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Empirical Evidence of the Livelihood Vulnerability to Climate Change Impacts: A Case of Potato-Based Mountain Farming Systems in Bhutan

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Abstract: Potato (*Solanum tuberosum*) is an indispensable commodity, mainly cultivated by high-altitude mountain households, that sustains and supports the livelihood of an overwhelming 51% of the Bhutanese population. The popularity of potato cultivation among Bhutanese farmers can be attributed to the crop's adaptability to a wide range of agroclimatic conditions such as a rainfed crop, high productivity, an assured market, and a reliable source of income for the farming families. We hypothesize that the changing climate would make the livelihood associated with potato cultivation in Bhutan more vulnerable. We tested this hypothesis to identify the sources of vulnerability of smallholder farming households using the Livelihood Vulnerability Index (LVI) and LVI-IPCC (Intergovernmental Panel on Climate Change) approaches in six potato growing districts of Bhutan: Bumthang, Chukha, Gasa, Mongar, Tashigang, and Wangdue. Primary data were generated through a semi structured sample survey of 240 households on the seven major livelihood components of sociodemographic profiles, livelihood strategies, social networks, health, food, water, natural disasters, and climate variability. The results showed that the LVI (range 0.302 to 0.375) and LVI-IPCC (range −0.005 to 0.030) differed significantly ($p < 0.001$) across the districts. The districts of Tashigang and Mongar were less vulnerable than the other four districts by the LVI approach, whereas Bumthang was also revealed to be less vulnerable using the LVI-IPCC approach. The degree of vulnerability in a district differed according to their level of exposure and adaptive capacity to the climate change impacts of the potato farming household. The results are expected to serve as empirical evidence for designing a future course of actions to mitigate the negative impacts.

Keywords: farmers; climate change; adaptive capacity; exposure; sustenance

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Citation: Rai, P.; Bajgai, Y.; Rabgyal, J.; Katwal, T.B.; Delmond, A.R. Empirical Evidence of the Livelihood Vulnerability to Climate Change Impacts: A Case of Potato-Based Mountain Farming Systems in Bhutan. *Sustainability* **2022**, *14*, 2339. https://doi.org/10.3390/su14042339

Academic Editor: Hossein Azadi

Received: 30 December 2021
Accepted: 15 February 2022
Published: 18 February 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

Despite its location in the fragile mountain topography of the eastern Himalayas, Bhutan has committed to the global community to remain carbon negative. The country has adopted a unique development philosophy of the Gross National Happiness (GNH) that accords the highest priority for the conservation of the environment. It is a less developed country where agriculture, livestock, and forestry sectors contribute 15.82% to the GDP [1] but provide a major source of livelihood, engaging 50.8% of the population [1]. Currently, 66% of the population resides in rural areas [2] and depends on integrated subsistence family farming practiced under a typical mountain environment to eke out their livelihood [3]. Bhutan's location and geophysical setting make it highly vulnerable to the unprecedented impacts of climate change. A majority of the farming households are small-scaled subsistence farms with average landholdings of 0.1 to 3.6 acres. Further, the highly scattered settlements are mostly located in deep valleys, gorges, and rugged terrain, which makes sustainability of their livelihood very challenging even with minor disruptions [3–5]. In addition, due to large topographical differences accompanied by huge altitudinal variation, erratic climatic natural hazards—such as glacier lake outburst floods (GLOF), flash floods, erosions, and landslides—have been predicted to occur and are likely to intensify in the future in Bhutan [6,7]. Typical characteristics of the mountain environment include fragile geo-ecology, marginality, inaccessibility, subsistence livelihoods, limited land resources, low productivity, and limited off-farm employment opportunities [8]. In the rugged topographies and delicate mountainous settings, the amenities such as networks of accessibilities (roads), means of connectivity, and other infrastructure developments have been relatively poor, making them highly vulnerable to external stresses [9].

Notwithstanding such difficulties, Bhutan had reduced its national poverty to 8.2% in 2017 from 23.2% in 2007; however, rural poverty (11.9%) dominates urban poverty (0.8%) [5]. In terms of food consumption, 6.2% of the total 163,001 households are categorized as "not having enough food to feed their families" [4,5]. Historical evidence indicates that Bhutan has been severely affected by several flood disasters caused by cyclones and natural hazards. For example, Cyclone Aila completely destroyed 29 rural households and killed 12 people, besides damaging thousands of hectares of land across 17 districts [10]. It has been projected that the majority of Bhutanese farmers are likely to succumb to the climate change impacts (hereafter referred to as 'CCIs') [11]. Bhutan is expected to experience an alarming increase in temperature (by 0.8–3.2 °C) with a larger increase predicted in higher altitudes and a 10% to 30% annual increase in precipitation, respectively, according to recent forecasts [12–14]. Despite the fact that Bhutan's forest carbon sequestration is almost three times its greenhouse gas emission [15], the country is facing major climate-related threats, particularly in climate-sensitive sectors, such as agriculture [15,16]. Further, a recent study in Bhutan reported that unpredictable weather was experienced by 79% of the farmers [17].

Although assessments on the impacts of climate change on the agriculture and allied sectors have been undertaken, the vulnerability of farming communities' livelihoods has not been assessed. The concept of livelihood is fast emerging and commonly used in contemporary studies on assessments of poverty and rural development [18]. By definition, livelihood comprises the capabilities, assets (including both material and social resources), and activities required as a means of living [19]. However, livelihood is often challenged by the vagaries of vulnerabilities and deemed sustainable only when people can effectively cope with and recover from stresses and maintain or enhance its capabilities both now and in the future, without depleting the resource base [18–20]. Unless these vulnerabilities are addressed, livelihood will be challenged and thus will impact their livelihood assets [21]. Therefore, an understanding of vulnerability is the integral component required to identify and characterize appropriate adaptation measures and enhance the resiliency of the poor who own limited quantities of livelihood assets [22]. However, addressing the vulnerabilities is not straightforward; rather, it involves varied disciplines and expertise. For example, some of the prominent research fields that it covers are ecology, public health, sustainability science, land-use change, and climate change [18]. From the development perspective, vulnerability has its roots in famine, poverty, food insecurity, unemployment, inequality, political economy, and sociocultural norms [23,24]. Owing to this complexity, the study of vulnerability demands multidisciplinary approaches but context-specific analysis using context-specific indicators [23].

For this study, vulnerability is described as a state of defencelessness to secure livelihood due to the limited ability of an individual or group to counteract the external shocks that they face in their day-to-day life [19,25]. Of various such stresses, CCIs have been considered one of the primary factors affecting the livelihood of the marginal rural farming households around the world [26]. This is because CCIs pose a direct threat to the limited and friable livelihood assets that most smallholder farmers generally possess at the household level and to their ecological systems or surroundings [19,27]. Without qualification, the climate is one of the most fundamental external factors influencing agriculture growth and development [28]; however, the CCIs have persistently hindered the sector's growth resulting in increased vulnerability, especially amongst the smallholder farm households of the global south [29,30]. Due to the households' minimal adaptation capacity, their livelihood and economies are further predicted to be aggravated and to incur severe consequences due to the climate change impacts [31,32].

The Intergovernmental Panel on Climate Change (IPCC) describes climate change as "the result of the interaction between the biophysical drivers (including climatic exposure) and the function of the system's sensitivity and adaptive capacity" [32,33]. The change in global climate has been reported to be a result of both human activities and natural variabilities [34].

Global surface temperature is projected to increase 1.5 to 2.5 °C by the end of the twenty-first century, with higher frequencies and longer durations of heatwaves [35]. Such impacts of climate change have been recognized as one of the serious obstacles in attaining food and nutrition security or achieving major global sustainable development agendas, especially in the global south [35,36]. From a continental view, the fourth assessment report of the IPCC stated that by the 2050s, 300 to 600 million Africans would face acute vulnerabilities, predominantly in the northern and southern part of the continent, due to increased water stress (drought) for both drinking and farming [32]. Given the very low adaptive capacity accompanied by acute levels of poverty and limited abilities to mitigate CCIs, Sub-Saharan regions of Africa are considered one of the most vulnerable regions in the world [34,37]. In Africa, a majority of the farmers are heavily dependent on climate-sensitive sectors such as agriculture, so they are the most vulnerable due to a lack of means to appropriate adaptation measures and counteract CCIs [38,39].

Scenarios of CCI in Asia are similar to that of its African counterparts, with most of the countries equally dependent on agricultural farming and natural-based resources for their livelihood [40]. About 5% to 30% crop yield decline is projected in most parts of Asia due to CCI [30]. Freshwater availability, such as the large river basins of Changjiang, is likely to decrease due to CCI, severely affecting approximately 1.2 billion people who are largely dependent on agriculture and related farming by the 2050s [30,40]. Intriguingly, the Indian subcontinent alone would experience an overall temperature increase of 1 to 4 °C, an increase in precipitation of 9% to 16%, and increases in other erratic occurrences of extreme events such as droughts, floods, cyclones, and landslides by the 2080s, all of which are projected to disproportionately affect small-scale farming households [41]. In particular, the Indo-Gangetic Plains of India, that account for about 14% to 15% of the global wheat production, are likely to incur yield loss of 8% to 36% due to heat stress and erratic precipitation [42], impacting millions of people worldwide. With such scenarios developing and overall agriculture yield declining, the current 55% of the Indian population, who are largely dependent on agricultural sectors, is likely to face even higher risks to the CCI in the future [43]. Similarly, Karki et al. [44] have reported the rapid retreat of glaciers (>30 m/year), increase in temperature (>0.060 °C), and an increase in irregular frequencies of weather variabilities in Nepal. In Bangladesh, the two major sources of livelihood of the farmers—rice and fish farming—have been hit hard, resulting in a loss of 0.5 million tons of rice annually and sharp declines in fish production due to prolonged floods and salinization caused by climatic anomalies in recent past [45–47].

Of the various crop-based farming systems in Bhutan [48], the typical mountain-based potato farming system has played a vital role in supporting the livelihood of farmers since its formal introduction in the 1970s [49]. From its humble beginnings as a homestead garden crop [49], the potato has become the most widely cultivated, consumed, and traded crop in Bhutan [50,51]. It is currently cultivated by 34,000 rural households, mostly in the temperate agroecological zone, for their livelihood [4,51]. The revenue generated through the sale of potatoes was BTN 709.81 million in 2019 (USD 1 ≈ BTN 72) [52]. The income farmers receive from the sale of potatoes directly helps them purchase their staple food products, such as rice and other household necessities [50,53]. Within a short span of time, this crop was adopted by many Bhutanese farmers [54]; however, the CCIs have not spared the potato crop and instead have brought about substantial consequences in the overall agricultural sector in Bhutan [15,16]. Further, studies have forecasted that the land currently suitable for potato cultivation will become unsuitable by the 2050s, and the high-elevation areas (>3000 masl) will be affected due to larger temperature increases [12,55]. Against this backdrop, this paper attempts to understand the vulnerabilities caused by the CCIs at a household level in the communities whose livelihood hinges on a fragile mountain-based potato farming system, using the lens of a livelihood vulnerability framework/index. Accordingly, the objectives of the study are: (1) to assess and ascertain the vulnerability status of mountain-based potato growing farmers across the six districts in relation to climate change impacts; and (2) to generate empirical evidence and information on the impacts of climate change on livelihood source of the farming community using LVI approaches that will serve as a basis for informed decision making in future.

2. Materials and Methods

2.1. Data Collection

This study was conducted in the six major potato growing districts of Bumthang, Chukha, Gasa, Mongar, Tashigang, and Wangdue, where the potato crop is one of the main sources of livelihood for farmers (Figure 1). The research sites are located at elevations ranging from 1500 to 3500 m above sea level, which are characterized by warm to cool temperate agroecological climatic zones with mean temperatures ranging from 1 to 22 °C, and an annual rainfall ranging from 650 to 750 mm [12,56]. The potato-harvested area ranged from 14.97 ha (Gasa) to 863.80 ha (Wangdue), and the production ranged from 118.58 tons (Gasa) to 15,661.85 tons (Wangdue) in the study districts [57].

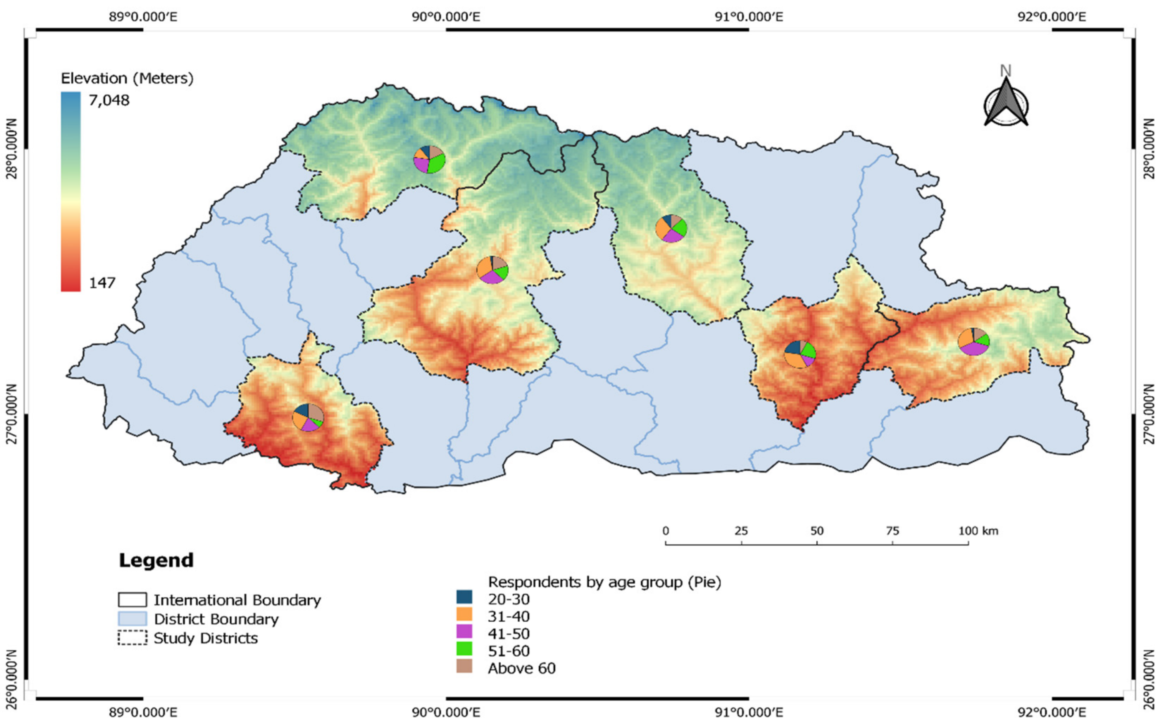

Figure 1. The six study districts where questionnaire survey was undertaken.

The study was based on primary data collected from the six study districts (Figure 1) by employing a semi structured questionnaire field survey. The survey was undertaken by a team of researchers, including the local agriculture extension agents, in the final quarter of 2020. Prior to the implementation of the questionnaire survey, a sampling frame of the potato-growing households in each district was constructed. Purposive sampling was employed as this approach allowed a random selection of households without bias [58]. A five-year period from 2016 to 2020 was used to recall events or occurrences of 'natural disaster and climate variability' because respondents might not recall incidences accurately beyond five years [59] due to memory fading over longer durations. The surveyor staff were briefed and trained to ensure uniformity in the administration of the survey. In each district, 40 randomly selected potato farmers from the constructed sampling frame were interviewed, which surpassed the required 5% sample size recommended for representative research [60] and resulted in 240 samples from across the six study districts. There are seven major relevant components of Sociodemographic Profile (SDP), Livelihood Strategies (LS), Health (H), Social Networks (SN), Food (F), Water (W), and Natural Disaster and Climate Variability (NDCV); and their subcomponents are explained in Table 1. The data collected on above seven major components and their corresponding subcomponents are presented in Table 2. Household sociodemographic indicators of literacy level, age range, gender, land, and family sizes were also captured.

Table 1. Major components and subcomponents comprising the Livelihood Vulnerability Index (LVI) developed for six study districts.

Major Component	Subcomponents	Explanation of Subcomponents	Sources
Sociodemographic Profile (SDP)	Dependency ratio	Ratio of the population under 15 and over 65 years of age (inactive population) to the population between 15 and 65 years of age (active population)	[61]
	% Households, female-headed	Percentage of female-headed households during the time of the interview	[61]
	Avg. age of head of household	Average age of the heads of households	
	% Households where the head of household has not attended school	Percentage of households where the head of the household (female/male) reports that they have attended 0 years of school.	[61]
	% Households with at least one orphan	Percentage of households with at least 1 orphan living in their home (orphans are children below 18 years old who have lost either one or both parents)	[61]
Livelihood Strategies (LS)	% Households with family working outside community/country	Percentage of households that report at least 1 family member working outside of the community for their primary work activity and earning a wage	[61]
	% Households dependent on agriculture for income	Percentage of households that report only agriculture as a source of income	
	% Households without incoming remittances	Percent of households who do not receive remittances	
	Avg. agriculture livelihood diversification index	The additional livelihood activities undertaken by households, calculated as the inverse of the number of agriculture livelihood activities (+1) reported by a household (e.g., a household that cultivates potato as the main crop and also cultivates vegetables for sale, and collects mushrooms from forests will have a Livelihood Diversification Index = 1/ (3 + 1) = 0.25)	[61] & modified
Social Networks(SN)	Avg. help received/given ratio, in-kind	The ratio of the number of types of help received by a household in the past month (+1) to the number of types of help given by a household to someone else in the past month (+1) (e.g., help received during the sale of crops divided by the help given during times of need/emergency)	[61]
	Avg. money borrowing/lending ratio	The ratio of a household borrowing money (in the past month) to a household lending money (in the past month) (e.g., if a household borrowed money but did not lend money, the ratio is 2:1 or 2; if a household lent money but did not borrow any, the ratio is 1:2 or 0.5)	
	% Households with poor neighbor relations	Percentage of households reporting to have poor relations with their neighbors	
	% Households with no recent local government assistance	Percentage of households that reported they had not asked their local government for any assistance in the past 12 months	[61]

Table 1. *Cont.*

Major Component	Subcomponents	Explanation of Subcomponents	Sources
Health	Avg. time to the nearest health facility (Basic Health Unit)	The average time taken by the households to get to the nearest health facility on foot	[61] & modified
	% Households with a family member with chronic illness	Percentage of households that report at least 1 family member with chronic illness, where 'chronic illnesses' was defined subjectively by respondents	
	% Households with a recent dreadful disease	Percentage of households that report at least 1 family member with a dreadful disease, where 'dreadful disease' was defined subjectively by respondent	
	% Households attending no recent health awareness programs	Percentage of households reporting that no family member attended any health awareness programs in the past 12 months	[61]
Food	% Households dependent on the family farm for food	Percentage of households reporting that they depend solely on the family farm for their food	
	Avg. months of household food shortage	The average number of months households face food shortage for their family members	modified (note: 'food shortage' does not reflect household 'food insufficiency')
	Avg. Crop Diversity Index	Calculated as the inverse of the number of crops grown by a household (+1) (e.g., a household that grows pumpkin, maize, chili, and beans will have a Crop Diversity Index = 1/ (4 + 1) = 0.2)	
	% Households not saving crops	Percentage of households that report that they do not save crops	
	% Households not saving seeds	Percentage of households that report that they do not save seeds for next seasons	
Water	% Households reporting water conflicts	Percentage of households reporting having conflicts over water in their community	
	% Households reporting watershortage for farming	Percentage of households reporting having water shortage in their community	
	% Households utilizing natural primary water source	Percentage of households reporting utilization of water through a natural source (spring, river/stream)	
	Avg. walking time to a water source	The average time it takes the households to travel to their primary water source	
	% Households with inconsistent water supply	Percentage of households reporting that they do not have consistent water supply	
	% Households with recent drying up of water sources	Percentage of households reporting increasing drying up of water sources	
Natural Disasters and Climate Variability(NDCV)	% Households not receiving natural disaster warnings	Percentage of households reporting not receiving any warnings prior to natural disasters	
	% Households with recent natural-disaster-related injury	Percentage of households reporting an injury due to natural disasters in the past 12 months	
	% Households reporting recent production-reducing crop, pest, or disease outbreak	Percentage of households reporting crop, pest or disease outbreak that affected their crop production in the past 5 years	
	% Households reporting more storms affecting crops recently	Percentage of households reporting increasing occurrences of hailstorm and affecting their crop production in their community in the past 5 years	
	% Households reporting recentcrop yield decline	Percentage of households reporting a decline in crop yield in their community in the past 5 years	
	% Households reporting increasing occurrences of natural hazards (landslides and flashflood)	Percentage of households reporting increasing occurrences of natural hazards affecting crop production in the past 5 years	
	% Households reporting a recent increase in erratic rainfall	Percentage of households reporting increasing occurrences of erratic rainfall affecting crop production in the past 5 years	

Table 1. *Cont.*

Major Component	Subcomponents	Explanation of Subcomponents	Sources
	Mean standard deviation of daily avg. maximum temperature	The standard deviation of the average daily maximum temperature by month between 2010 and 2020, averaged for each study district	[61] & modified
	Mean standard deviation of daily average maximum temperature	The standard deviation of the average daily minimum temperature by month between 2010 and 2020, averaged for each study district	[61] & modified
	Mean standard deviation of dailyaverage maximum precipitation	The standard deviation of the average daily maximum temperature by month between 2010 and 2020, averaged for each study district	[61] & modified

Table 2. Livelihood Vulnerability Index (LVI) subcomponent values and maximum and minimum subcomponent values calculated for study districts.

			Study Districts							
Major Component	Subcomponent	Units	Bumthang	Chukha	Gasa	Mongar	Tashigang	Wangdue	Max	Min
Socio-Demographic Profile	Dependency ratio	Ratio	0.89	0.88	0.98	0.67	0.81	1.22	5.00	0
	% Household, female-headed	Percent	83	50	73	65	90	55	100	0
	Avg. age of head of household	Years	45.75	47.05	48.00	41.13	47.30	47.38	79	20
	% Households where the head of household has not attended school	Percent	50	52.5	65	55	72.5	60	100	0
	% Households with at least one orphan	Percent	7.5	0	0	2.5	0	5	100	0
Livelihood Strategies	% Households with family working outside community/country	Percent	72.5	30	22.5	15	50	27.5	100	0
	% Households dependent on agriculture for income	Percent	55	62.5	50	42.5	12.5	45	100	0
	% Households without incomingremittances		53	27.5	53	2.5	2.5	53	100	0
	Avg. agricultural livelihood diversification index	1/# livelihoods	0.35	0.31	0.33	0.26	0.25	0.32	0.50	0.25
Social Networks	Avg. help received/given ratio, in-kind	Ratio	0.99	1.05	1.01	0.97	0.97	0.97	1.5	0.5
	Avg. money borrowing/lending ratio	Ratio	1.09	1.13	0.99	1.11	1.14	1.09	2	0.5
	% Households with poor neighbor relations	Percent	20.0	5.0	12.5	5.0	0.0	7.5	100	0.0
	% Households with no recent local government assistance	Percent	12.5	52.5	25	72.5	65	57.5	100	0
Health	Avg. time to nearest health facility (Basic Health Unit)	Minutes	96	105	68	89	77	90	240	60
	% Households with a family member with chronic illness	Percent	40	10	25	17.5	10	10	100	0
	% Households with a recent dreadful disease	Percent	30	12.5	7.5	15	7.5	5	100	0
	% Households attending no recent health awareness programs	Percent	12.5	0	2.5	7.5	15	12.5	100	0
Food	% Households dependent on the family farm for food	Percent	97.5	80	95	60	25	95	100	0
	Avg. months of household food shortage	Months	0.83	0.40	0.70	0.23	0.00	0.18	12	0
	Average Crop Diversity Index	1/# crops	0.17	0.20	0.23	0.16	0.17	0.27	1	0.13
	% Households not saving crops	Percent	0.00	0.00	0.00	0.00	0.00	0.00	100	0
	% Households not saving seeds	Percent	5	0	0	0	0	0	100	0

Table 2. *Cont.*

Major Component	Subcomponent	Units	Study Districts							
			Bumthang	Chukha	Gasa	Mongar	Tashigang	Wangdue	Max	Min
Water	% Households reporting water conflicts	Percent	65	47.5	27.5	12.5	5	22.5	100	0
	% Households reporting water shortage for farming	Percent	23	55	10	30	27.5	22.5	100	0
	% Households utilizing natural primary water source	Percent	100.0	100.0	100.0	100.0	100.0	100.0	100	0
	Avg. walking time to a water source	Minutes	261	366	279	294	288	300	1020	0
	% Households with inconsistent water supply	Percent	90	63	23	33	58	38	100	0
	% Households with recent drying up of water sources	Percent	50	73	85.0	95.0	100.0	97.5	100	0
Natural Disasters and Climate Variability	% Households not receiving natural disaster warnings	Percent	32.5	62.5	90	17.5	27.5	72.5	100	0
	% Households with recent natural-disaster-related injury	Percent	0	0	2.5	0	0	0	100	0
	% Households reporting recent production-reducing crop, pest, or disease outbreak	Percent	70	60	77.5	42.5	45	47.5	100	0
	% Households reporting more storms affecting crops recently	Percent	27.5	35	47.5	15	20	67.5	100	0
	% Households reporting recent crop yield decline	Percent	32.5	45	50	30	37.5	70	100	0
	% Households reporting increasing occurrences of natural hazards (landslides and flash floods)	Percent	40	25	25	45	22.5	27.5	100	0
	% Households reporting a recent increase in erratic rainfall	Percent	67.5	60	77.5	60	37.5	72.5	100	0
	Mean standard deviation of daily avg. maximum temperature	Celsius	0.83	1.29	1.56	1.34	1.50	1.08	2.5	0.6
	Mean standard deviation of dailyavg. maximum temperature	Celsius	1.12	2.20	1.60	1.28	1.11	1.07	3.3	0.4
	Mean standard deviation of dailyavg. maximum precipitation	Millimeters	21.13	68.62	53.20	40.38	42.78	26.79	280.0	2.5

2.2. Data Analysis

2.2.1. Livelihood Vulnerability Index (LVI) Approach

The vulnerability of potato farming households was analyzed using the vulnerability assessment model [61], which is commonly applied in LVI studies [26,36,62]. The LVI approach provides a comprehensive framework to analyze the key components that make up household's livelihood and the contextual factors that influence them in determining their livelihood status quo [36,61,63]. Accordingly, the LVI was derived for each household and district level. We used seven major components that were relevant to the Bhutanese context (Table 2): Sociodemographic Profile (SDP), Livelihood Strategies (LS), Social Networks (SN), Health (H), Food (F), Water (W), and Natural Disaster and Climate Variability (NDCV). Hence, some of the subcomponents under each of the major components were modified to suit the relevance and context of Bhutanese farmers. In addition, some of the subcomponents were measured on a different scale. It was necessary to standardize each one of them as an index developed [61,64] using

$$Index_{s_d} = \frac{s_d - s_{min}}{s_{max} - s_{min}} \quad (1)$$

where s_d is the original subcomponents for district d, and s_{min} and s_{max} are the minimum and maximum values, respectively, for each subcomponent determined using data from all the households of the six study districts. Each of the minimum and maximum values of these subcomponents was used to standardize the index. For example, the subcomponent 'average time to nearest health facility (Basic Health Unit)' under the major component 'Health' ranged from 60 to 240 min (Table 2). Similarly, for the variables measured in frequencies—such as the percentage of households reporting where the head of household has not attended school—the minimum value was set at zero and the maximum at 100 (Table 2). While some subcomponents (e.g., 'average agriculture livelihood diversity index' under major component 'Livelihood Strategies') were created because of an increase in the crude indicator, as in this instance, the larger number of livelihood activities undertaken by a household is assumed to decrease vulnerabilities or reduce exposure. In other words, households that cultivate more than one main crop are assumed to be less vulnerable than households with only one main crop. This is due to increased adaptive capacity in general, and it serves as an additional basis to support their livelihood (Table 3). By using the inverse of the crude indicator, we created a number that assigns higher values to the households with a lower number of livelihood activities. In other words, lesser values were assigned to the households with higher numbers of livelihood activities.

After each of the subcomponents was standardized, the subcomponents were further averaged, using Equation (2) to calculate the value of each major component such as SDP:

$$M_d = \frac{\sum_{i=1}^{n} index_{s_d i}}{n} \tag{2}$$

where M_d is one of the seven major components for study district d sites. $Index_{s_d i}$ represents the subcomponents, indexed by i, that make up each major component, and n is the number of subcomponents in each major component. It is notable that, irrespective of the numbers or types of livestock possessed by the household, every household was assigned equal values. In other words, every surveyed household would have +1 LS of the livestock subcomponents. Therefore, a detailed analysis of contribution by livestock to a household's livelihood outcomes was not assessed.

Table 3. Categorization of major components under respective contributing factors (category) in determining the LVI-IPCC (vulnerability definition) for the study districts.

IPCC Contributing Factors to Vulnerability	Major Components
Exposure	Natural Disasters and Climate variability
Adaptive Capacity	Sociodemographic Profile Livelihood Strategies Social Networks
Sensitivity	Health Food Water

Once the values for each of the seven major components for the six study districts were calculated, they were averaged using Equation (3) to obtain the specific district-wise LVI:

$$LVI_d = \frac{\sum_{i=1}^{7} w_{Mi} M_{di}}{\sum_{i=1}^{7} w_{Mi}}. \tag{3}$$

Equation (3) can also be expressed as follows:

$$LVI_d = \frac{W_{SDP}\, SDP_d + W_{LS} LS_d + W_{SN} SN_d + W_H H_d + W_F F_d + W_W W_d + W_{NDC} NDCV_D}{W_{SDP} + W_{LS} + W_H + W_{SN} + W_F + W_W + W_{NDC}}, \tag{4}$$

where LVI_d is the Livelihood Vulnerability Index for district d, which equals the weighted average of the seven major components for the respective study district. The weights of each major component contribute equally to the overall LVI, w_{Mi} are the number of subcomponents that make up each major component and are included to ensure that all subcomponents contribute equally to the overall *LVI* [26,61,65]. For this study, *LVI* was scaled from 0 (least vulnerable) to 0.5 (highly vulnerable). To further clarify the model's inference, a stepwise calculation is illustrated for one of the major components, 'Food,' from one of the study districts (Appendix A).

2.2.2. Intergovernmental Panel for Climate Change Framework for Calculating LVI (LVI-IPCC)

Further expanding the vulnerability findings using the LVI approach, we incorporated the seven major components of LVI with that of vulnerability defined by IPCC, which incorporates the levels of 'exposure,' 'sensitivity,' and 'adaptive capacity.' Exposure is the magnitude and duration of climate-related events, such as a drought/dry spell, change in precipitation, or temperature aberrations. Sensitivity is the degree to which the system is affected by exposure. In other words, it is the impact of climate change, variability, or extreme events. Adaptive capacity is the system's ability to withstand, cope, or recover from exposure or shocks such as droughts/dry spells or extreme events [32]. Generally, exposure and sensitivity tend to have a direct relationship with vulnerability and an inverse relationship with an adaptive capacity [61,66]. For example, a farmer with low adaptive capacity is more likely to suffer from the effects of climate change (increased temperature), resulting in decreased crop yields.

Using the LVI-IPCC approach, we grouped the major components of LVI under each category of exposure, adaptive capacity, and sensitivity (Table 3. For example, the index of category exposure contains the major component 'natural disaster,' measured by numbers or percentages of households reporting extreme occurrences. On the other hand, 'climate variability' is measured by the average standard deviation of the maximum and minimum monthly temperature and precipitation over the period of ten years [56]. We assumed that higher frequencies of natural hazards and higher rates of change in the climate variables correspond with higher exposure of households to CCI. Similarly, adaptive capacity is quantified by the 'SDP' of a study district (for example, the percentage of female-headed households), the types of 'LS' they possess to secure livelihood (for example, whether they are predominantly agriculture-based or whether they rely on alternative resources for livelihood). Similarly, we also considered the existing strength of social networks (for example, the percentage of households having linkages with the government institutions and the percentage of households assisting neighbors or seeking financial help during hours of need or destitution). Lastly, major components of food, water, and health status/security were categorized under a sensitivity category.

The categorizations in Table 3 were first combined using the following equation:

$$CF_d = \frac{\sum_{i=1}^{n} w_{Mi} M_{di}}{\sum_{i=1}^{n} w_{Mi}}, \tag{5}$$

where CF_d are contributing factors (exposure, sensitivity, and adaptive capacity) for the district d, M_{di} are the major components for the study districts d indexed by i, w_{Mi} is the weight of each major component, and n is the number of major components in each contributing factor. Further, once CF_d values were calculated, the three contributing factors were combined using Equation (6) to calculate the LVI-IPCC [26,32,36,61,62]:

$$LVI - IPCC_d = (e_d - a_d) \times s_d \tag{6}$$

where $LVI - IPCC_d$ is a formula to measure the vulnerability of the study districts d using the IPCC vulnerability framework, with e as the calculated exposure values of the major component (NDCV) for the respective study districts d. Similarly, a is the calculated value of adaptive capacity for major components (SDP, LS, and SN), and s is the calculated sensitivity value or score for the study district d that comprises a weighted average of major components (such as F, W, and H). Accordingly, the LVI- IPCC was scaled from −1 (least vulnerable) to 1 (most vulnerable). The detailed stepwise calculation is also shown to clarify inferences made from the model (Appendix B).

Further, to enhance the value of the method used by [61] on livelihood vulnerability, we delved one step further and used inferential statistics. The overall LVI values for both methods (LVI and LVI-IPCC) were analyzed using the household-level data for 40 households per district. Given that the data generated in this study were nonparametric in nature, the Kruskal–Wallis test of ranks was used, and the significantly different values were segregated using a Dunn test to make inferences across the study districts. These commonly used methodologies are found to be appropriate to analyze nonparametric or ordinal data by scholars and academia [67,68]. Raw data were processed and computed using Microsoft Excel, and more detailed analysis and plots were generated using Python.

3. Results

3.1. Demographic Profile of Surveyed Respondents

Survey participants were farmers across the six study districts. Approximately 69.17% identified as female (30.83% as male), and just over half were between 31 and 50 years old (52.09%). A majority of the respondents were illiterate (59.17%), and only 0.42% had a diploma or higher educational qualifications. The average family size among respondents was 7.5 members per household, and the average landholding was 3.17 ha per household. To ensure the reliability of the information, only respondents that were 20 years and above were considered for the individual interview (Table 4).

Table 4. Demographic profile of the study respondents (n = 240) of the surveyed households in six study districts.

Particulars	Category	Overall Study Districts (%)
Gender	Male	30.83
	Female	69.17
Age	20–30	10.83
	31–40	27.50
	40–50	24.59
	51–60	20.00
	>60	17.08
Education level	None	59.17
	Non-formal education	18.33
	Primary School	15.00
	High School	5.83
	Certificate/Vocational	1.25
	Diploma and above	0.42
Family Size	Average household member	7.5
Land size	Average landholding (Acre)	3.17

3.2. Livelihood Vulnerability Index (LVI) for the Six Study Districts

The overall LVI comprising of major components (composite) and the subcomponents for each of the study districts are presented in Table 5. In terms of the SDP major component, the Tashigang district was the most vulnerable (with an index value of 0.450), followed by Gasa (0.409), Bumthang (0.403), Wangdue (0.381), Mongar (0.343), and the least vulnerable Chukha (0.332). On the 'dependency ratio' subcomponent of SDP, the highest was for the Wangdue district (0.24), and the least was Mongar (0.13), indicating the respondents in the former district had a much higher percentage of 'inactive' household members. Tashigang exhibited the highest percentage of the respondents reporting female-headed households (90%), while the lowest was Chukha (50%). The average ages of heads of households ranged from 36 to 47 years across all the districts. Tashigang district reported the largest percentage of heads of households who had not attended school (73%), with all other districts falling between 50% and 65%. Orphans are very uncommon, with only Bumthang (0.08) and Wangdue (0.05) reporting an orphan in their households.

Regarding the LS major component, Bumthang district demonstrated the highest vulnerability score (0.546) and Mongar (0.158) the lowest—a substantially larger spread than for the SDP major component. This aggregate disparity was driven by similar disparities in each of the subcomponents. For instance, Bumthang district reported the highest percentage of households with a family member working outside the community or country (73%), while Mongar reported only 15%. Likewise, 53% of households in Bumthang, Gasa, and Wangdue reported not receiving any external remittances, compared with only 3% of households in Mongar and Tashigang districts, indicating a much stronger degree of vulnerability in the latter districts. Mongar reported 43% of households being dependent solely on agriculture for income, which, taken in conjunction with the remittances results, indicates compounded vulnerability. Chukha, on the other hand, had a high dependency on agriculture (63%), but 28% of households reported receiving remittances, hence decreasing susceptibility for localized risks. In terms of the agriculture livelihood diversification index, Bumthang showed the highest index value of 0.38, indicating the lowest levels of diversification activities among the study districts (and hence the highest levels of vulnerability).

Analyzing results for the SN major component, we see a tighter distribution of vulnerabilities on aggregate than for the LS major component. Average help received-to-given ratios were similar across study districts, as were money borrowing-to-lending ratios. While rates differ across districts regarding neighbor relations, most report low levels of poor relationships. The one subcomponent demonstrating a marked disparity among districts was the number of households reporting not having received any local government assistance in the past 12 months. Mongar district reported at the highest rate (73%) and Bumthang at the lowest (13%). That alarmingly high rate for Mongar (and the similar rate of 65% for Tashigang) warrants further examination.

The vulnerability scores for the health major component at the aggregate level were highest for Bumthang (0.256) and lowest for Gasa (0.098). These results were driven by the responses in all four subcomponents, where Bumthang remained at or near the top and Gasa at or near the bottom (with the exception being a chronic illness, where Gasa scored the second highest at 25%). Tashigang (0.104) and Wangdue (0.110) also recorded low levels of vulnerability for the heath component at the aggregate level. For the food major component, districts were clustered very closely. Between 80% (Chukha) and 98% (Bumthang) reported dependence on the family farm for food. None reported saving crops, and only Bumthang reported saving seed (5%).

Whereas overall vulnerability levels were low for health and food, the vulnerability was much higher for water. Indices ranged from 0.622 for Chukha to 0.454 for Gasa. All households across all study districts utilized natural water as their primary water source. For Bumthang, 65% of households reported water conflicts, and 90% reported an inconsistent water supply, in both cases the highest for those respective subcomponents. Chukha exhibited water shortages, which are a major vulnerability for agricultural communities. By comparison, only 10% of households in Gasa reported water shortages.

Last, the NDCV major component also demonstrated some disparity across districts, with vulnerability scores ranging from 0.479 (Gasa) down to 0.275 (Tashigang). Notable subcomponents included households not receiving early warnings for natural disasters (90% for Gasa compared with 18% in Mongar and 28% in Tashigang), pest, or disease outbreaks (78% for Gasa compared with 43% for Mongar and 45% for Tashigang) and more hail/windstorms and erratic rainfall (48% and 78%, respectively, for Gasa and 20% and 38% for Tashigang, respectively). More evidence of climate change and the absence of an early warning system indicate considerable risk for districts of Gasa, Chukha, and Wangdue.

Table 5. Indexed subcomponents, major components, and overall LVI for six study districts in Bhutan.

Components/Indicators	Bumthang	Chukha	Gasa	Mongar	Tashigang	Wangdue
Sociodemographic Profile (Major component)	0.403	0.332	0.409	0.343	0.450	0.381
Subcomponents						
Dependency ratio	0.18	0.18	0.20	0.13	0.16	0.24
% Households, female-headed	0.83	0.50	0.73	0.65	0.90	0.55
Avg. age of head of household	0.44	0.46	0.47	0.36	0.46	0.46
% Households where the head of household has not attended school	0.50	0.53	0.65	0.55	0.73	0.60
% Households with at least one orphan	0.08	0.00	0.00	0.03	0.00	0.05
Livelihood Strategies (Major component)	0.546	0.356	0.392	0.158	0.163	0.383
Subcomponents						
% Households with family working outside community/country	0.73	0.30	0.23	0.15	0.50	0.28
% Households dependent on agriculture for income	0.55	0.63	0.50	0.43	0.13	0.45
% Households without incoming remittances	0.53	0.28	0.53	0.03	0.03	0.53
Avg. agriculture livelihood diversification index	0.38	0.23	0.32	0.03	0.00	0.28
Social networks (Major component)	0.302	0.384	0.304	0.413	0.386	0.377
Subcomponents						
Avg. help received/given ratio, in kind	0.49	0.55	0.51	0.47	0.47	0.47
Avg. money borrowing/lending ratio	0.39	0.42	0.33	0.41	0.43	0.39
% Households with poor neighbor relations	0.20	0.05	0.13	0.05	0.00	0.08
% Households with no recent local government assistance	0.13	0.53	0.25	0.73	0.65	0.58
Health (Major component)	0.256	0.119	0.098	0.140	0.104	0.110
Subcomponents						
Avg. time to the nearest health facility (Basic Health Unit)	0.20	0.25	0.04	0.16	0.09	0.17
% Households with a family member with chronic illness	0.40	0.10	0.25	0.18	0.10	0.10
% Households with recent dreadful disease	0.30	0.13	0.08	0.15	0.08	0.05
% Households attending no recent health awareness programs	0.13	0.00	0.03	0.08	0.15	0.13
Food (Major component)	0.229	0.184	0.225	0.201	0.201	0.225
Subcomponents						
% Households dependent on the family farm for food	0.98	0.80	0.95	0.95	0.95	0.95
Avg. months of household food shortage	0.07	0.03	0.06	0.02	0.00	0.01
Avg. Crop Diversity Index	0.05	0.09	0.12	0.04	0.05	0.16
% Households not saving crops	0.00	0.00	0.00	0.00	0.00	0.00
% Households not saving seeds	0.05	0.00	0.00	0.00	0.00	0.00
Water (Major component)	0.588	0.622	0.454	0.498	0.530	0.516
Subcomponents						
% Households reporting water conflicts	0.65	0.48	0.28	0.13	0.05	0.23
% Households reporting watershortage for farming	0.23	0.55	0.10	0.30	0.28	0.23
% Households utilizing natural primary water source	1.00	1.00	1.00	1.00	1.00	1.00
Avg. walking time to a water source	0.26	0.36	0.27	0.29	0.28	0.29
% Households with inconsistent water supply	0.90	0.63	0.23	0.33	0.58	0.38
% Households with recent drying up of water sources	0.50	0.73	0.85	0.95	1.00	0.98
Natural Disasters and Climate Variability(Major component)	0.313	0.409	0.479	0.292	0.275	0.414
Subcomponents						
% Households not receiving natural disaster warnings	0.33	0.63	0.90	0.18	0.28	0.73
% Households with a recent natural disaster-related injury	0.00	0.00	0.03	0.00	0.00	0.00
% Households reporting recent production-reducing crop, pest, or disease outbreak	0.70	0.60	0.78	0.43	0.45	0.48
% Households reporting more storms affecting crops recently	0.28	0.35	0.48	0.15	0.20	0.68
% Households reporting recent crop yield decline	0.33	0.45	0.50	0.30	0.38	0.70
% Households reporting increasing occurrences of natural hazards (landslides and flashflood)	0.40	0.25	0.25	0.45	0.23	0.28
% Households reporting a recent increase in erratic rainfall	0.68	0.60	0.78	0.60	0.38	0.73
Mean standard deviation of daily avg. maximum temperature	0.13	0.37	0.50	0.39	0.47	0.26
Mean standard deviation of daily average maximum temperature	0.24	0.61	0.41	0.29	0.23	0.22
Mean standard deviation of dailyaverage maximum precipitation	0.07	0.24	0.18	0.14	0.15	0.09
Overall LVI	0.375	0.364	0.365	0.302	0.310	0.362

Overall index values should be interpreted as relative values to be compared within the study sample only. The LVI is on a scale from 0 (least vulnerable) to 0.5 (most vulnerable).

Considering the overall LVI for the seven major components aggregated for the six study districts, we observe the highest vulnerability levels for Bumthang (0.375) and Gasa (0.365) and the lowest for Mongar (0.302). The complete LVI is illustrated in Figure 2. The integrated results of the overall seven major components showed that the water major component is the most vulnerable, and health is the least vulnerable (Table 5).

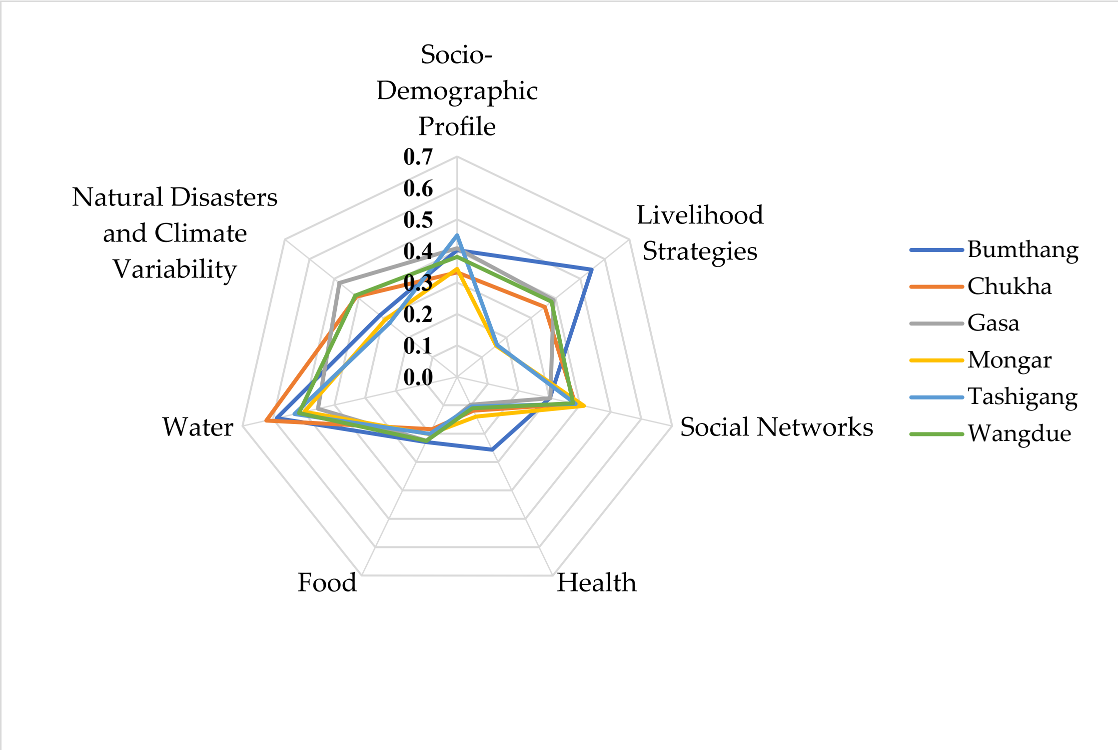

Figure 2. Illustration of collective results of the LVI major components for the six study districts. The scale of the diagram ranges from 0 (least vulnerable) to 0.7 (most vulnerable).

Further, the aggregated LVI of the seven major components based on the Kruskal–Wallis H test and multiple comparison analysis showed that the Tashigang and Mongar districts were less vulnerable than the other four (Figure 3), and those results were highly statistically significant (H = 42.80, $p < 0.001$).

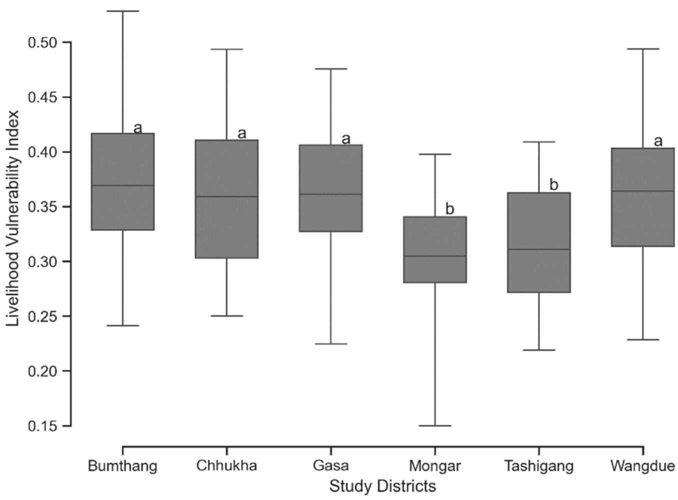

Figure 3. The LVI with the same letter are not significantly different at $p < 0.05$ among the study districts.

3.3. LVI-IPCC for the Six Study Districts

The LVI-IPCC models yielded fairly dissimilar but captivating results (Table 6). The vulnerability triangle depicts the scores of the contributing factors—exposure, adaptive capacity, and sensitivity, respectively—for each of the study districts (Figure 4). A higher value for the vulnerability index represents higher vulnerability; however, negative values of the vulnerability index do not mean that the districts are not vulnerable—it merely indicates they are comparatively less vulnerable than the others. Accordingly, Gasa (0.479) was the most exposed to CCI, with the least exposed district being Tashigang (0.275). Bumthang was the most sensitive to CCI (0.380) but with the highest adaptive capacity (0.416) among the study districts. On the other hand, Gasa (0.304) was the least exposed, and Mongar (0.333) had the lowest adaptive capacity.

Table 6. LVI-IPCC contributing factors for the six study districts.

IPCC Contributing Factors to Vulnerability	Bumthang	Chukha	Gasa	Mongar	Tashigang	Wangdue
Exposure	0.313	0.409	0.479	0.292	0.275	0.414
Adaptive Capacity	0.416	0.356	0.371	0.308	0.342	0.381
Sensitivity	0.380	0.342	0.283	0.304	0.307	0.311
LVI–IPCC	−0.039	0.018	0.030	−0.005	−0.021	0.010

Index values interpreted as relative values to be compared within the study sample only. The LVI-IPCC is on a scale from −1 (least vulnerable) to 1 (most vulnerable).

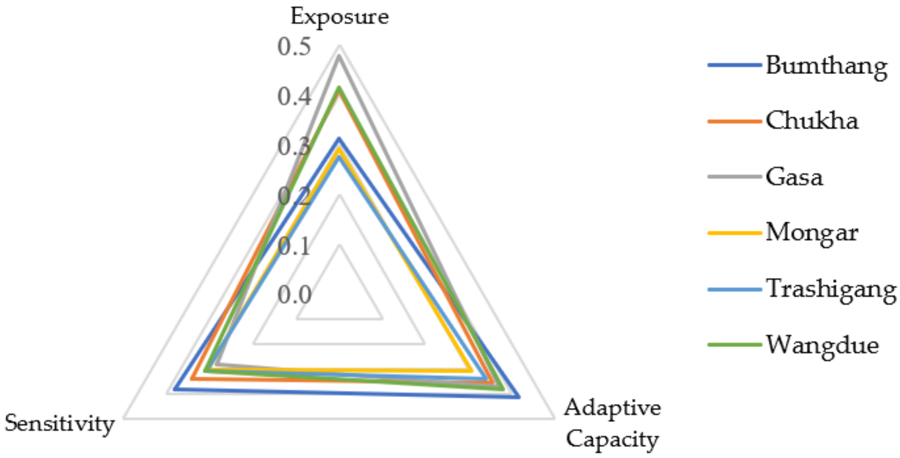

Figure 4. Vulnerability triangle diagram of the contributing factors of LVI-IPCC for the six study districts. *The LVI–IPCC is on a scale from −1 (least vulnerable) to 1 (most vulnerable).*

Unlike the findings of the LVI, the overall LVI-IPCC indicated that the Gasa district (0.030) was the most vulnerable among the six study districts to CCI, while the Bumthang district (−0.039) was the least so, which stems largely from the latter's high adaptive capacity.

Further, the LVI-IPCC results of the three contributing factors based on the Kruskal–Wallis H test and multiple comparison analysis showed significant ($p < 0.05$) differences between the districts (Figure 5).

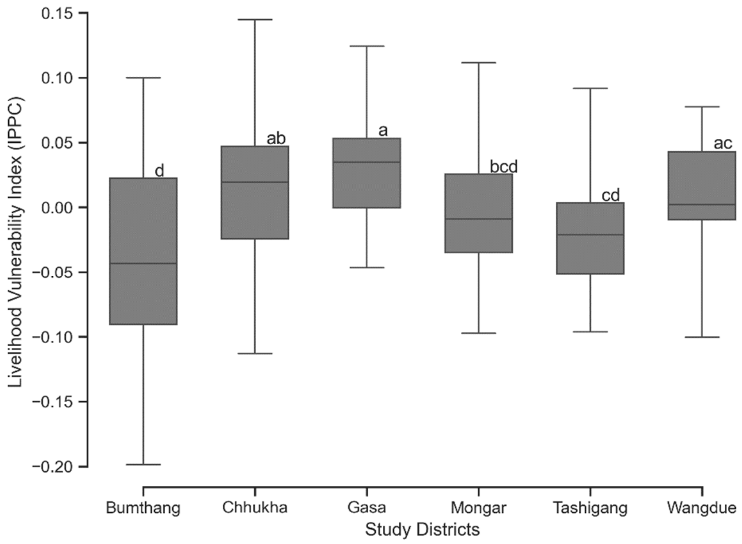

Figure 5. The LVI-IPCC values were calculated at the household level and aggregated for each district. Inference based on the Kruskal–Wallis H test and LVI-IPCC with same letter is not significantly different at $p < 0.05$ amongst the districts.

Similar to the combined LVI results, when we examine the statistical differences among the study districts for the combined LVI-IPCC, our post hoc analysis indicates the following patterns (Figure 5): Bumthang district was statistically different to Chukha, Gasa, and Wangdue; whereas, Chukha was significantly different from Bumthang and Tashigang only. Gasa exhibited significant differences with Bumthang, Mongar, and Tashigang. Mongar was significantly different from Bumthang only, and Tashigang was significantly different from Chukha and Gasa. Lastly, Wangdue district was significantly different from Bumthang only. Generally, the study districts were statistically different with overall test statistics of (H = 38.89, $p < 0.001$).

4. Discussion

4.1. Livelihood Vulnerability Index for the Six Districts

The result of the overall LVI for the seven major components aggregated for the six study districts showed Bumthang as the most vulnerable district and Mongar as the least vulnerable (Table 5). One key finding from our data analysis is that the districts of Tashigang and Mongar were statistically less vulnerable than the other four districts (Figure 3). When considered at the individual major-component level, the results are slightly different. For SDP, for example, Tashigang was the most vulnerable district, although it is one of the least in overall LVI (Table 5 and Figure 2). This is because 73% of household heads have not attended school, and 90% of the households were female-headed in Tashigang (Table 5). School enrollment was very low in Tashigang compared with the other districts due to relatively challenging topography, the scattered nature of the settlement, and inadequate infrastructure development. Lower literacy levels and lower educational attainment could leave people more vulnerable, owing in part to their lesser abilities to make correct decisions to execute livelihood strategies, implying that they lack skills in planning or negotiations to achieve better livelihood outcomes, which consequently increases their vulnerability to CCI, compared with those with higher literacy levels or education [36,69]. Further, the LVI results of the major component of the six study districts illustrate (Figure 2) the larger variation between the districts, with the water component as the most vulnerable—and health as the least—across the districts.

4.1.1. Sociodemographic Profile

Tashigang district was the most vulnerable, as it had 90% female-headed households and 73% of the heads of households had not attended schools. Chukha was the least vulnerable because it had no orphans, and its dependency ratio was as low as 0.18 (Table 5). Tashigang lacks adequate road networks and market accessibility, and it has scattered settlements with shortages in farm labor as a result of increasing rural–urban migration. Taken together, these play a significant role in making Tashigang more vulnerable than other districts [5,70,71]. Furthermore, female-headed households tend to be more vulnerable to CCI than male-headed households, largely due to women's multiple responsibilities (for example, family-related responsibilities and concerns other than farming) as indicated by existing literature on Nepalese and Bhutanese culture [26,72–74]. Additionally, Tashigang has a high poverty rate (16.7%) compared with other study districts [5]. Vulnerability remains prevalent, as livelihood is constrained within a vicious poverty cycle with limited means to counteract its effects [24,75]. On the other hand, districts of Paro and Chukha, located in the western part of Bhutan, received the first development initiatives, such as modern road networks that were built in the First Five Year Plan in the early 1960s [76]. These might have influenced them positively to achieve better livelihood outcomes through better accessibility, market connections, and better livelihood options over time.

4.1.2. Livelihood Strategies

The four districts of Bumthang, Chukha, Gasa, and Wangdue were more vulnerable than Tashigang and Mongar districts (Table 5) in terms of livelihood strategies. This pattern also agrees with the findings of the overall LVI and the result of the Kruskal–Wallis H test (Figure 3) due to the strong influence of livelihood strategies on the overall result. It is noteworthy that 73% of the households in Bumthang reported that at least one of their family members resides outside of the community/district; however, 53% of the households of Bumthang, Gasa, and Wangdue have not received any remittances for supporting their livelihood. In contrast, 97% of households in Mongar and Tashigang districts received remittances, although their percentage of family members living outside of the community was comparatively lower than the other four districts. In other words, family members residing outside a district cause a weakening of livelihood assets in terms of both financial and human capital for the household's sustenance due to reduce farm output. Paradoxically, not every household with a greater number of family members who have migrated out of the district will have better livelihood outcomes. Many of the migrants are able to fulfill only their own needs, often lacking the required skills and connections to be successful in the unfamiliar complex environment [77]. A higher percentage of households are dependent on agriculture for their primary income in Chukha, Bumthang, Gasa, and Wangdue, indicating the higher vulnerability to risks from climatic aberrations. This is because districts like Bumthang or Gasa have short favorable cropping seasons accompanied by long, cold winter months, where diversification of agriculture is difficult [56]. In other words, crop diversification opportunities (other than potato farming) seem to be less feasible agroecologically in the high-altitude districts [48,55] compared with Mongar and Tashigang, rendering them more vulnerable to CCI in general [7,16,17]. Similar studies have highlighted that the households with less diversified cropping were more vulnerable due to their limited coping mechanisms to resist CCI at the household level [18,71,78]. Due to comparatively better crop diversification opportunities (such as cultivating paddies and vegetables) in the warmer mid-altitude, the Mongar and Tashigang districts exhibited lower vulnerability than Bumthang or Gasa [13,57].

4.1.3. Social Networks

Unlike in the case of livelihood strategies, Mongar (0.413) and Tashigang (0.386) districts showed a higher vulnerability index compared with the rest of the districts ($\leq$0.384). This could be because $\geq$65% of the households have not sought agriculture support/assistance from the local government. However, 87% of the households in Bumthang and 75% in Gasa have sought such support. Not seeking support could lead to (as well as stem from) ignorance of new agriculture innovations such as high-yielding seeds or advisories and can potentially affect crop productivity [79,80]. Similarly, Sujakhu et al. [26]

highlighted that communities with less access to or unable to reap benefits from community-based institutions (such as Agriculture Centers) were found to be more vulnerable (as is the case for Mongar and Tashigang) than those with awareness of and access to innovation. This may be intricately linked to the lower literacy of heads of households, which hinders decision making and consequently access to extension and development programs. Tran et al. [81] found that in Vietnam, households with higher literacy levels were more likely to adopt and adapt to innovations than the households with high levels of illiteracy. The findings for the 'average receive: give and borrow: lend money ratio' were somewhat similar across the districts. However, ≥95% of households in Tashigang, Mongar, and Chukha showed community bonding by way of having good relationships with neighbors, which are not only beneficial for decreasing CCI [82] but also serve as a strong basis to initiate a resiliency program for the community against CCI in the future [83]. Such bonding exists in the other three districts as well.

4.1.4. Health

The purpose of assessing the 'health' component was to understand the current status of households since it is an important livelihood indicator and plays a substantial role in augmenting agricultural development [84]. The overall vulnerability in the health major component was low for all districts (≤0.119) except for Bumthang (0.256), implying less vulnerability across the study districts (Table 5, Figure 2). The highest vulnerability in terms of the average distance to reach the nearest health unit on foot was for Chukha, followed by Bumthang, and these were determined by locations of health facilities in relation to settlements. A low percentage (≥13%) of households have experienced or reported a prevalence of dreadful diseases in the six districts, except Bumthang with 30%. On the other hand, ≥85% of respondents reported having attended the rural health awareness program across all the study districts. Such presence amongst the rural populace suggests a positive relation to agricultural development because adequate access to health services increased the health status of the farming households and, as a result, decreased their vulnerability to climatic aberrations [36] in achieving better livelihood outcomes. Additionally, Bhutan is among the top global performers in gains in life expectancy in the past 40 years, going from 39.06 in the 1970s to 71.46 in 2018 [85]. Likewise, immunization coverage was as high as 95% in 2010. Such substantial health achievements are, at least, partly attributable to the 'one village health worker per each health center' initiative put in place at the grassroots level by the Royal Government of Bhutan [86]. Moreover, all the health services are state funded and provided for free, as guaranteed in the constitution of Bhutan. In addition, the average age of farmers from 36 to 47 years indicates that new agricultural innovations such as farm mechanization and modern irrigation technologies could be easily adopted to enhance better food and nutrition security.

4.1.5. Food

There was a narrow range of vulnerability index (from 0.184 to 0.229) for the 'food' major component, indicating rough similarities among the districts. The primary food source for Bhutanese farmers, in general, is the food produced from their own farms [57], as evidenced by more than 80% of households reporting to be dependent solely on the family farm for their food source across the six districts. These indicate a very high vulnerability because farming is highly sensitive and responsive to any climatic aberrations [61,84]. Simply put, any slight anomalies in climatic conditions would alter the farm productivity and thus negatively impact food security, especially for smallholder households [87]. Although the dependency on agriculture farming for food was very high across all the study districts (≥95%, except in Bumthang), the average number of months faced with food shortage was 0.07 or less. The highest numbers of months facing food shortages were reported by the respondents from Bumthang (0.07); however, they were also known to have better purchasing abilities to meet their food shortage using the revenue generated through potato sales [51,52], which is their primary source of income. The short window of food shortages was filled employing different livelihood diversification strategies, such as taking up off-farm activities, to meet the households' food needs in Bhutan [71]. In the context of Bhutan, those households employing more livelihood strategies were more food secure than households employing fewer [88]. Impressively, at least 95% of the respondents across all the study districts reported having saved seeds or crops for the next season, which is a coping mechanism used to secure food and has been used as a strategy to combat the probable repercussions of CCI. Such practices among the farmers were considered to be indications of resiliency during times of external stresses, such as crop failure due to natural hazards or other unforeseen calamities in Nepal and Ghana [74,84]. Even though every household in the study districts reported to have ensured their food demand, it is important to consider that food's nutrition content. Currently, 44% of children between 6 and 59 months old are anemic, 31% under five years are stunted, and 10% of children under two years are wasted (37.6% of those wasted children are severely wasted) [89–91]. Further, one out of twelve persons is unable to meet the food expenditure of BTN 2195 (USD 1 $\approx$ 72) per person per month and unable to meet the daily dietary intake of 2124 Kcal per day per person in Bhutan [5]. Hence, there is a need to conduct future research on nutrition security in the rural food basket.

4.1.6. Water

The vulnerability of the households on the 'water' major component was comparatively higher ($\geq$0.511, except Gasa with 0.54) relative to all other major components across the six study districts (Table 5). As illustrated (Table 5 and Figure 2), 65% and 48% of households reported water conflicts in Bumthang and Chukha, respectively, highlighting the water shortage. A large percentage of households (50% to 100%) reported an increase in the drying up of water sources in the past five years across the districts, while inconsistent water supply was substantial (58% to 90% of households) in Bumthang, Chukha, and Tashigang. The emerging issues of water sources drying up, conflicts, inconsistent supplies, and shortages are signs of CCIs that are threats to the Department of Agriculture's vision of achieving food and nutrition security [92]. In general, our findings are consistent, indicating that water shortages are one of the major farming issues faced by the Bhutanese farmers [57], resulting in severe yield decline in major crops such as rice and maize in Bhutan [17]. A Nepalese study also reported severe yield declines of vegetable crops due to shortage and deteriorated quality of water [93]. Further, slight variations in climatic conditions could result in the decline of crop productivity, such as potato yields in India [94], and Bhutanese farming is no exception. Since all households in the study districts depend entirely on natural water as the primary source for both domestic use and farming, the drying up of water sources, conflicts, inconsistent supplies, and shortages are likely to severely affect farming and farming productivity in the future. Therefore, context-specific maintenance and development of water management infrastructure would be useful in addressing these challenges.

4.1.7. Natural Disasters and Climate Variability

In terms of NDCV, the highly vulnerable study districts included Chukha, Gasa, and Wangdue (index of greater than 0.409), and the other three districts were moderately vulnerable (Table 5). Crop pest outbreaks were a significant issue, with three districts—Gasa, Bumthang, and Chukha—experiencing the most outbreaks (more than 60 households per district). Furthermore, such slight climatic anomalies or variations have also been shown to aggravate the emergence of new and unidentified pests, spur disease outbreaks and directly affect the crop yield, such as in potato crop farming [16]. Similar to our findings, potato farming was forecasted to be severely impacted in the future, especially in the higher-altitude districts such as Wangdue or Bumthang, due to increasing temperatures [12]. Such emerging climatic threats would mean that the livelihood of most of the 34,000 households currently residing in these altitudinal ranges and depending solely on potato crop farming may face a substantial risk [51]. Other studies suggest similar findings, with dwindling agricultural productivity impacting the poorest household inordinately due to natural disasters and climate variability [95,96]. However, our secondary climatic variability data (2010–2020) did not reveal significant differences. Intriguingly, at least 63% of households in Gasa, Wangdue, and Chukha have not received any early warnings during times of natural disasters (such as landslides or situations with a strong probability of property damage), even though Bhutan has experienced glacial lake outburst (GLOF), massive landslides, and swollen rivers causing damages to properties such as farm roads and other infrastructure damages [15]. Studies suggest that the absence of functional warning systems leaves households particularly exposed to natural disasters. This is especially the case for smallholder farmers due to their limited capacities to counteract [84]. Furthermore, warning systems were found to have a positive effect on rural farm populations during times of emergency and tryouts [10]. Therefore, it is evident that there is a need to put a functional early warning system in place to address hazards in the future, which will have a more pronounced effect on more vulnerable populations.

4.2. LVI-IPCC for the Six Study Districts

The LVI-IPCC results showed a statistically significant ($H = 38.89$, $p < 0.001$) difference in vulnerability across the study districts (Figure 5); however, the findings are dissimilar to that of LVI (Tables 5 and 6). For example, Bumthang (−0.039) district was least vulnerable under the LVI-IPCC, whereas it (0.375) was most vulnerable under the LVI model. The differences are due to the variation in assumptions and model parameters used in the calculation. The research and development interventions need to reduce the level of exposure and design contextual adaptive mechanisms to safeguard the livelihood of potato farmers in the future.

4.2.1. Exposure

The indices of exposure (≥0.313) showed that districts located in western Bhutan, Bumthang, Chukha, Gasa, and Wangdue, were more exposed to the NDCV compared with Mongar and Tashigang (≤0.292), the districts in the eastern part. Due to extreme climatic conditions, Gasa (0.479) was found to be the most exposed to the NDCV, consequently resulting as the most vulnerable district (Table 6 and Figure 4) under the LVI-IPCC model. The places located toward the northwestern part of the country are predominantly characterized by high altitude, steep, or rugged topography, accompanied by incessant rainfall during monsoon and very low temperature with perpetual snowfall during winter months such as in Gasa [97], making them more exposed and thus, more vulnerable. Further, high valleys, gorges, and huge topographical surface differences often result in the significant occurrences of extreme microclimatic variation [3,7]. Similarly, Devkota and Zhang [98] revealed that the eastern Himalayas, of which the Bhutanese mountain range is a part, are constantly exposed to changing climate such as increased temperature resulting in glacial melt and consequently posing a threat to more than 400 million inhabitants residing across south Asia and pacific region. One such devastating instance was the GLOF which originated in the Gasa district and swept through the Punakha-Wangdue valley, killing 21 people, ruining 12 houses, and damaging more than 728 hectares of farmland [10]. In a more recent case in Phuentsholing under Chukha district, GLOF wreaked havoc, killing 49 people, destroying 46 houses, and washing away 268 hectares of land [99]. Such extreme events were also found to be a huge threat to the livelihood of smallholder households in Nepal and Ghana [84,98]. Furthermore, due to experiencing such catastrophes and upheavals in the past, Bhutan is considered as the fourth most vulnerable in terms of exposure to CCI (recurrent and seasonal hazards) and projected to intensify in the future [10,100], and that is why there is an urgent need to mitigate exposure.

4.2.2. Sensitivity

Accounting the sensitivity that comprises the aggregated index of health, food, and water major components and the range of indices were somewhat close to each other (0.283

to 0.380) (Figure 4 and Table 6). The highest sensitivity was found in Bumthang due to its temperate location that has a longer chilling hour with snow coverage during winter and erratic precipitation during summer [56], while the Gasa district was least sensitive. The high-altitude districts have less scope of crop diversification (other than potato as the major crop), which resulted in the increased number of days with food shortages, compared with mid-altitude districts of Mongar or Tashigang, thus the higher sensitivity. Although Gasa district was highly exposed to the NDCV, it was the least sensitive to CCI because crop diversification such as paddy and vegetable cultivation is feasible in its mid-altitude areas. Farmers in mid-altitudes like Tashigang, Mongar, or Chukha employ more diversified crops in their farms and are, therefore, more resilient because different crop types respond differently to different climatic conditions and could reduce production losses during periods of extreme climatic events [101]. However, the diversification is limited by climatic constraints for high-altitude districts like Bumthang. Furthermore, weak market connections between producers and market, lack of market information, and transportation constraints tend to increase and aggravate sensitivity on food [88]. Referring to LVI (Table 5), 90% of the households in Bumthang have inconsistent water supply, and 100% of them in Tashigang reported to have increased cases of drying up of water, indicating high sensitivity to CCI (water component), which could severely impede potato farming across all the districts. Further, studies have attributed yield losses of crops such as rice and maize to water scarcity in Bhutan [16,17]. Studies such as cold-tolerant paddy trials [102] are necessary to generate technologies suited for altitude to reduce food sensitivity at the household level in high-altitude districts.

4.2.3. Adaptive Capacity

The indices of adaptive capacity within the study districts had a somewhat narrow range of 0.308 to 0.381, indicating similarities and high capacity to adapt to the three major components of sociodemographic profile, livelihood strategies, and social networks. The high number of female-headed households, household heads that have not attended school, and higher dependency ratio resulted in a low sociodemographic profile. Education is one of the essential components because households with higher education levels increase households' willingness to adopt new agricultural technologies to better cope with adverse climate variability [84] and, in turn, higher farm productivity. A combination of higher literacy levels with lower family dependency can better cope with CCI than the reverse. Since Bumthang district had fewer livelihood strategies (Table 5), the district is more vulnerable than other districts in terms of LVI [103]. In contrast, districts of Mongar and Tashigang showed the least vulnerability due to their better opportunity toward crop diversification and financial options because 97% of the respondents reported having received remittances from their relatives living outside. Communities with strong social networks were not only found to adapt and adopt agriculture innovations faster but have better access to market information and government structures because of their similar ideologies and way of life [104,105]. Thus, the districts of Tashigang and Mongar, where $\geq$95% of social networks have a better capacity to adapt to changing CCIs [106]. Although livestock farming is very much an integral part of the farming system, none of the households would engage in commercialization activities such as the sale of beef, pork, or chicken due to religious sentiments in the study districts. In a nutshell, if their sole potato crop fails, then the livelihood outcomes of an individual household will be determined by their adaptive capacity in the future.

5. Conclusions

The six districts represent the difficult mountain farming environment with unique physical, environmental, and socioeconomic constraints and the livelihood of the households largely dependent on potato cultivation. Both the LVI and LVI-IPCC indicated highly significant vulnerability of the households to the indicators of the impact of climate change, although the degree of vulnerability varied amongst the districts. The key aspects of this study are the use of seven major components to derive LVI and three contributing factors of exposure, sensitivity, and adaptive capacity to derive the LVI-IPCC vulnerability indices. It is apparent that while some districts are highly vulnerable to the CCI, the overall vulnerability can be positively offset by its adaptive capacity, which relates to the alternative coping strategies that are available at the disposal of the farming households. Further, the climate threats can be mitigated by developing both coping strategies within agriculture and alternative income sources from off-farm activities, wherever opportunities exist. The strengths such as closeness to markets, ability to grow different crops, and high levels of remittances could be balanced against weaknesses such as isolation and poor infrastructure, vulnerability to glacial flooding, and monocropping. Opportunities such as early warning systems for floods, better roads and other communications, and water storage for drought should be gainfully utilized while threats must be appropriately managed. Due to the lack of opportunity to grow alternative crops, owing to the short growing season, Bumthang was found to be most vulnerable s in terms of LVI. This claim can be further substantiated by the fact that LVI for Tashigang and Mongar was found to be the least vulnerable as these districts are in the mid-altitudes with longer growing seasons and more opportunities for other crops after potato. The holistic findings from this study on CCI, the exposure, sensitivity, and adaptive capacity of farming households have several benefits in designing and prioritizing future agriculture interventions and climate change coping strategies. Where agriculture options are limited due to agroecological and seasonal limitations, nonfarm interventions make more sense for the communities. Based on the adaptive capacity of a district, the resources can be allocated rigorously and logically, prioritizing to better achieve the intended outcome. The empirical evidence from this study gives compelling insights into more specialized researcher because the two measures of LVI and LVI-IPCC did not necessarily generate convergent conclusions in some instances. However, the paper provides valuable insights to general readerships of policymakers, planners, development workers, and farmers to design appropriate interventions to cope with CCI based on underlying vulnerability pre-conditions of a community.

Author Contributions: Conceptualization, P.R., Y.B. and T.B.K.; data curation, P.R.; formal analysis, P.R. and J.R.; funding acquisition, P.R., Y.B. and T.B.K.; investigation, P.R. and Y.B.; methodology, P.R., Y.B., J.R. and A.R.D.; supervision, Y.B.; validation, P.R.; visualization, P.R.; writing—original draft, P.R.; writing—review & editing, P.R., Y.B., T.B.K. and A.R.D. All authors have read and agreed to the published version of the manuscript.

Funding: The field survey for the research was supported through Food Security and Agriculture Productivity Project funded by Global Agriculture and Food Security Program (GAFSP), and the APC was funded by Food and Agriculture Organization, Bhutan (FAO-Bhutan).

Institutional Review Board Statement: This research study was approved by the 3rd Agriculture Research and Coordination meeting (ARCM) of the Department of Agriculture, Bhutan, held from 28 to 30th January and the 6th Project Steering Committee (PSC) meeting of the Food Security and Agriculture Productivity Project (FSAPP) held on 27th February 2020.

Informed Consent Statement: Farmers were briefed and asked for their consent prior to participation in individual interviews. Only farmers who consented were interviewed. In addition, the basic principles of The Belmont Report (1979), such as interviewing only consenting participants and voluntary participation were applied.

Data Availability Statement: Data is available on demand.

Acknowledgments: The authors are grateful to the Food Security and Agriculture Productivity Project (FSAPP), funded by Global Agriculture and Food Security Program (GAFSP) and managed by World Bank for financing the fieldwork. We are also indebted to FAO-Bhutan, Chadho Tenzin, for providing 70% of the article processing charge for the publication. The authors are also grateful and extend our appreciation for the logistical support provided by the District Agriculture Officers (DAOs) and Block agriculture staff in Bumthang, Chukha, Gasa, Mongar, Tashigang, and Wangdue. We are also thankful to all participating farmers for their participation and input. We are indebted to the National Center for Organic Agriculture, Yusipang, and above all, to the Department of Agriculture for support. In addition, we would like to thank MDPI for waiving 30% of the article processing charge. Further, we would like to extend our gratitude to Isaac Lepcha and Rachna Tiwari of The University of Tennessee at Martin, USA, for improving the initial draft. Lastly, we would also like to express our gratitude to colleagues from the National Potato Program for their support in data collection and fieldwork.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Stepwise calculating the food major component for the LVI for Bumthang District, Bhutan.

Subcomponents for FOOD Major Component	Subcomponent Values for Bumthang	Maximum Subcomponent Value for Study Population	Minimum Subcomponent Value for Study Population	Index Value for Bumthang	Food Major Component Value for Bumthang
% Households dependent on the family farm for food	97.50	100	0	0.975	0.229
Avg. months of household food shortage	0.83	12	0	0.069	
Avg. Crop Diversity Index	0.17	1	0.125	0.053	
% Households not saving crops	0.00	100	0	0	
% Households not saving seeds	5.00	100	0	0.050	

Step 1 (repeat for all subcomponent indicators): $Index_{Food\ Bumthang} = \frac{97.5-0}{100-0} = 0.98$
Step 2 (repeat for all major components):

$$Food_{Bumthang} = \frac{\sum_{i=1}^{n} Index_{s_{di}}}{n} = \frac{F_{1Bumthang} + F_{2Bumthang} + F_{3Bumthang} + F_{4Bumthang} + F_{5Bumthang}}{5} = \frac{0.975 + 0.069 + 0.053 + 0 + 0.050}{5} = 0.229$$

Step 3 (repeat for all study areas):

$$LVI_{Bumthang} = \frac{\sum_{i=1}^{n} W_{M_i} M_{di}}{\sum_{i=1}^{n} W_{Mi}} = \frac{5(0.403) + 4(0.546) + 4(0.302) + 4(0.256) + 5(0.229) + 6(0.588) + 10(0.313)}{5 + 4 + 4 + 4 + 5 + 6 + 10} = 0.375$$

Appendix B

Table A2. Stepwise calculating LVI–IPCC for Bumthang district, Bhutan.

Contributing Factors	Major Components for Bumthang District	Major Component Values for Bumthang	Number of Subcomponents Per Major Component	Contributing Factor Values	LVI–IPCC Value for Bumthang
Adaptive capacity	Sociodemographic Profile	0.403	5	0.416	−0.039
	Livelihood Strategies	0.546	4		
	Social Networks	0.302	4		
Sensitivity	Health	0.256	4	0.380	
	Food	0.229	5		
	Water	0.588	6		
Exposure	Natural Disasters and Climate Variability	0.313	10	0.313	

Step 1 (calculate indexed subcomponent indicators and major components as shown in Appendix A).

Step 2 (repeat for all contributing factors: exposure, sensitivity, and adaptive capacity):

$$Adaptive\ Capacity_{Bumthang} = \frac{\sum_{i=1}^{n} W_{M_i} M_{di}}{\sum_{i=1}^{n} W_{Mi}} = \frac{5(0.403) + 4(0.546) + 4(0.302)}{5 + 4 + 4} = 0.416$$

Step 3 (repeat for all study areas):

$$LVI - IPPC_{Bumthang} = \left(e_{Bumthang} - a_{Bumthang}\right) \times s_{Bumthang} = (0.313 - 0.416)\ \times\ 0.380 = -0.039$$

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