American Journal of Environment and Climate (AJEC)

ISSN: 2832-403X (ONLINE)

VOLUME 3 ISSUE 1 (2024)

PUBLISHED BY

E-PALLI PUBLISHERS, DELAWARE, USA

American Journal of Environment and Climate (AJEC)
Volume 3 Issue 1, Year 2024
ISSN: 2832-403X (Online)
DOI: https://doi.org/10.54536/ajec.v3i1.2535
https://journals.e-palli.com/home/index.php/ajec

Sustainability of Agricultural Practices in Various Agro-Ecological Zones of Bhutan

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Article Information

Received: February 15, 2024

Accepted: March 20, 2024

Published: March 25, 2024

Keywords

Agriculture, Agro-Ecological Zones, Bhutan, Sustainability

ABSTRACT

Bhutan's agriculture sector has consistently advocated sustainable agricultural practices, yet it grapples with a range of interconnected challenges. These challenges encompass limited arable land, labour shortages, human-wildlife conflicts, and inadequate irrigation facilities, outbreaks of pests and diseases, and impacts of climate change. Therefore, this study assessed the sustainability of agricultural practices at the farm level across three agro-ecological zones: dry subtropical, cool temperate, and alpine. A total of 392 households were selected through simple random sampling for face-to-face interviews. The data collection, analysis, and reporting adhered to the guidelines of Sustainable Development Goals Indicator 2.4.1. The study focused on three dimensions of sustainability, comprising eight themes and eight sub-indicators for agriculture sustainability. The sustainability status was visualized using traffic light approach: green for desirable, yellow for acceptable and red for unsustainable. Results showed social dimensions across the study areas were in a desirable status. The environmental dimension exhibited desirable status in alpine zone. However, around 60% of agricultural land in dry subtropical and 77% in cool temperate zones have acceptable fertilizer management, while about 38% and 23% respectively fall into unsustainable category. Similarly, only about 73% of agricultural areas in the cool temperate zone are in acceptable status in pesticide management, and 23% under unsustainable status. Furthermore, the economic dimension across agro-ecological zones displayed unsustainable status in farm output value with 30% of farms in cool temperate, 78% in dry subtropical, and 74% in alpine zones. Strategic interventions are imperative in addressing economic and environmental dimensions to promote resilient and sustainable agricultural practices in Bhutan and analogous regions. Findings underscore the importance of identifying that similar impacts could potentially extend to other dry subtropical regions worldwide.

INTRODUCTION

Bhutan, a landlocked nation situated in the eastern Himalayas bordered by China and India, spans 38,394 km2 with a population of 770,276 (National Statistics Bureau [NSB], 2023). In 2022, 69.71% of the country maintained forest cover, meeting the constitutional requirement of 60% (Department of Forest & Park Services [DoFPS], 2023). Agriculture employs 43.5% of the population and contributes 14.67% to the GDP in 2022 (NSB, 2023). With only 7% (268,825.81 ha) of arable land due to rugged terrain, 2.96% is cultivated (Department of Surveying and Mapping [DoSAM], 2023). The average landholding accounts to 1.38 ha per household in which smallholder farmers practice integrated farming (NSB, 2021). Major cereals cultivated are rice, maize, wheat, barley, buckwheat, and millet, with rice as the staple crop (Katwal *et al.*, 2015). Over the years from 2006¬¬¬ to 2019, the self-sufficiency ratio for cereals averaged 77.30%, with rice declining to 47.08% (Bajgai *et al.*, 2021). Bhutan imports 143 agricultural items, notably rice, and exports 27 such as large cardamom, potato, and betel nut, primarily to Bangladesh and India (Department of Revenue & Customs [DRC], 2022).

Bhutan's development philosophy of Gross National Happiness resonates strongly with Sustainable Development Goals (SDGs) and of the 17 SDGs, seven are directly related to agriculture. Therefore, Bhutan is committed to sustainable agriculture, evidenced by various acts such as Forest and Nature Conservation Act (1995), Biodiversity Act (2003), Pesticide Act (2000), and others. Moreover, the country aspires to be organic formalized through the National Framework for Organic Farming in 2006 (National Organic Programme [NOP], 2019). Currently, 5,708.19 ha, are organically registered, with 65 certified products (Royal Government of Bhutan [RGoB], 2023). Agrochemical use are restricted, with 37% of farmers applying them on only 19% of cultivated land (International Centre for Integrated Mountain Development [ICIMOD] & Ministry of Agriculture & Forests [MoAF], 2018). Agrochemicals used are weedicides such as butachlor, metribuzin and glyphosate (Tshoki & Dhimal, 2021). The focus is on selected agro-ecological settings and high value niche agriculture and livestock products. Therefore, Gasa district is declared organic, owing to its agro-ecological setting of clean environment due to inaccessibility of agrochemicals (Wangmo & Iwai, 2018).

Bhutan confronts multiple agricultural challenges, jeopardizing sustainability. With 31% of farmland on steep 50% gradient slopes, farming is arduous (National Environment Commission [NEC], 2022) though 3111.05 ha of vulnerable land now brought under sustainable

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land management (Bhutan Trust Fund for Environment Conservation [BTFEC], 2019). Farm labor shortage is a concern, as 21.7% of the population has migrated to urban areas leaving 4,800 households empty and 26,769.34 ha of fallow land (NSB, 2018). Only 18% of land is under assured irrigation, exacerbating water-related fallowing issues (Tenzin *et al*., 2019). Wildlife contributes to 30% of crop loss (Japan International Cooperation Agency [JICA], 2012), leading farmers to either cultivate one crop or abandon farming for off-farm activities (Wangchuk *et al*., 2023). Positioned in the fragile Himalayas, Bhutan is highly climate-sensitive, facing increased risks from extreme climatic events that threaten agricultural productivity and food system sustainability (Wester *et al*., 2019). Therefore, this study aims to compare sustainability status of agriculture in three agro-ecological zones of the six zones since these agro-ecological zones (AEZs) has varying land use patterns, farming practices, cropping systems and crop production, dictated by climate, altitude and topography. Moreover, extreme weather events exhibit significant variations in both frequency and severity across different AEZs.

MATERIALS AND METHODS

Study Areas

The study covered five sub-districts across three districts of Bhutan: Kabisa and Dzome in Punakha (representing the dry subtropical zone), Phobjikha and Gangtey in Wangdue Phodrang (representing the cool temperate zone), and Laya in Gasa (representing the alpine zone) (Figure 1). The altitudes of study sites range from 1,131 m in the dry subtropical zone to 3,920 m in the alpine zone. In Kabisa and Dzome, various crops are cultivated, with paddy as the main crop. Phobjikha and Gangtey focus on cash crops such as potatoes, along with various vegetables such as radish, turnip, cabbage, cauliflower, broccoli, and spinach grown at homesteads. In Laya, yak farming and cordyceps (Ophiocordyceps sinensis) collection are primary livelihood activities supplemented by cereals and vegetables. The nearest motorable road is approximately a five-hour walk away.

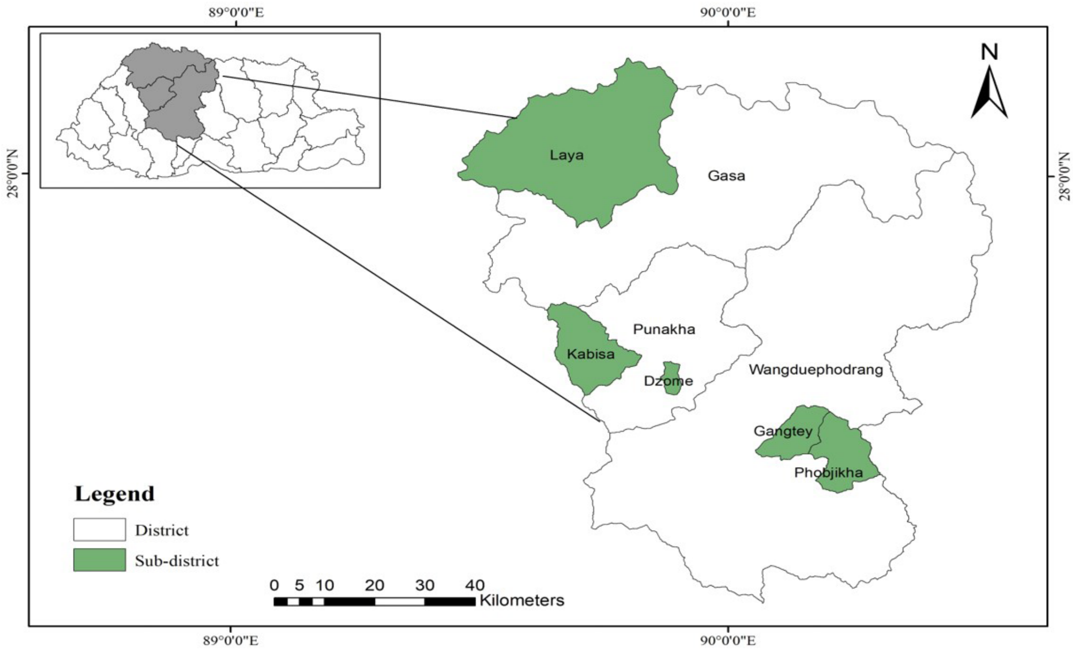

Figure 1: Study area

Framework for Determining the Sustainable Agriculture Practices

The sustainability of agriculture in the three AEZs was assessed using the Food and Agriculture Organization's (FAO) SDG Indicator 2.4.1 which assesses the proportion of agricultural area under productive and sustainable agriculture. This method, approved by the inter-agency and expert group on SDG indicators (FAO, 2023) includes economic, environmental and social dimensions consisting of 11 themes and 11 sub-indicators. Due to data constraints, this study focused on eight themes and eight indicators (Table 1). A traffic light approach was used to visualize the sustainability status: green for desirable, yellow for acceptable and red for unsustainable. It is important to note that there is no single blueprint for assessing sustainability as economic, environment and social systems differ widely among countries (Brundland, 1987). However, the three dimensions i.e. economic, environmental and social have been used in most studies, with varying themes and sub-indicators appropriate to the country. In this study SDG Indicator 2.4.1 was adapted.

Questionnaire Design

Data on agricultural holdings were primarily collected through farm surveys, using a set of questions derived from the data module of SDG Indicator 2.4.1. The survey on three dimensions of sustainability, covering eight themes and eight sub-indicators for assessing agriculture sustainability.

Sample Size and Selection

A total of 392 households were randomly selected for interviews as determined by using the following formula: $n=N/(1+Ne^2)$

Where: n = sample size; N = population size; e = 0.04 or 4% (Yamane, 1987). The surveys were conducted from October 2022-January 2023, with each interview lasting between 45 to 60 minutes. Majority of the respondents were female, as they typically stay at home while males engage in other economic activities, especially during non-peak farming season. The literacy rate was low among the respondents. Therefore, the data were mostly based on their memory. However, cross checking was done on the outliers of output data to minimize the errors. It is also important to note that the term 'respondents' is used interchangeably with 'farms' or 'farmers' wherever appropriate.

Statistical Analysis

Data collection utilized a Computer Assisted Personal Interviewing (CAPI) application. Results were computed by following the guidelines for SDG Indicator 2.4.1 using Microsoft Excel 2013. Additionally, chi-square tests of independence was conducted at 5% significant level, assessing the association between sub-indicator variables of sustainability and AEZs, using the Statistical Package for Social Sciences (SPSS).

Table 1: SDG Indicator 2.4.1 Framework

Dimension	Theme	Sub-indicator	Variables	Sustainability criteria
Economic	Land productivity	Farm Output per Hectare (FOVH) (Last calendar year)	1. Farm output value (main crops and livestock)	• Green (desirable): FOVH is ≥ 2/3 of the corresponding 90th percentile
			2. Agriculture holding category: (i) irrigated cropping, (ii) rainfed cropping, (iii) livestock farming, (iv) integrated (irrigated cropping and livestock) farming, (v) integrated rainfed cropping and livestock	• Yellow (acceptable): FOVH is ≥ 1/3 and < 2/3 of the corresponding 90th percentile
				• Red (unsustainable): FOVH is < 1/3 of the corresponding 90th percentile
	Resilience	Risk mitigation mechanisms (Last calendar year)	1. Access to or availed credit	• Green (desirable): Access to or availed at least two of mitigation mechanisms
			2. Access to or availed insurance	• Yellow (acceptable): Access to or availed at least one mitigation mechanism
			3. On farm diversification	• Red (unsustainable): No access to mitigation mechanisms
Environment	Water use	Variation in water availability (Last three calendar years)	1. Use of water for irrigation on at least 10 percent of agricultural area	• Green (desirable): Water availability remains stable over the years for farms irrigating crops on more than 10% of its agriculture area.
			2. Variation in water availability over time	• Yellow (acceptable): Uses water to irrigate crops on at least 10% of the agriculture area, does not have experiences on water reduction but there is an organization that effectively allocates water among users.
			3. Water user association	• Red (unsustainable): In all other cases.
	Fertilizer risk	Management of fertilizer (Last calendar year)	1. Use of fertilizers	• Green (desirable): The farm uses fertilizers but takes at least three specific measures to mitigate environmental risks. Default result for farms not using fertilizers

			2. Fertilizer management adopted: i. follow protocols as per extension service ii. use of organic fertilizers or in combination with synthetic fertilizers iii. grow legume crops iv. consider soil type and climate in fertilizer application v. soil sampling at least every 5 years	• Yellow (acceptable): The farm uses fertilizers and takes at least two measures to mitigate environmental risks • Red (unsustainable): The farm uses fertilizer and does not take any of the specific measures to mitigate environmental risks
	Pesticide risk	Management of pesticide (Last calendar year)	1. Use of pesticides	• Green (desirable): Farm takes all three health-related measures and at least four of the environment-related measures. Default result for farms not using pesticides
			2. Health measures adopted: i. adherence to label recommendations including use of protection equipment while applying pesticides ii. maintenance of protection equipment iii. safe disposal of waste	• Yellow (acceptable): Farm adheres at least two measures each to mitigate health and environmental risks
			3. Environment measures adopted: i. adhere to label recommendations for pesticide application ii. crop rotation iii. mixed cropping iv. use of traditional methods to control pests v. manual removal of plants infested by pests vi. maintenance and cleansing of spray equipment vii. Minimal use of pesticide	• Red (unsustainable): Farm adheres less than two specific measures to mitigate environmental or health risks associated with their use
	Biodiversity	Use of agro-biodiversity-supportive practices (Last calendar year)	1. Produces products that are organically certified	• Green (desirable): The agricultural holding meets at least two of the above criteria
			2. Practice crop-pasture rotation	• Yellow (acceptable): The agricultural holding meets at least one of the above criteria
			3. Locally adapted livestock breeds	• Red (unsustainable): The agricultural holding meets none of the above criteria
Social	Decent employment	Wage rate in agriculture (Last calendar year)	1. Daily wage	• Green (desirable): Farm labor is paid above the minimum national agricultural wage rate. Default result for farms not hiring labor

			2. Number of farm laborers hired	• Yellow (acceptable): Wage rate paid equals to minimum national agricultural wage rate
				• Red (unsustainable): Wage rate paid is below the minimum agricultural wage rate
	Food security	Food Insecurity Experience Scale (FIES) (Last calendar year)	1. Worried about not having enough food	• Green (desirable): Mild food insecurity: if the probability of a household of the holder of the holding to be moderate to severe food insecure is less than 0.5 and the probability to be severe food insecure is less than 0.5.
			2. Healthy and nutritious food	• Yellow (acceptable): Moderate food insecurity: if the probability of a household to be moderate to severe food insecure is greater than 0.5 and the probability to be severe food insecure is less than 0.5.
			3. Few kinds of food	• Red (unsustainable): Severe food insecurity: if the probability of a household to be severe food insecure is greater than 0.5.
			4. Skipped a meal	
			5. Ate less food	
			6. Ran out of food	
			7. Stayed hungry	
			8. Skipped meals for whole day	

Adapted from FAO (2023)

RESULTS

Economic Sustainability

Land Productivity

Land productivity was assessed based on the farm gate prices and quantities of crop and livestock produced by the farm. Farming practices were categorized as

(i) rainfed,
(ii) irrigated,
(iii) livestock,
(iv) integrated (rainfed), and
(v) integrated (irrigated) farming.

Integrated farming involves both crop and livestock. In dry subtropical zone (DSZ), farming practiced were rainfed, irrigated, integrated (rainfed), and integrated (irrigated). Similarly, these types of farming were practiced in cool temperate zone (CTZ), excluding irrigated farming. While in alpine zone (AZ), rainfed, integrated (rainfed), and livestock farming were prevalent.

The sustainability of each farm category was determined based on the farm output value per hectare (FOVH) in relation to the thresholds set for different farm categories (Table 2 & 3). The rainfed category in AZ was found to be the most desirable in 0.52 ha (68.42%) with FOVH equal to or more than US$3437.50. A low FOVH threshold due to small farm size and fewer crops cultivated as a result of unfavorable climatic conditions influences this result. Similarly, rainfed farming in CTZ was found desirable in 1.56 ha (49.37%) with FOVH equal to or more than US$8219.79. The integrated (rainfed) in CTZ was found to be acceptable in 27.04 ha (48.34%) with FOVH equal to US$6046.88 or more than US$12093.75. The integrated (rainfed) category in DSZ resulted as acceptable in 4.19 ha (33.07%) with FOVH equal to US$2531.40 or greater than US$5062.81. The majority of farms exhibited unsustainable FOVH, measuring less than 1/3 of the 90th percentile (Table 2).

In DSZ, the rainfed category had 18.44 ha (91.83%) identified as the most unsustainable. The average rainfall over 27 years was 592.05 mm, contributing to the unsustainability of the rainfed category (data source: National Center of Hydrology and Metrology [NCHM]). Additionally, 42% of respondents in DSZ reported a perceived reduction in water availability in springs, streams and rivers.

Sustainability Status

The land area under unsustainable category was highest in the DSZ (78.02%), followed by AZ (74.63%) according to the FOVH (Table 3 & Figure 3). The CTZ was in acceptable category with 46.26% of farm area.

Table 2: Farm classification and threshold farm output (US$/ha)

Category of farm	90 percentile value	2/3 of the 90 percentile	1/3 of 90 percentile
Dry Subtropical Zone			
Rainfed	15625.00	10416.67	5208.33
Irrigated	12634.38	8422.92	4211.46
Integrated (rainfed)	7594.21	5062.81	2531.40
Integrated (irrigated)	14375.00	9583.33	4791.67
Cool Temperate Zone			
Rainfed	12329.69	8219.79	4109.90
Integrated (rainfed)	18140.63	12093.75	6046.88
Integrated (irrigated)	17140.63	11427.08	5713.54
Alpine Zone			
Rainfed	5156.25	3437.50	1718.75
Livestock	122500.00	81666.67	40833.33
Integrated (rainfed)	100781.25	67187.50	33593.75

Table 3: Proportion of agriculture area in sustainability categories based on farm output value (USD/ha)

Category of farm	Desirable	Acceptable	Unsustainable
Dry Subtropical			
Rainfed	1.24	0.40	18.44
	(6.17%)	(1.99%)	(91.83%)
Irrigated	1.97	5.83	28.66
	(5.39%)	(15.99%)	(78.60%)
Integrated (rainfed)	1.31	4.19	7.16
	(10.36%)	(33.07%)	(56.56%)
Integrated (irrigated)	0.62	8.76	32.07
	(1.49%)	(21.14%)	(77.36%)
Total land area (ha)	**5.14**	**19.16**	**86.33**
	(4.65%)	**(17.33%)**	**(78.02)**
Cool Temperate			
Rainfed	1.56	0.80	0.80
	(49.37%)	(25.32%)	(25.32%)
Integrated (rainfed)	13.05	27.04	15.84
	(23.33%)	(48.34%)	(28.33%)
Integrated (irrigated)	0.40	0.79	1.60
	(14.35%)	(28.26%)	(57.39%)
Total land area (ha)	**15.01**	**28.63**	**18.24**
	(24.25%)	**(46.26%)**	**(29.48%)**
Alpine			
Rainfed	0.52	0.00	0.24
	(68.42%)	(00.00%)	(31.58%)
Livestock	1.28	2.20	11.31
	(8.65%)	(14.85%)	(76.50%)
Integrated (rainfed)	1.08	0.90	6.02
	(13.49%)	(11.24%)	(75.26%)
Total land area (ha)	**2.88**	**3.10**	**17.58**
	(12.23%)	**(13.14%)**	**(74.63%)**

Resilience

Risk mitigation mechanisms of resilient farms were evaluated through farm diversification and credit access. Diversification was determined by ensuring that the share of a single agricultural commodity or activity did not exceed 66% of the total production value. High dependence on specific commodity can pose risk to the farm's economic stability. In DSZ, 31% (n =152) of farms were diversified, 34% (n = 120) in the CTZ and 11% (n =120) in the AZ, showing significant difference across AEZs (p < .001) (Table 4 & Figure 2a). DSZ mainly focused on paddy and cattle farming, contributing 66% to the total production value. Other activities included poultry farming, and vegetable production (chili, cabbage, cauliflower, garlic, beans, tomato, spinach and coriander). In CTZ, potato production was dominant, followed by cattle, yak, horse and sheep farming. In AZ, yak and horse farming contributed over 66% to the total value followed by potato, spinach, and cattle farming. Diversification is crucial in all AEZs, particularly in AZ, promoting diversification based on the crop and livestock suitability is essential for sustainability.

Access to credit across AEZs, with only 1% in DSZ, and a substantial 70% in AZ indicating significant difference (p < .001). Notably, in AZ, 70% of respondent formally accessed credit from relatives and neighbors to meet their livelihood needs, particularly due to pandemic restrictions affecting their primary income source, i.e. cordyceps collection.

Sustainability Status

None of the AEZs meet the desirable category for risk mitigation mechanisms. In the AZ, 54.15% of the 35.24 ha falls into the acceptable category, where farms adopt at least one risk mitigation mechanism. Unsustainable practices were observed in DSZ and CTZ, with 69.88% and 67.67%, respectively, reporting a lack of farm diversification and limited credit accessibility or availability (Figure 3).

Environmental Sustainability

Water Use

The evaluation of water availability considered factors such as irrigated land, water availability status, and the presence of water user association. In DSZ, 96% (n = 152) of the farms are irrigated mainly due to paddy cultivation. In CTZ, only 4% (n = 120) of farms are irrigated, as rainfed farming is prevalent for potato cultivation and vegetable cultivation. No irrigated land was found in AZ (n =120), where rainfed farming is the primary practice for crops like wheat, barley, buckwheat, radish and turnip. A significant difference was found between AEZs and irrigated land (p < .001) (Table 4 & Figure 2b).

Water reduction reported in all zones: 42% in DSZ, 19% in CTZ, and 18% in AZ, revealing a significant difference across AEZs (p < .001). While water user association existed in all AEZs, only 61% of farmers in DSZ reported having such association, compared to 75% in CTZ and 89% in AZ, reporting a significant difference (p < .001).

Sustainability Status

Both the CTZ and the AZ exhibited a desirable status, while approximately 30% of DSZ farms categorized as unsustainable, primarily attributed to variations in water availability (Figure 3).

Fertilizer Management

Environmental risks associated to synthetic fertilizers use through mitigation measures, such as following extension services protocols, utilizing farmyard manure (FYM) or compost, and cultivating legume crops for soil fertility management. In Gasa district, located in the AZ, the government declared it as an organic district, prohibiting farms from applying fertilizers. Therefore, fertilizer management strategies were not assessed and considered desirable.

In DSZ, 61% (n = 148) of farms followed extension services protocols and 80% (n = 117) in CTZ, reporting a significant difference (p < .05) (Table 4 & Figure 2c). All DSZ and CTZ farms were found applying FYM or compost as sources of organic nutrients, indicating no significance difference (p > .05). There were only 3% (n = 148) of farms growing legume crops in DSZ, while no legumes were cultivated in CTZ and AZ, reporting no significant difference (p = .07).

Sustainability Status

Most farms in both AEZs fell into the acceptable category for fertilizer management. However, 38% of DSZ farms and 22.92% of CTZ farms were classified as unsustainable. Notably, legume crop cultivation as soil fertility management strategy was limited in DSZ, and no legumes were grown in CTZ and AZ (Figure 3).

Pesticide Management

Health risk measures associated with use of pesticide was assessed based on adherence to label recommendations, maintenance of protective equipment, and safe waste disposal. In DSZ, 91% (n = 69) of farms adhered to pesticide label recommendations, and 84% (n = 80) in CTZ, indicating no significant difference (p =.16) (Table 4 & Figure 2d). Maintenance of protective equipment were implemented by 68% of farms in DSZ and 93% in CTZ, showing significant difference (p < .01). In DSZ 61% of farms and 81% in CTZ were found adhering to safe disposal practices, revealing significant difference (p < .01).

Environmental risk measures for pesticide management, including adherence to label recommendations, crop rotation, mixed cropping, traditional pest control, manual removal of infested plants, maintenance of spray equipment, and minimal pesticide use were assessed. Similar to the findings in health risk measures, significant differences across AEZs were observed in both adherence to label recommendations and maintenance and cleansing of spray equipment. In DSZ, 81% (n = 69) of farms and 100% (n = 80) in CTZ were found practicing crop rotation, showing significant difference (p < .01) (Table 4 & Figure 2e). Mixed cropping were also practiced in 90% of farms in DSZ and 100% in CTZ, showing significant difference ($p < .05$). There were 57% of farms in DSZ and 70% in CTZ employing traditional pest control methods revealing no significant difference in the zones ($p = .08$). Another environmental risk measures practiced was manual removal of infested plants where 83% of farms were found practicing in both DSZ and CTZ, showing no significant difference ($p = .98$). Use of pesticides was minimal by 91% of farms in DSZ and 84% in CTZ, revealing no significant difference ($p = .16$).

Sustainability status

In DSZ, pesticide management achieved a desirable status, covering 77.94% of the agricultural area. In contrast, in CTZ, 73.43% of the area was categorized as acceptable, and 22.92% fell under the unsustainable status (Figure 3).

Use of Agro-Biodiversity Supportive Practices

The adoption of agro-biodiversity supportive practices, such as antimicrobials use, crop-pasture rotation, and rearing locally adapted livestock breeds, were assessed. In DSZ, 48% ($n = 152$) of farmers used antimicrobials in livestock, compared to 92% ($n = 120$) in CTZ and 81% ($n = 120$) in AZ, showing significant difference ($p < .001$) (Table 4 & Figure 2f). Crop-pasture rotation was also practiced by 82% of farms in DSZ, 99% in CTZ, and 98% in AZ with a significant difference observed in all AEZs ($p < .001$). Additionally, 72% of farmers in DSZ reared locally adapted breeds, compared to 68% in CTZ and 96% in AZ, revealing a significant difference ($p < .001$).

Sustainability Status

In DSZ, 83.29% of farms, 97.41% in CTZ and 94.74% of farms achieved a desirable status (Figure 3).

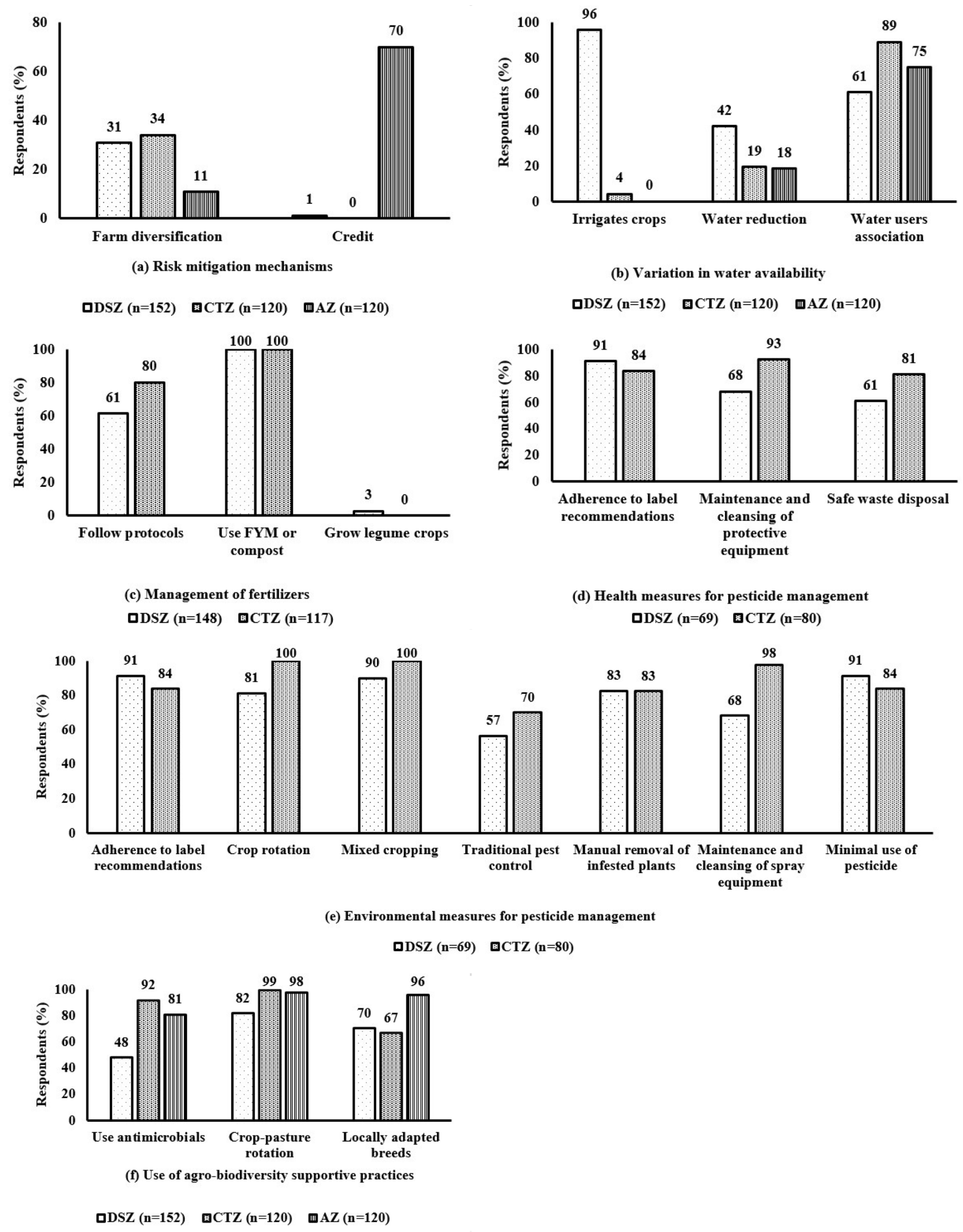

Figure 2: Sub-indicator variables indicating levels of agriculture sustainability in three AEZs

Table 4: Chi-square tests of sub-indicator variables in three AEZs

Sub-indicator	Variables	Chi-square statistic	Critical value	Degrees of freedom	Accepted Hypothesis
Risk mitigation mechanisms	Farm diversification	21.00	5.99	2	H_1
	Credit	231.20	5.99	2	H_1
Variation in water availability	Irrigated crops	352.43	5.99	2	H_1
	Water reduction	25.99	5.99	2	H_1
	Water users association	17.42	5.99	2	H_1
Management of fertilizers	Follow protocols	8.99	5.59	1	H_1
	FYM or compost application	0.00	5.59	1	H_0
	Grow legume crops	3.21	5.59	1	H_0
Management of pesticides: Health risk measures	Adherence to label recommendations	1.90	5.59	1	H_0
	Maintenance and cleansing of protective equipment	23.67	5.59	1	H_1
	Safe waste disposal	7.60	5.59	1	H_1
Management of pesticides: Environmental risk measures	Adherence to label recommendations	1.90	5.59	1	H_0
	Crop rotation	16.51	5.59	1	H_1
	Mixed cropping	8.51	5.59	1	H_1
	Traditional pest control	2.91	5.59	1	H_1
	Maintenance and cleansing of spray equipment	23.67	5.59	1	H_1
	Removal of plants infested by pests	0.00	5.59	1	H_0
	Minimal use of pesticide	1.90	5.59	1	H_0
Use of agro-biodiversity supportive practices	Use antimicrobials	69.77	5.99	1	H_1
	Crop-pasture rotation	35.07	5.99	2	H_1
	Locally adapted livestock breeds	35.07	5.99	2	H_1

Social Sustainability

Wage Rate in Agriculture

The wage rate in agriculture was assessed based on the daily wage rate paid to the farm laborers. Across all AEZs, the majority of the farms achieved a desirable status. Farmers compensated their labor force at rates exceeding the national minimum wage of Nu. 400 per day (US$4.81). On average, in DSZ and CTZ, the wage paid was Nu.500 per day (US$6.01), while in the AZ, laborers received Nu.1000 per day (US$12.01). These wage rates do not include additional benefits such as food and refreshments, which are approximately Nu.200 per day (US$2.40).

Sustainability Status

In all the three AEZs, a desirable status was achieved, with 99.56% of farms. In DSZ, 87.04% in CTZ and 94.74% in AZ. However AZ, 5% of the farms were reported as unsustainable, primarily associated with minor tasks such as repairing fences and clearing bushes (Figure 3).

Food Insecurity Experience Scale (FIES)

The Food Insecurity Experience Scale (FIES) gauges the severity of food insecurity in households using eight variables: (i) worry about not having enough food, (ii) access to healthy and nutritious food, (iii) variety of available food, (iv) skipped meals, (v) reduced food intake, (vi) running out of food, (vii) experiencing hunger, and (viii) skipping meals for an entire day. The prevalence rate of moderate to severe (Mod + Sev) food insecurity is highest in AZ at 11.31%, followed by CTZ at 1.37% and DSZ with 1.22%. Similarly, the prevalence rate of severe (Sev) food insecurity was higher in AZ with 6.04% compared to 1.30% in CTZ, and 0 in DSZ (Table 5).

Sustainability Status

The FIES scores in DSZ labeled 98.93% of farms as desirable, while it was 100% in CTZ, and 78.47% in AZ. However, only 0.36% of farms in DSZ, and 21.53% of farms in AZ fell into the acceptable category. Additionally, 0.71% of farms in DSZ were categorized as unsustainable (Figure 3).

Table 5: Prevalence rates of FIES of three AEZs

AEZs	Prevalence rate (Mod + Sev)	Prevalence rate (Sev)
DSZ	1.22%	0.00%
CTZ	1.37%	1.30%
AZ	11.31%	6.04%

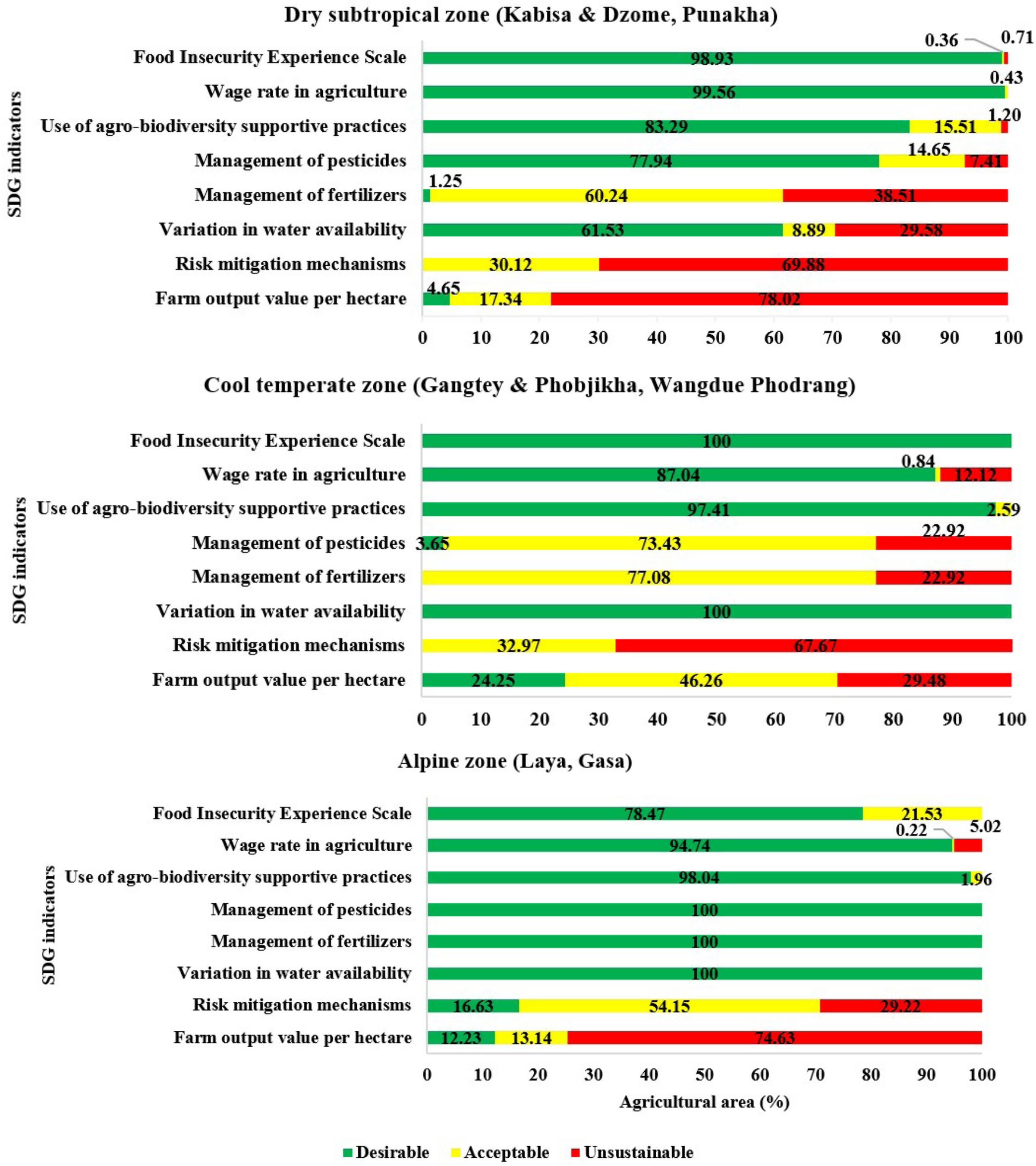

Figure 3: Agriculture sustainability status

DISCUSSION

Economic Sustainability

The economic dimension included farm productivity and risk mitigation mechanisms. Land productivity, as measured by FOVH predominantly fell into the unsustainable category in all the zones, potentially due to Bhutan's low-input agriculture resulting in lower productivity. Only 37% of Bhutanese farmers use agrochemicals on 19% of the total cultivated land (NOP, 2019). Moreover, a decline in nitrogen (N) availability in crops and limited adoption of improved soil fertility management practices (Feuerbacher *et al*., 2018) could contribute to lower output per hectare. Bhutan's susceptibility to the impacts of climate change, such as irregular rainfall patterns, floods, and landslides could also be attributed to lower farm output (Chhogyel *et al*., 2020). The reliance on climate-sensitive livelihoods, such as farming and livestock rearing has experienced greater exposure to vulnerabilities in the Eastern Himalayas (Bhadwal *et al*., 2019).

The farm's risk mitigation mechanisms in response to external shocks varied across AEZs. Farm diversification, assessed by the total value of one or more commodities or activities exceeding 66%, indicated lower diversification in all AEZs. In CTZ and AZ, low temperature in these zones restricts the cultivation of variety of crops and livestock. Although different types of crops are grown in DSZ due to the favorable climatic conditions, it indicates less diversification as the value of production of paddy and cattle farming exceeded 66%. Farm diversification enhances economic returns and agricultural resilience, reducing vulnerability to crop-specific pests, improving soil health, and promoting food security (Hossain *et al*., 2021). Additionally, it contributes to the conservation of indigenous crop varieties (Hunter & Fanzo, 2013).

Farmers, in general, did not avail formal loans in 2021, indicating high self-sufficiency or potential financial literacy challenges. Informal borrowing, common in AZ, offers flexibility but entails social collateral and potential higher costs (Karaivanov & Kessler, 2018). Access to credit has been linked to substantial gains in agricultural productivity, and economic well-being of farmers (Assouto & Houngbeme, 2023; Lagria, 2021). Although provisions for support such as facilitation and subsidies for inputs are provided, there is an absence of crop insurance policy to ensure profitable venture (Tashi & Dendup, 2020). Therefore, improving the financial literacy among farming communities is crucial for informed decision-making on credit and investment, contributing to enhanced agriculture sustainability. Hence, interventions such as crop insurance, credit facilities, and livelihood diversifications are crucial in all three zones.

Environment Sustainability

Farm environmental sustainability assessed variables such as water variability, soil fertility management, agrochemical use and management, and environmental risks. In the DSZ, water reduction in streams, springs and rivers was experienced mostly by the farms, an emerging issue reported in the Himalayas as 60% of the low discharge springs have been declining over the last couple of decades (Verma & Jamwal, 2022). Farmers in DSZ experienced water reduction attributed cultivation of irrigated paddy and commercial vegetables exacerbated by declining low discharge springs. Rainfall in the DSZ over the past 27 years indicate decreasing trend (1996-2022, data source: NCHM). CTZ and AZ, practicing rainfed farming, experience less water reduction. The predominance of rainfed farming practices contribute to water resource sustainability; however, are sensitive to climate change impacts. While DSZ and CTZ follow recommended synthetic fertilizer protocols, AZ is an organic region. Low literacy rate in DSZ could have contributed to low adherence to recommended agrochemical rates which corroborates the findings where none of the rice farmers adopted recommended synthetic fertilizer rate in Bhutan due to lack of awareness (Yeshey, 2012). Education is identified as a crucial for informed agricultural decisions on adoption and application of agricultural input (Asfaw & Admassie, 2004). Farms exclusively use FYM or compost for organic nutrients, aligning with traditional Soil Fertility Management (SFM) practices incorporating forest leaf litter, dung, and crop residues (Norbu & Floyd, 2004). The current SFM integrates synthetic fertilizers with organic sources in Integrated Plant Nutrition Systems (Chhetri, 2019). Effective fertilizer management is critical to minimize environmental risks, protect ecosystems, and ensure food safety (Pretty *et al*., 2018). The use of inorganic fertilizers in Bhutan is minimal with only 13.41kg/ha applied, compared to other Asian countries, 86.9 kg/ha in Nepal, 138.3 kg/ha in Sri Lanka, 156 kg/ha in Pakistan, 175 kg/ha in India (National Soil Services Center [NSSC], 2022). Bhutan's commitment to organic farming, exemplified by the organic district initiative (NOP, 2019), supports global efforts to reduce the agriculture's ecological footprint (Pretty *et al*., 2018). Yet, the adoption of practices like growing legumes, beneficial for soil fertility and weed control, is limited, highlighting the need for increased education and awareness (Jensen *et al*., 2012; Amosah *et al*., 2023).

Farmers in Bhutan is increasingly embracing organic farming, employing an Integrated Pest Management (IPM) approach with minimal pesticides and chemical fertilizer use (Tshoki & Dhimal, 2021). While the farmers in DSZ and CTZ, adhere to the recommended pesticide use; there were fewer reports of safe waste disposal in DSZ. The education level in DSZ might contribute to this disparity, with more respondents having limited schooling, revealing potential gaps in awareness and training. Similar challenges in India underline the importance of education in proper pesticide use to reduce health risks associated with direct exposure, such as skin and respiratory issues (Pathak *et al*., 2022).

Farmers in all AEZs employ cost-effective and traditional pest control practices, including the use of wood ash, crushed Artemisia water, and manual removal of infested plants. Artemisia, known for antimicrobial and insecticidal properties, has historical significance in ancient China, where its extracts were used to protect crops from insect pests (Gao *et al*., 2020). Wood ash, similarly, has been utilized by farmers in Yemen and Sikkim for pest control (Ba-hassan, 2020; Gopi *et al*., 2016). Additionally, manual removal of infested plants is a common practice among farmers in the AEZs aligning with control strategies observed in Ghana and Zambia for managing pests like fall armyworm on maize (Tambo *et al*., 2020).

Crop rotation and mixed cropping, collectively known as multiple cropping, serve as effective measures for managing agricultural pests in the AEZs. The National Plant Protection Centre (NPPC) in Bhutan promotes Integrated Pest Management (IPM) principles and underscores multiple cropping as a key long-term strategy for pest control (Katwal, 2013). This practice minimizes weeds and pathogens, enhances soil health, and leads to increased crop yields, offering economic benefits (Bowles *et al*., 2020). Multiple cropping is widely adopted in two AEZs. Paddy as the main crop with various vegetables and fodder crops are cultivated in DSZ, and potatoes as the main crop with vegetables such as radish and turnips for livestock feed, particularly during winter in CTZ. Crop rotation, adopted by 91.41% of farmers in Western

Bhutan could increase the soil water storage capacity, as evidenced by a Chinese experiment involving maize and potato rotation (Dendup *et al*., 2023; Wang *et al*., 2021). Mixed cropping not only enhances agricultural resilience but also diversifies income sources, contributing to improved livelihoods (Tittonell *et al*., 2010).

Antimicrobials play crucial role in preventing and treating infectious diseases in animals, ensuring their well-being, and enhancing growth rates for increased food production (Economou & Gousia, 2015). All farms across AEZs utilize antimicrobials to treat livestock. Although locally adapted breeds are already being reared across AEZs, it should be consistently encouraged to reduce the reliance on antimicrobials. Despite the positive historical and current impact of antimicrobial use in animal health and production, there are potential disadvantages linked to their use in food-animals (Gemeda *et al*., 2020). Therefore, encouraging the preservation of local livestock breeds can enhance biodiversity, improve livestock resilience, and ensure unique genetic resources (FAO, 2023).

Social Sustainability

Under the social sustainability dimension, two variables were measured: wage rates in agriculture and food insecurity experience scale. Wage rates paid to farm laborers across the AEZs exceeded the national rate of Nu. 400/day (US$4.81). Despite the age old tradition of labor exchange within communities, there is a significant shortage of farm labor, mainly due to rural-urban migration. Approximately, 21.7% of the population has migrated to urban areas, resulting in fallow agricultural lands and 4,800 vacant households, as reported by 2017 population and housing census (NSB, 2023). This scarcity has led to escalation in wage rates, increasing production costs, affecting commodity prices, and reducing the competitiveness of local produce in the market. A study in Uttar Pradesh, India highlighted the adverse impact of labor shortages on farmers, particularly those engaged in large-scale farming (Prasad, 2017). Moreover, research indicates that despite the willingness of elderly farmers to continue farming, their productivity declines; thereby, heightening vulnerability to food insecurity and decline in the labor force (Poungchompu *et al*., 2012). In Bhutan, the sustainability of agriculture is intricately linked to the availability of an affordable farm labor force and the adoption of technological advancement to alleviate drudgery in agricultural practices.

The Food Insecurity Experience Scale (FIES) indicates that the majority of the farms experience mild food insecurity or considered desirable. This is often attributed to cordyceps collection as a major income source, in Laya sub-district under the AZ. Similarly, in Phobjikha and Gangtey under CTZ, potato cultivation is a key commercial activity, and in Kabisa and Dzome under DSZ, paddy is the main crop, and vegetables production is commercially viable. The decline in poverty rate from 23.2% in 2007 to 8.2% in 2017 is attributed to agriculture commercialization, improved farm connectivity and hydropower (World Food Programme [WFP], 2023). However, the poverty rate increased to 12.4% in 2022 during Covid-19 pandemic, signifying that 12 out of every 100 people reside in households with a monthly per capita real expenditure below the upper-bound poverty line of Nu. 6,204 (US$74.57) (NSB, 2022). Hence, safeguarding the country's food and nutrition security is crucial, given that 43.5% of the population is engaged in the agricultural sector (WFP, 2023).

CONCLUSIONS

The study evaluated agricultural sustainability on farm level using FAO's SDG indicator 2.4.1 assessing eight themes and eight sub-indicators across three AEZs. The social dimension obtained desirable status in all AEZs, however, only two sub-indicators were assessed. Inclusion of variables such as community vitality, quality of life, happiness and wellbeing, decision-making, gender equality could have produced comprehensive results. Environmental dimension attained desirable status only in AZ requiring improvements in DSZ and CTZ. Fertilizer management in DSZ and CTZ was deemed acceptable, and pesticide management achieved desirability in CTZ. In DSZ and AZ, while CTZ scored as acceptable. Risk mitigation mechanisms showed acceptability in AZ but unsustainability in the other AEZs. Positive trends in water availability and agro-biodiversity practices were noted. Overall, agricultural sustainability reveals strengths in the social dimension. Targeted interventions are needed for farm output and risk mitigation mechanisms in all AEZs, pesticide and fertilizer management in DSZ and CTZ. The findings contributes valuable insights for developing resilient and sustainable agricultural systems in Bhutan, aligning policies with environmental and social responsibility. This also serves as a valuable framework for developing and enacting sustainable agricultural practices in regions facing analogous challenges, thereby extending the relevance of the research beyond Bhutan's specific circumstances.

Acknowledgements

The authors would like to extend gratitude to the International Development Research Centre, Canada through the collaborative research project between Tarayana Centre for Research and Development and the College of Natural Resources, Royal University of Bhutan under Bhutanese Knowledge for Indigenous Development (B-KIND) (Grant- 109442-001). The authors would also like to acknowledge district administrations, respondents, and enumerators for their valuable assistance, and National Center for Hydrology and Meteorology for providing historical weather data.

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