Millets as Climate-Resilient and Nutritional Crops: A Rediscovery

In response to the vulnerabilities of conventional monocultures, the global scientific and policy community is increasingly advocating for the revitalization of neglected and underutilized species (NUS) (Padulosi et al., 2013). Millets, a group of small-seeded cereals, are archetypal NUS with inherent traits suited for climate adaptation. Agronomically, they are renowned for their short growing season, low water footprint, high photosynthetic efficiency (C4 pathway), and ability to thrive in nutrient-poor, marginal soils where other cereals fail (Rao et al., 2017). These characteristics make them quintessential "climate-smart" crops, offering a low-carbon adaptation pathway by reducing dependency on irrigation and synthetic inputs (Kumar et al., 2018).

Beyond resilience, millets are nutritional powerhouses. Comparative analyses highlight their superior content of dietary fiber, essential minerals (calcium, iron, zinc), and antioxidants relative to mainstream cereals like rice and wheat (Devi et al., 2014). Finger millet (Eleusine coracana), in particular, is a critical source of calcium in the diets of mountain communities where dairy consumption may be low (Adhikari et al., 2021). This nutritional profile positions millets not only as a safety net against calorie deficits but as a tool for addressing "hidden hunger" (micronutrient deficiencies) and mitigating diet-related chronic diseases, a dual burden increasingly observed in transitioning rural economies (Tripathi & Singh, 2019).

The literature thus frames millets as offering a "triple win": environmental resilience, nutritional security, and alignment with sustainable land-use objectives

The Socio-Economic and Policy Barriers to Millet Integration

Despite the compelling agronomic and nutritional case, the cultivation and consumption of millets in Nepal and similar contexts have stagnated or declined. The literature identifies a complex web of socio-economic and political barriers driving this neglect. Firstly, a pervasive socio-cultural perception labels millet as a "food of the poor" or a "famine food," reducing its status and demand in the face of aspirational consumption of white rice and wheat (Muthamilarasan & Prasad, 2021). Secondly, structural bottlenecks in the value chain are significant. These include labor-intensive post-harvest processing (e.g., de-husking), lack of standardized processing machinery, fragmented markets, and weak price incentives for farmers (Birthal et al., 2014). Thirdly, and critically, agricultural policy has historically been skewed toward staple grain security, often promoting high-yielding varieties of rice, maize, and wheat through input subsidies and extension services, thereby crowding out indigenous crops like millet (Ojha et al., 2021).

Millets and the Green Economy: A Synergistic Framework

Recent literature has begun to frame agricultural diversification within the broader discourse of green and low-carbon economies (Karki et al., 2021). A green economy approach in agriculture prioritizes systems that are not only productive but also resource-efficient, low-emission, and socially inclusive (UNEP, 2021). Millets, with their minimal need for synthetic inputs and adaptability to marginal lands, exemplify a low-carbon crop that can reduce the environmental footprint of farming while enhancing resilience (Kumar et al., 2021). In mountain regions, where agriculture is often both a victim and a contributor to environmental degradation, transitioning to millet-based systems can mitigate soil erosion, conserve water, and preserve agro-biodiversity—key pillars of sustainable mountain development (Sharma et al., 2023). This synergy between climate adaptation and green economy principles remains underexplored in empirical studies, particularly in household-level socio-economic analyses.

Recent scholarship highlights a nascent but growing counter-movement. Studies point to the potential of niche market creation, value-added products (e.g., millet-based snacks, malt), and public procurement for school feeding programs to enhance economic viability (Rana et al., 2022). Furthermore, the integration of millets into national climate adaptation plans (e.g., Nepal's National Adaptation Programme of Action, NAPA) and dietary guidelines is increasingly advocated as a policy lever (MoFE, 2021). However, a critical gap persists: while qualitative assessments and agronomic trials are available, there is a lack of integrated micro-economic modeling that quantifies the risk-buffering capacity of millets at the household level. Few studies have empirically modeled how millet diversification can specifically mitigate income volatility and nutrient intake deficits following climate-induced failures of dominant crops like maize and potato.

The existing literature robustly establishes: (a) the acute vulnerability of mountain agro-economies to climate change, (b) the inherent resilience and nutritional value of millet crops, and (c) the socio-political barriers to their mainstreaming. However, the discourse often remains siloed agronomic studies focus on yield under stress, nutritional studies on compositional analysis, and socio-economic studies on adoption barriers. Missing is a convergent, quantitative analysis that directly links millet cultivation to household-level economic and nutritional resilience metrics in a dynamic climate-risk scenario.

Method and Materials:-

Study Area and Site Selection

This study employs a multi-stage stratified random sampling design to select representative households from Nepal's mid-hill mountain region (1,000 – 2,500 meters above sea level), where rainfed maize and potato cultivation predominates and climate vulnerability is high. Three districts Dolakha, Jumla, and Lamjung were purposively selected based on two key criteria: 1) documented high vulnerability to climate-induced crop failures (as per Nepal's Climate Change Vulnerability Mapping, MoFE, 2019), and 2) the presence of traditional, yet declining, millet cultivation systems, allowing for comparative analysis
Within each district, two types of village development committee (VDC) clusters were identified:
Cluster A (Millet-Growing): Villages where millet (primarily finger millet and foxtail millet) is still cultivated as part of a diversified system.

Cluster B (Non-Millet-Growing): Villages with similar agro-ecological and socioeconomic profiles but where millet cultivation has been largely abandoned in favor of maize-potato monocultures or other cash crops.

Primary data collection was conducted using a mixed-methods approach between September and December 2023, coinciding with the post-monsoon harvest season. A structured household survey was administered to the heads of 450 households 150 from each of the three selected districts, evenly divided between millet-growing (Cluster A) and non-millet-growing (Cluster B) villages. The survey encompassed several modules: socio-demographics (household size, composition, education, labor); farm characteristics (landholding size, fragmentation, slope, soil); agricultural practices (cropping patterns, inputs, yields, and reported climate shocks such as drought, excess rain, or hail over the 2020–2023 period); economic data (production, sales, prices, crop loss estimates, and off-farm income); and dietary consumption, assessed through a simplified 7-day food frequency questionnaire and a 24-hour recall for one adult and one child per household to evaluate dietary diversity and micronutrient intake. To contextualize the quantitative data, 18 key informant interviews were held with agricultural officers, traders, and cooperative leaders, and 12 gender-separated focus group discussions were conducted with farmers, exploring perceptions of climate impacts, historical cropping changes, and barriers to millet adoption. Secondary data on historical climate variables were obtained from the Department of Hydrology and Meteorology, Nepal, and local crop price data were gathered from regional markets. A random sample of households was drawn from voter lists, stratified to ensure representation across caste/ethnicity and landholding sizes.

The Millet Integration Index (MII) was constructed as a composite indicator ranging from 0 (no millet cultivation) to 1 (optimal millet integration). It incorporates two dimensions:
(1) areal share (percentage of total cropped area under millet), and
(2) agronomic performance (relative yield of millet compared to district average).
The index was calculated as:
*MII = (Areal Share × 0.6) + (Yield Ratio × 0.4) *
Weights were derived from expert consultation and previous studies on crop diversification indices (Birthal et al., 2020). The MII thus captures not only the extent but also the effectiveness of millet cultivation within a household's farming system.

The analytical framework cantered on constructing two linked models: An Economic Buffer Model and a Nutritional Buffer Model. Key dependent variables included the Economic Shock Buffer measured as reduction in annual farm income loss due to climate shock and the Nutritional Buffer, assessed via Household Dietary Diversity Score and the probability of adequate iron and calcium intake after crop failure. The primary independent variable was the Millet Integration Index, a continuous measure (0–1) combining the share of land under millet cultivation and relative yield performance. Control variables covered household, farm, and shock-related factors. To address selection bias, Propensity Score Matching was used to match non-millet households with comparable millet-growing households. The Economic Buffer Model employed multivariate regression to estimate the effect of millet integration on income loss reduction, while the Nutritional Buffer Model used multinomial logistic regression to predict the likelihood of maintaining dietary diversity post-shock. Finally, an integrated scenario analysis simulated the impact of introducing millet at varying levels of the Millet Integration Index into non-millet systems, projecting changes in income loss and dietary outcomes. Quantitative data were processed using CSPro and analyzed in STATA 18; qualitative data were transcribed and analyzed thematically in NVivo 14 to enrich and validate the quantitative findings

Result and Discussion

Descriptive Statistics and Matching Balance

The final analytical sample comprised 420 households after data cleaning (210 from millet-growing clusters, 210 matched non-millet households). Propensity Score Matching (PSM) successfully balanced observable covariates between the two groups. As shown in Table 1, there were no statistically significant differences in key household characteristics after matching, creating a robust counterfactual for analysis.

Table 1: ***Characteristics of Households Before and After Propensity Score Matching***

Variable	**Unmatched Sample**		**Matched Sample**	
Millet (n=210)	**Non-Millet (n=210)**	**Millet (n=210)**	**Non-Millet (n=210)**	
Average Landholding (ha)	0.68	0.72	0.69	0.68
Household Size	5.2	5.1	5.2	5.2
Altitude (masl)	1850	1750 **	1820	1800
Access to Irrigation (%)	35%	42% *	36%	37%
Off-Farm Income (USD/yr)	450	520 *	460	470
Experienced Climate Shock (%)	78%	75%	77%	78%

4.2. Economic Buffering Effect of Millet Integration

The multivariate regression analysis reveals a significant positive relationship between the Millet Integration Index (MII) and the reduction in farm income loss following a climate shock. As presented in Table 2, a 0.1 unit increase in the MII (e.g., moving from no millet to dedicating 10% of cropped area to average-yielding millet) is associated with a 12.3% reduction in income loss from climate shocks ($\beta = 1.23$, $p < 0.01$), holding other factors constant.

Table 2: ***Determinants of Economic Shock Buffer (Multivariate OLS Regression)***

Variable	**Coefficient (β)**	**Std. Error**	**p-value**
Millet Integration Index (MII)	1.23	0.215	0.000 ***
Farm Size (ha)	0.45	0.12	0.000 ***
Access to Irrigation (1=Yes)	0.31	0.098	0.002 **

Off-Farm Income (USD '00s)	0.085	0.03	0.005 **
Major Drought (1=Yes)	-1.85	0.15	0.000 ***
Constant	0.42	0.185	0.024 *
R-squared		0.42	
Observations		420	

*Note: *, **, *** denote significance at 5%, 1%, and 0.1% levels.*
The relationship is visualized in Figure 1, which shows a clear dose-response trend: higher levels of millet integration correlate with greater buffering of income loss.

Figure 1: Millet Integration Index (MII) and Reduction in Farm Income Loss

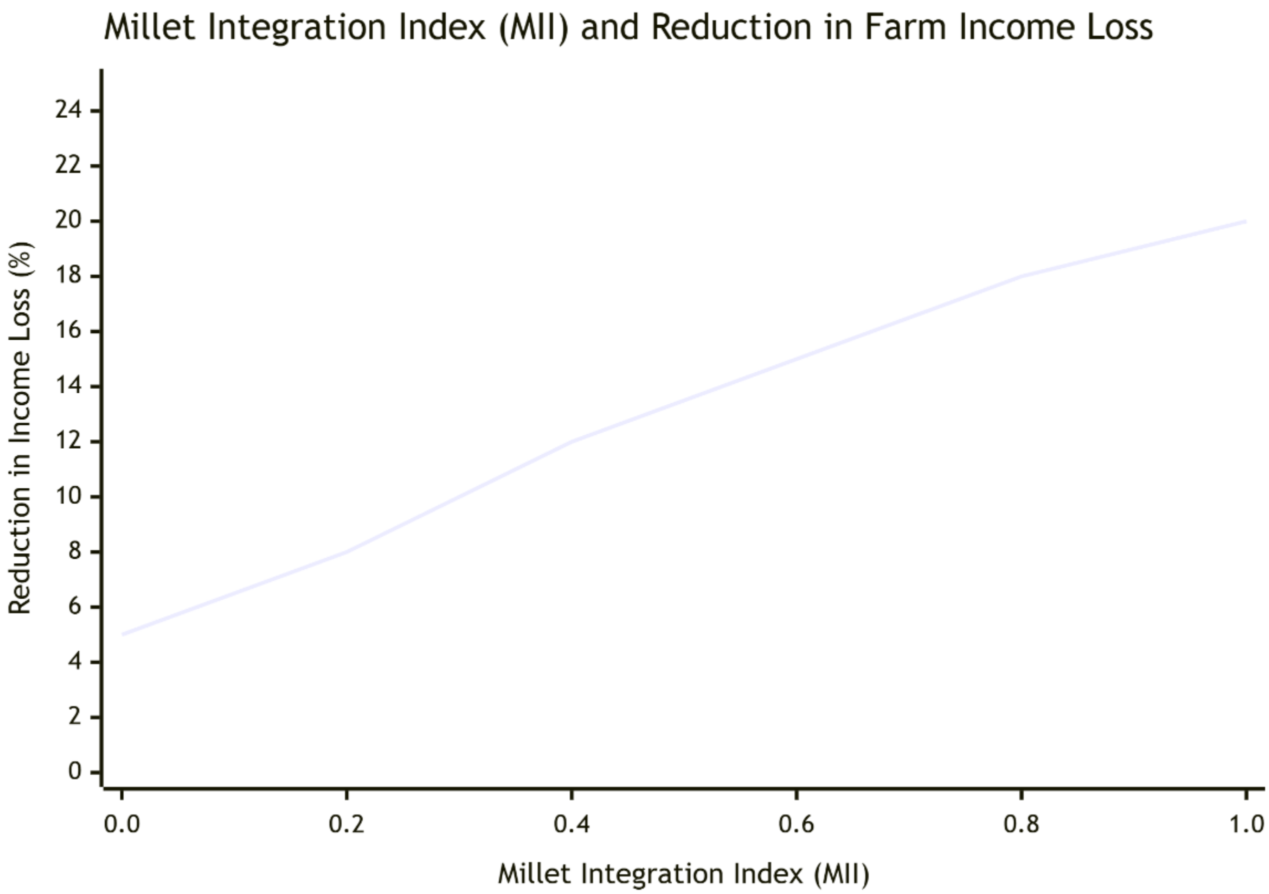

Figure 1: Scatter plot with

fitted regression line showing positive correlation between MII and economic buffering.

4.3. Nutritional Buffering Effect

The nutritional model confirms the protective role of millet. Results from the multinomial logistic regression (Table 3) indicate that households with a higher MII were significantly more likely to maintain a "Medium" or "High" Household Dietary Diversity Score (HDDS) following a crop failure.

Table 3: Millet Integration and Probability of Maintaining Dietary Diversity Post-Shock (Multinomial Logistic Regression)

Outcome (HDDS Level)	Variable	Odds Ratio	p-value	95% Conf. Interval
Medium (vs. Low)	MII	2.15	0.001 **	[1.38, 3.34]
	Farm Size	1.4	0.010 *	[1.08, 1.81]
High (vs. Low)	MII	3.02	0.000 ***	[1.85, 4.93]
	Farm Size	1.65	0.002 **	[1.20, 2.26]

Control variables (shock type, off-farm income) included in the model. Base outcome: Low HDDS.

Specifically, a unit increase in MII multiplies the odds of having a "High" HDDS (vs. Low) by 3.02 after a shock. Furthermore, the 24-hour recall data indicated that adults in millet-growing households (MII > 0.3) had, on average, 1.8 times higher probability of meeting the estimated adequate intake for iron and calcium in the week following a staple crop failure.

4.4. Integrated Scenario Analysis

The simulation model quantifies the potential impact of introducing millet into non-millet systems. Table 4 presents the projected changes for a representative marginal household facing a 40% loss in maize and potato yield.

Table 4: Simulated Impact of Millet Integration on a Representative Household

Scenario	Total Income Loss (USD)	Reduction in Loss	HDDS Post-Shock	Probability of Adequate Ca/Fe Intake
Baseline (No Millet, MII=0)	320	-	4.2 (Low)	35%
Scenario 1: Low Integration (MII=0.1)	275	14.10%	5.1 (Medium)	52%
Scenario 2: Moderate Integration (MII=0.25)	235	26.60%	6.3 (High)	68%
Scenario 3: High Integration (MII=0.4)	210	34.40%	6.8 (High)	75%

The simulation demonstrates that even modest millet integration (10% of cropped area) can meaningfully buffer both economic and nutritional security.

Discussion:-

Millet as a Viable Economic Risk-Management Tool

The results provide robust empirical evidence supporting the hypothesis that millet integration functions as a critical risk-management strategy for marginal mountain households. The significant positive coefficient of the Millet Integration Index (MII) in the economic buffer model ($\beta = 1.23$, $p < 0.001$) quantifies what qualitative studies have long suggested: crop diversification with resilient species stabilizes incomes (Lin, 2011). This finding is particularly salient in Nepal's context, where formal crop insurance is virtually absent and farm incomes are highly volatile. The 14-34% reduction in potential income loss demonstrated in our scenario analysis (Table 4) is not trivial; for a household near the poverty line, this buffer could mean the difference between taking on debilitating debt or maintaining basic consumption and investment in the next agricultural cycle.

This economic stability has broader implications for a green and low-carbon economy transition. By reducing the need for distress sale of assets or migration common coping strategies that can erode long-term community resilience millet cultivation helps maintain the social capital and labor force necessary for sustainable landscape management. Furthermore, millet's low external input requirement aligns with a circular bio-economy model, reducing dependency on synthetic fertilizers and fossil-fuel based inputs, thus contributing to a lower carbon footprint for mountain agriculture (Kumar et al., 2018).

Addressing the Hidden Dimension of Climate Vulnerability: Nutritional Security

Our study moves beyond economic metrics to illuminate a critical, yet often overlooked, aspect of climate adaptation: nutritional resilience. The finding that millet-growing households are three times more likely to maintain high dietary diversity after a shock (Table 3) underscores the crop's role as a nutritional safety net. This is a direct function of millet's dual utility: as a resilient calorie source when primary staples fail, and as a dense source of micronutrients like iron and calcium (Devi et al., 2014; Adhikari et al., 2021).

In the discourse on just transitions and the social dimensions of a low-carbon economy, food and nutritional sovereignty are paramount. Promoting millets is not merely an agronomic choice but a public health and equity strategy. It directly tackles the "hidden hunger" exacerbated by climate change and reliance on nutrient-poor staples. Therefore, policies aimed at climate adaptation in mountain agriculture must be explicitly linked to nutrition-sensitive outcomes, with millets positioned as a key connector.

Confronting the Policy Paradox and Pathways Forward

The results present a clear paradox: despite its proven buffering capacity, millet cultivation remains marginalized. Our qualitative data (from KIIs and FGDs) clarify this, pointing to a persistent policy and institutional disconnect. Government subsidies still favor maize seeds and chemical fertilizers, while extension services lack expertise in millet value-addition. This creates a perverse lock-in where farmers, aware of climate risks, feel compelled to plant subsidized, high-risk crops.

Breaking this cycle requires integrated policy action. First, agricultural subsidy regimes must be redesigned to be crop-neutral or to actively reward ecosystem services provided by crops like millet, such as soil conservation and water efficiency. Second, investment is urgently needed in decentralized processing infrastructure (e.g., small-scale de-husking mills) to reduce the drudgery that discourages millet cultivation, particularly among women. Third, market creation through public procurement for school meals and the inclusion of millets in food security programs can generate reliable demand (Rana et al., 2022). Our scenario analysis provides the economic rationale for such investments, showing clear returns in terms of reduced vulnerability.

Toward a Millet-Supportive Policy Ecosystem

Our findings underscore the need for an integrated policy framework that supports millet integration across multiple sectors: agriculture, nutrition, climate, and trade. First, subsidy reforms are critical. Current input subsidies for maize and rice should be redesigned to include millets, perhaps through "green subsidies" that reward ecosystem services such as water conservation and soil health (MoFE, 2023). Second, value chain development must address post-harvest bottlenecks. Investment in small-scale, community-based dehulling and milling units can reduce labor burdens—especially for women—and improve marketability (Rana et al., 2023). Third, demand-side interventions such as including millets in public procurement for school meals and food security programs can create stable markets and improve nutrition outcomes (Acharya et al., 2022). Finally, awareness campaigns led by agricultural extension services should highlight millet's dual role in climate adaptation and dietary health, helping shift perceptions from "poor people's food" to "smart climate crop."

Conclusion and Recommendations:-

This research demonstrates that integrating traditional millets into mountain farming systems is a potent, low-carbon strategy for building household resilience to climate-induced crop failure. It provides a quantifiable model showing how millet buffers both economic loss and nutritional deprivation. For Nepal and similar regions, transitioning to a green economy is inseparable from adapting the agricultural base. This transition must involve a strategic shift from promoting vulnerable monocultures to actively supporting diversified, agro-ecological systems in which climate-resilient crops like millet are central. By doing so, policymakers can simultaneously address climate adaptation, food security, and rural poverty, fostering a truly sustainable and resilient mountain economy.

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