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Contribution of irrigation practices for reducing farmers' vulnerability to climate change and variability

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Abstract

Climate change and variability pose major challenges to agricultural productivity and rural livelihoods in Ethiopia, where most smallholder farmers depend on rain-fed systems. This study investigates how small-scale irrigation (SSI) contributes to reducing farmers' vulnerability and enhancing their adaptive capacity to climate variability in Southern Ethiopia. Using a multi-stage sampling approach, data were collected from 144 households (72 irrigation users and 72 non-users) through surveys, focus group discussions, and key informant interviews. Climate trends were analyzed using the Mann–Kendall test, Sen's slope estimator, coefficient of variation, and Standardized Anomaly Index (SAI) from 1987 to 2022. Results revealed a significant increase in annual maximum and minimum temperatures at rates of 0.0238°C and 0.0844°C per year, respectively, and a positive annual rainfall trend (Kendall's Tau = 0.344, p = 0.003). Vulnerability analysis using Principal Component Analysis indicated that irrigation users were less vulnerable, with indices ranging from 0 to –0.90, compared to non-users (0 to 0.75). Irrigation users demonstrated higher adaptive capacity due to improved access to water, agricultural inputs, income diversification, and enhanced awareness of climate risks. Conversely, non-irrigators remained highly sensitive to rainfall fluctuations and resource constraints. The study concludes that SSI significantly enhances farmers' resilience by stabilizing production and income, thereby mitigating the adverse effects of climate variability. Hence, strengthening institutional support, promoting farmer-led irrigation management, and scaling up SSI technologies are recommended to improve climate adaptation and ensure sustainable rural livelihoods.

Keywords: Adaptation strategy, Climate variability, Climate change, Ethiopia, Small-scale irrigation

Article Type: Research Article

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1. Introduction

Undoubtedly climate change is the most important and complex challenge confronting modern society, involving multiple industries and intertwined with other global challenges. Climate change is widely recognized as one of the most critical environmental challenges of the modern era, influencing numerous human activities especially in nations where agriculture forms the backbone of the economy (Simane et al., 2016). Developing countries remain highly susceptible to its impacts due to their strong dependence on climate-sensitive sectors such as agriculture. The livelihoods of most smallholder farmers, who rely primarily on rain-fed agricultural systems, are particularly exposed to the adverse effects of climate change (Mume et al., 2023). The implications for agricultural productivity are severe, as shifts in climate patterns directly disrupt the livelihoods of these farmers (Yazew & Hordofa, 2023).

Agricultural systems that depend mainly on rain-fed cultivation, use traditional technologies, and are managed by smallholders face heightened vulnerability to climatic shocks (Harvey et al., 2018). In Ethiopia, climate change remains a major threat to the livelihoods of rural communities (Matewos, 2019). Variations in rainfall distribution, increasing temperatures, and declining precipitation levels contribute to unstable production and low productivity, limiting smallholders' adaptive capacity. The country's low economic development and reliance on rain-fed farming exacerbate its exposure to the negative consequences of climate variability (Demem, 2023).

To address these challenges, the Ethiopian government introduced the Climate-Resilient Green Economy (CRGE) strategy, aimed at safeguarding the nation from climate-related threats while promoting sustainable economic growth toward middle-income status by 2025 (Bhopal et al., 2021). A central pillar of the CRGE framework involves transforming agricultural practices to ensure food security, raise farmers' incomes, and enhance climate-resilient production systems. Achieving these goals requires the adoption of climate-smart agriculture (CSA) approaches (Kaur et al., 2014). Implementing CSA strategies strengthens farmers' adaptive capacity to climatic fluctuations (Baffour et al., 2023). Households that effectively utilize CSA techniques are more resilient, overcoming vulnerability and escaping poverty over time (Zakaria et al., 2020). Strengthening farming systems through CSA adoption is therefore essential for building climate resilience and improving rural livelihoods.

Among CSA practices, small-scale irrigation plays a pivotal role in enhancing productivity and mitigating climate-related risks in developing countries (Nyasimi et al., 2017). The relevance of CSA and the decision to adopt its practices depend largely on local resources, agro-ecological conditions, and contextual factors (Kifle et al., 2023). As one of the most promising CSA interventions, small-scale irrigation supports rural livelihoods by stabilizing production, diversifying crops, and increasing income and employment opportunities (Assefa et al., 2022; Maru et al., 2023; McDonald et al., 2022).

Ethiopia has an estimated irrigation potential of about 5.54 million hectares, of which 4.26 million hectares have already been developed (Mekonen et al., 2022). The southern region alone possesses substantial water and land resources, with approximately 1.7 million hectares of irrigable land—1.35 million hectares of which are currently under irrigation. In districts such as Kersa, numerous rivers and streams offer favorable conditions for small-scale irrigation development. Support from organizations like the International Fund for Agricultural Development (IFAD) has been instrumental in expanding irrigation schemes in these areas, thereby improving farmers' livelihoods. Similarly, smallholder households in Humbo district have benefited significantly from small-scale irrigation practices (Wana & Senapathy, 2023).

Despite this potential, empirical evidence on how small-scale irrigation contributes to smallholders' livelihood improvement and climate change resilience in the study area remains limited. Therefore, this study aims to examine the extent to which small-scale irrigation reduces farmers' vulnerability to climate change and variability, while providing evidence-based insights to inform future research and policy interventions. Rain-fed agriculture productivity varies widely in

Ethiopia, depending on the amount and distribution of rainfall. Small-scale irrigation practices have been identified as a viable adaptation option for reducing the effects of climate change and increasing agricultural resilience. However, it is unresolved how effectively these practices reduce farmers' vulnerability and improve food production in Humbo District. Existing literature emphasizes the benefits of irrigation in increasing crop yields, but there is little empirical evidence focusing on the application, effectiveness, and sustainability of small-scale irrigation systems in the context of climate variability in this region. Furthermore, farmers' access to and adoption of these irrigation practices is influenced by a variety of socioeconomic, environmental, and institutional factors, complicating our understanding of their role in climate resilience. Without a detailed examination of these processes, policymakers and development practitioners may struggle to devise successful interventions that improve the adaptive capacity of farmers in the region. The purpose of this study was to look into how small-scale irrigation practices in Humbo District help farmer's livelihoods through reducing their sensitivity to climate change and variability. It will investigate current irrigation practices and evaluate their effectiveness in increasing agricultural yield. The study therefore was aimed to give useful insights that might improve sustainable agricultural policies and practices, therefore ensuring food security for smallholder farmers in the face of continued climate change difficulties.

2. Materials and Methods

2.1. Description of the study area

Humbo District Figure 1 is one of the District of Wolaita zones, South Ethiopia located in the Great Rift Valley. It is bounded on the southeast by Lake Abaya, which separates it from the Oromia Region; on the south by the Gamo Zone; on the west by Offa; on the northwest by Sodo Zuria; on the northeast by Damot Woyde; and on the east by the Bilate River, which separates it from the Sidama Zone. It is located in 6° 39' 59.99" N latitude 37° 49' 59.99" E longitude. Based on the 2007 Census conducted by the CSA, Humbo District has a total population of 125,441, of whom 63,017 are men and 62,424 women; 6,247 or 4.98% of its population are urban dwellers. Besides, the District is located at an altitude of 1100-2335 meters above sea level.

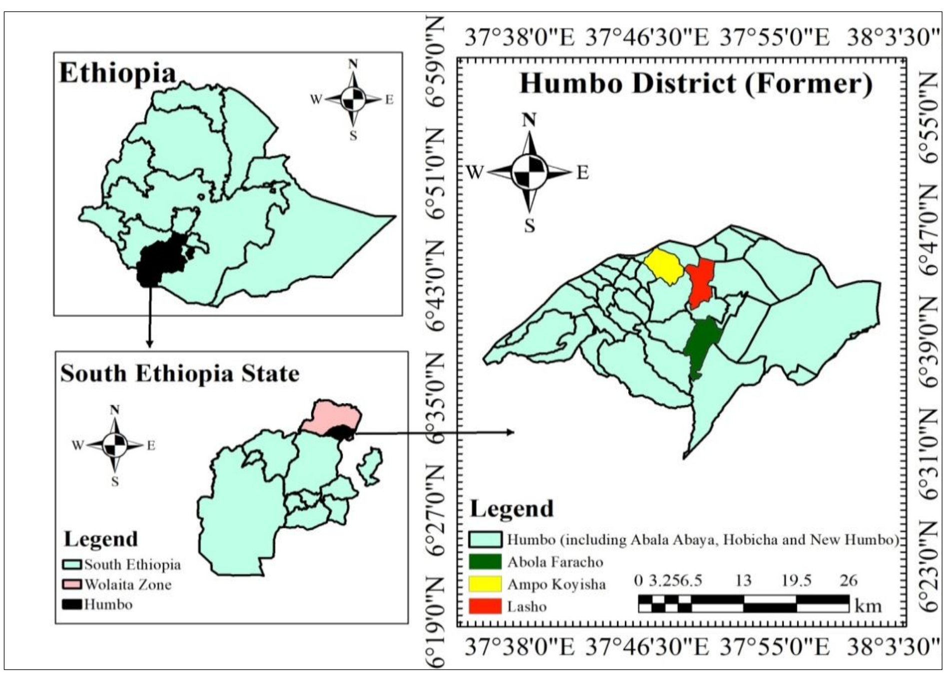

Figure 1. Study area map Source: ARC GIS (2024)

The district has an average annual rainfall of 840-1400mm, with temperatures ranging from 15°C to 29°C. Humbo District principal crops include maize, sweet potato, teff and haricot beans, coffee, cotton, and peas. Mixed agriculture is the primary economic activity in the area. Cereals such as teff, maize, sorghum, and cotton are grown in the research region, as are root crops such as sweet potatoes, Enset, and carrot, as well as fruits such as mango, avocado, and banana. The district's population is primarily involved in farming, with an average land holding of 0.25 ha. Subsistence agriculture thus serves as the primary source of income for the community.

2.2. Sampling techniques and sample size determination

Humbo District, located in the Wolaita Zone of Southern Ethiopia, was purposefully selected for this study. The district was chosen due to the critical role that small-scale irrigation (SSI) plays in enhancing smallholder farmers' livelihoods and adaptive capacity to climate variability, as well as the existing challenges constraining SSI practices in the area.

A two-stage sampling technique was employed. In the first stage, three kebeles (the smallest administrative units in Ethiopia) with active small-scale irrigation practices were deliberately selected. Prior to household selection, the sampling frame was stratified into two categories: irrigation users and non-users. From each group, sample households were then randomly selected. Thus, the total sample population was divided into irrigators and non-irrigators, listed by name, and chosen using a simple random sampling procedure. Appropriate sample sizes were subsequently determined for each group.

The three selected kebeles (Ampo Koysha, Abela Faracho, and Abela Maraka) were identified based on their population density, the type of SSI systems practiced, and recommendations from the District Agriculture Office. For every irrigator selected, a proportional number of non-irrigators was included to ensure representativeness, taking into account their proximity to irrigation water sources and their farmland's location relative to rivers used for irrigation. Moreover, farmers' prior experience with irrigation activities in the area was considered. Accordingly, irrigation-user households were drawn from areas with similar access to water sources and cultivable land.

The total sample size was distributed proportionally among both irrigation-user and non-user households across the selected kebeles (see Table 1). To determine the required sample size, the simplified formula proposed by Yamane (1967) was applied at a 95% confidence level and 8% (0.08) level of precision. The formula used to calculate the sample size is expressed as follows (Equation 1):

$$n=\frac{N}{1+N(e)^2} \quad (1)$$

Where: n = the number of required samples of each irrigation kebeles; N = total households of each irrigation kebeles; confidence level (95%) and (e = is the level of precision 8% (0.08); and $\sum n$ =total households of the three irrigation kebeles. The required sample households of each kebeles were calculated used the following formula (Equation 2).

$$n_1=\frac{N_1 * n}{\sum N} \quad (2)$$

The proportional sampling technique was used to develop the overall sample size; accordingly, 41 irrigators and 103 non-irrigators with a total of 144 sample households were taken respectively as shown in the Table 1.

Table 1. Number of Sample Households in each kebeles

Sample Kebeles	Total HH	HH Irrigation user		HH Non irrigation user		Total Samples HHs
		HHs in Kebeles	Samples HHs	HHs in Kebeles	Samples HHs	
Ampo Koysha	720	200	16	520	41	57
Abela Faracho	400	150	12	250	20	32
Abela Lasho	700	170	13	530	42	55
Total	1820	520	41	1300	103	144

Source: Zone Agricultural Office (2024)

2.3. Data Collection Method

2.3.1. Primary data sources

Key informant interviews: Individual interviews with key informants were conducted to gather general information about the current trend of small-scale irrigated farming, with an emphasis on the difference between adaptive ability and respondents' socioeconomic status, as well as livelihood activities in the area. As with most qualitative data gathering, key informants were asked repeatedly to delve further into topics using open-ended questions. It featured two agriculture office experts, two irrigation experts, one cooperatives expert, and two district administrators.

Focus group discussions: A focus group discussion invites people who share similar issues and experiences about a topic to participate. The FGD involve 8-10 people each group (McLafferty, 2004). As a result, two focus group discussions (FGDs) were conducted: one with user 8 members and another with non-user 9 members among respondents. The researcher and enumerators were assisting the discussion, encouraging group members to speak freely. The key themes to be addressed during the group discussion were adaptation measures and their restrictions, as well as existing small-scale irrigation practices and their contribution. The checklist of questions was used to facilitate all FGDs.

Household's survey: The household survey was done using houses simple randomly picked from the list of stratified in the two groups' user and non-user. The structured questionnaire was included the following topics: adaptation strategy and limits, income-generating activities, existing small-scale irrigation methods, and the key factor influencing irrigation practices. The HHs survey were involve several stages, including the translation of the questionnaire into the local language (Wolaitegna) by researcher, the recruitment and in-depth training for respondent, the selection of field assistants and key informants, the protest of the prepared questionnaire (12 HHs from each sample kebeles), and the administration of the actual fieldwork. The questionnaires were included open and closed-ended questions. The data for this study was collected using a standardized questionnaire and administered via a face-to-face interview with homes.

Secondary data sources

The secondary data sources for the study were gathered by collecting relevant literature from hard copies and online materials, as well as data from electronic media. These sites were providing important information for researching relevant literature and validating findings. Data were also being gathered from institutions such as the District Rural Development and Agricultural Office, the Humbo District Bureau, and the National Metrological Agency. These institutions were providing information about districts such as irrigable farmland size and crop varieties, yield per hectare, adaptation strategies and limits, and a district profile.

2.4. Method of data analysis

2.4.1. Descriptive statistics

Data was examined using descriptive statistics by using Microsoft Excel. Following organization and categorization, quantifiable data was examined and described using subjective interpretations. Means with significant differences was compared at 95% confidence interval levels. The quantitative data was analyzed using descriptive statistics such as frequency and percentage distribution, mean, maximum and minimum, and standard deviation. Chi-square was employed as an inferential statistic to find connections between categorical factors, and the t-test was utilized for continuous variables to evaluate mean differences between two groups across the study variables, all while keeping the research purpose in mind. Finally, the summarization of quantitative data with Microsoft excels 2013 were the packages used in the analysis.

3. Results and Discussion

- Socioeconomic characteristic of respondents

A comparison of the socioeconomic characteristics and key farm resource holdings between irrigation beneficiaries and non-beneficiaries is presented in Table 2. The majority of respondents (52.8%) were within the age range of 40–49 years. This age group represents mature farmers who have accumulated considerable farming experience and possess a better understanding of both past and present climatic conditions. As noted by Jha and Gupta (2021), the age of a household head serves as a proxy for farming experience, which is critical for interpreting long-term climatic trends. Farmers within this age bracket are also considered to have directly experienced the impacts of climate change, typically observable over a 30–35-year period; hence, the reliability and accuracy of their responses are assumed to be high.

Diarra et al. (2021) observed that younger farmers tend to be more receptive to innovation and modern agricultural practices compared to older farmers, who are often more resistant to adopting new technologies. Regarding marital status, 95.8% of household heads were married, while only 4.2% were widowed (Table 2). A predominance of married household heads may contribute positively to agricultural productivity and adaptive capacity, as married individuals are more likely to share ideas, cooperate, and make joint decisions on livelihood and adaptation strategies compared to single, divorced, or widowed counterparts (Adego et al., 2019).

In terms of education, 27.1% of respondents were illiterate, 54.9% had completed primary education, and 18.1% had attended general secondary school (Table 2). Educational attainment is closely linked with farmers' awareness and understanding of climate change and variability. According to Asrat and Simane (2018), farmers with higher educational levels are more likely to adopt effective adaptation measures in response to climate-related challenges than those with limited formal education.

With respect to income distribution, 39.6% of respondents reported an annual income ranging between 1,000 and 10,000 Birr, while 30.6% and 27.8% earned between 10,001–30,000 Birr and 30,001–50,000 Birr, respectively. From an adaptation perspective, farmers with higher income levels are generally better positioned to implement coping and adaptive strategies to mitigate the impacts of climate variability. Ruzzante et al. (2021) also reported a positive association between household income and the adoption of agricultural technologies, as financial resources enable farmers to invest in improved farming methods. Field survey data further revealed that 9.7% of respondents derived their income primarily from crop production, 72.2% from mixed farming, and 18.1% from both farming activities. This indicates that the majority of farmers in the study area depend on agriculture as their main livelihood source, directly linking their income generation and wellbeing to climate variability and change. Understanding the interconnection between national and local climatic dynamics and farmers' perceptions is fundamental for designing effective development strategies, establishing early warning systems, and implementing context-specific adaptation measures. The present study revealed that a total of 144 households, including both irrigation users and non-users, had heard about, discussed, and personally experienced the adverse impacts of climate change and variability on their crop production. Farmers in the study area reported noticeable effects of changing temperature and rainfall patterns on agricultural productivity, underscoring the growing vulnerability of smallholder farming systems to climatic fluctuations. However, perceptions of the specific contribution of annual rainfall to agricultural outcomes varied among respondents, reflecting differences in experience and local conditions. When asked to identify the most significant indicators of climate change in their locality, the majority of farmers indicated that they had observed climatic changes over the past three decades. A large proportion of both irrigation beneficiaries and non-beneficiaries perceived shifts in temperature and rainfall patterns (Table 3). These findings align with the results of Tesfaye and Seifu (2016), who reported that 95% of farmers perceived changes in temperature and 86% perceived changes in rainfall. Evidence gathered from Focus Group Discussions (FGDs) and Key Informant Interviews (KIIs) also supported the survey findings. Consistent with Asrat and Simane (2018), this study found that farmers who had experienced frequent droughts in the past were more likely to recognize and report changes in climatic conditions. Moreover, approximately 46.34% of irrigation beneficiaries and 59.22% of non-beneficiaries perceived that rainfall in their area had become increasingly erratic, characterized by late onset and early cessation during the past 20 to 30 years. Notably, none of the respondents reported an increase in rainfall or a decrease in temperature during this period (Table 3).

Table 2. Socio economic characteristics of respondents (N=144)

Variable with categories		Farm group						X^2	P
		Irrigation user (41)	(%)	Non user (103)	(%)	Total (144)	(%)		
Age	20-29	0.0	0.0	5.0	4.9	5.0	3.5	6.78	0.14*
	30-39	5.0	12.2	15.0	14.6	20.0	13.9		
	40-49	28.0	68.3	48.0	46.6	76.0	52.8		
	≥50	8.0	19.5	35.0	34.0	43.0	29.9		
Mar. St	Single	0.0	0.0	0.0	0.0	0.0	0.0	0.43	0.807
	Married	40.0	97.6	98.0	95.1	138.0	95.8		
	Divorced	0.0	0.0	0.0	0.0	0.0	0.0		
	Widowed	1.0	2.4	5.0	4.9	6.0	4.2		
C. Educational level	Illiterate	5.0	12.2	34.0	33.0	39.0	27.1	8.57	0.03*
	Primary	30.0	73.2	49.0	47.6	79.0	54.9		
	2nd School	6.0	14.6	20.0	19.4	26.0	18.1		
	Graduate	0.0	0.0	0.0	0.0	0.0	0.0		
Annual income	<1000 ETB	0.0	0.0	3.0	2.9	3.0	2.1	80.7	0.00*
	1000-10000	2.0	4.9	55.0	53.4	57.0	39.6		
	10001-30000	6.0	14.6	38.0	36.9	44.0	30.6		
	30001-500000	33.0	80.5	7.0	6.8	40.0	27.8		
	> 500001	-	0.0	0.0	0.0	0.0	0.0		
Source of incomes	Cattle rearing	0.0	0.0	0.0	0.0	0.0	0.0	2.52	0.283
	Crop production	6.0	14.6	8.0	7.8	14.0	9.7		
	Mixed farming	30.0	73.2	74.0	71.8	104.0	72.2		
	Petty trading		0.0		0.0	0.0	0.0		
	Farmer and trader	5.0	12.2	21.0	20.4	26.0	18.1		
	Daily laborer		0.0		0.0	0.0	0.0		
	Total	41.0	100.	103.	100.	144.0	100.		
Farm land size	> 1	0.0	0.0	0.0	0.0	0.0	0.0	2.26	0.520
	1-1.5 ha	15.0	36.6	39.0	37.9	54.0	37.5		
	1.5-2ha	19.0	46.3	48.0	46.6	67.0	46.5		
	2-2.5 ha	7.0	17.1	12.0	11.7	19.0	13.2		
	<2ha	0	0.0	4.0	3.9	4.0	2.8		
	Total	41.0	100.	103.	100.	144.0	100.		

3.1. Temporal Trends and Variability of Rainfall and Temperature (1987–2022) in the Study Area

3.1.1. Temporal Variability and Trends of Temperature

Table 4 presents the temporal variability and long-term trends in temperature for Humbo District from 1987 to 2022. The analysis revealed that the mean minimum temperature during this period was 13.52°C, while the maximum temperature reached 30.95°C. The observed warming patterns during the Belg and Kiremt seasons are consistent with global climate change trends, with potential implications for crop growth cycles, water demand, and ecosystem balance.

The Mann–Kendall trend test results indicated a statistically significant upward trend in long-term mean monthly temperatures across all seasons. The overall rise in average maximum temperature was primarily attributed to increases observed during the Belg and Kiremt seasons. In contrast, minimum temperatures exhibited relatively greater variability compared to maximum temperatures, ranging from 13.13% in the Bega season to 3.96% during Kiremt.

Table 3. Farmers perception to rainfall and temperature changes indicators

Farmers Perception on selected representative variables of climate change		Users (41)	(%)	None (103)	(%)	Total	(%)	χ^2	P
Climate change	Perceived	39	95.12	98	95.15	137	95.14	0.00	1.0000
	Not perceived	2	4.88	5	4.85	7	4.86		
	Total	41	100.00	103	100.00	144	100.00		
Annual and seasonal temperature	Increased	35	85.37	95	92.23	130	90.28	5.49	0.4824
	Decreased	0	0.00	0	0.00	0	0.00		
	Not changed	4	9.76	3	2.91	7	4.86		
	I do not know	2	4.88	5	4.85	7	4.86		
	Total	41	100.00	103	100.00	144	100.00		
Rainfall pattern	Decreasing Change in Amount of Rainfall	28	68.29	85	82.52	113	78.47	5.89	0.2075
	Change in time of rainfall	13	31.71	18	17.48	31	21.53		
	Total	41	100.00	103	100.00	144	100.00		
The onset of rainfall	Early on the set of rainfall	6	14.63	25	24.27	31	21.53	3.34	0.5023
	Late rainfall of rain set	35	85.37	78	75.73	113	78.47		
	Total	41	100.00	103	100.00	144	100.00		
Early cessation and poor distribution of rainfall	Early cessation of rainfall	19	46.34	61	59.22	80	55.56	3.60	0.4622
	Poor distribution of rainfall	22	53.66	42	40.78	64	44.44		
	Total	41	100.00	103	100.00	144	100.00		
The volume of the flood and strong wind	Frequent high-volume flood	35	85.37	91	88.35	126	87.50	0.43	0.9798
	Strong wind	6	14.63	12	11.65	18	12.50		
	Total	41	100.0	103	100.0	144	100.0		

Meanwhile, variability in maximum temperature ranged between 5.86% and 2.95%, indicating a relatively stable pattern (Table 4).

Spatially, the Humbo Tebela area exhibited the highest annual and seasonal temperatures, which is consistent with expectations given the area's lower altitude. Notably, the study recorded significant increases in minimum temperatures during May and in maximum temperatures during March, suggesting a gradual warming of these months over time. The persistent warming observed during Belg and Kiremt seasons points to shifting temperature dynamics, which could substantially influence agricultural productivity and ecological processes that depend on moderate climatic conditions.

Regression analysis further confirmed increasing temperature trends, with coefficients of 0.0238°C per year for maximum temperature and 0.0844°C per year for minimum temperature (Figure 2). The trend equation ($y = 0.0198x - 7.189$) reflects a slight upward pattern in annual maximum temperature, although the low R^2 value (0.0238) indicates that only 2.38% of the temperature variation is explained by the linear trend. Despite this weak statistical association, a gradual increase in maximum temperature was observed from the late 1980s through the early 2000s, followed by fluctuations thereafter.

Seasonal analysis revealed statistically significant increases (at $p < 0.05$) in maximum temperatures during both Kiremt and Belg, with magnitudes of 0.36°C and 0.34°C per decade, respectively (Table 4). Such rising temperatures are likely to accelerate evaporation rates and soil moisture depletion, negatively affecting agricultural and forest ecosystems. This has direct implications for participatory forest management, as higher temperatures make soil moisture conservation more challenging, thereby requiring adaptive measures such as improved water retention techniques and climate-resilient tree planting practices.

These findings corroborate the results of Abdelmagid and Adil (2014), who reported increased soil erosion, erratic rainfall, and uncertainty in the onset of farming seasons under warming conditions. The present study also revealed that farmers' awareness of climate change has encouraged adjustments in farming practices a finding consistent with previous studies emphasizing the role of climate change awareness in promoting the adoption of adaptive agricultural technologies. Similar trends have been reported in other parts of Ethiopia by Teyso and Anjulo (2016); Asfaw et al. (2018); Befikadu et al. (2019); and Abebe and Arega (2019), all of whom documented long-term increases in mean annual maximum, minimum, and average temperatures.

Table 4. M-K Test and Sen's slope of Monthly Minimum, Maximum Temperature of study area (1987–2022)

Month	Tmin	CV (%)	Kendall's tau	P-Value	Sen's slope	Tmax	CV (%)	Kendall's tau	P-Value	Sen's slope
JAN	9.72	14.90	-0.075	0.531	-0.017	30.802	4.66	-0.032	0.796	-0.007
FEB	11.6	11.78	0.078	0.513	0.020	32.454	4.13	0.175	0.138	0.034
MAR	13.3	9.14	0.081	0.496	0.015	32.884	3.70	0.276	0.018	0.045
APR	15.0	5.52	0.180	0.127	0.022	30.793	6.69	0.107	0.368	0.031
MAY	15.5	3.15	0.307	0.009	0.018	27.128	4.56	-0.010	0.946	-0.003
JUN	15.4	2.66	0.046	0.703	0.003	25.523	4.76	-0.049	0.683	-0.008
JUL	14.6	3.81	0.226	0.055	0.018	25.334	5.55	0.088	0.462	0.016
AUG	13.7	4.65	0.184	0.117	0.016	25.952	5.63	0.127	0.282	0.021
SEP	13.7	5.14	0.207	0.079	0.021	26.906	6.29	0.079	0.504	0.014
OCT	14.5	7.59	0.145	0.220	0.020	26.818	6.14	0.021	0.870	0.004
NOV	13.8	12.59	0.097	0.414	0.026	27.518	5.70	-0.092	0.438	-0.017
DEC	11.9	15.88	-0.063	0.595	-0.014	28.847	5.12	-0.143	0.225	-0.020
Belg	11.2	11.14	-0.048	0.693	-0.009	33.327	2.95	0.261	0.026	0.036
Kermi	10.1	3.96	0.164	0.165	0.028	33.357	5.86	0.261	0.036	0.034
Bega	13.0	13.13	0.195	0.099	0.016	27.041	3.85	0.072	0.549	0.012
Annual	13.5	12.25	-0.107	0.369	-0.017	30.955	2.95	-0.024	0.849	-0.005

*Significant at $p \leq 0.05$.

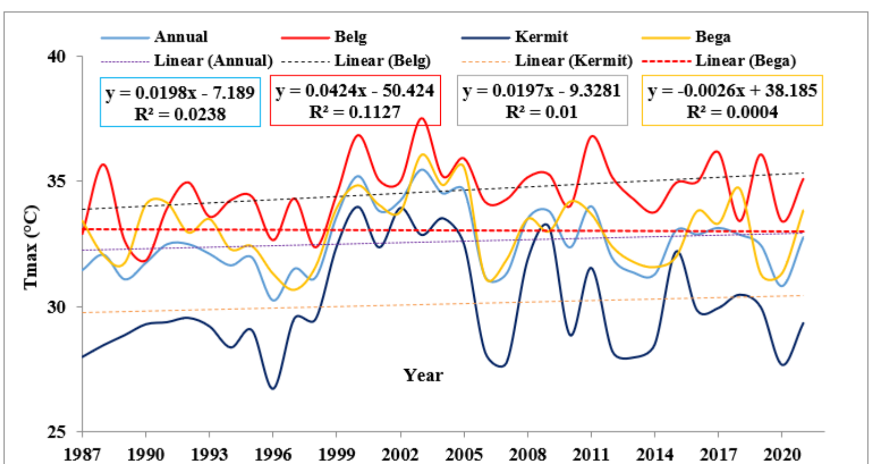

Figure 2. Temporal trends of annual and sessional maximum temperature of study area (1987-2022)

3.1.2. Temporal Variations of Annual Maximum Temperature Anomalies of the Study Area

Figure 3 presents the temporal variations in standardized anomaly indices (SAI) of annual maximum temperatures in Humbo District from 1987 to 2022. Each vertical bar depicts the deviation of a given year's maximum temperature from the long-term mean, where positive values represent warmer-than-average years and negative values indicate cooler-than-average conditions. A linear trend line is included to visualize the general trajectory of temperature changes across the period.

The figure reveals that the earlier years (late 1980s to mid-1990s) were predominantly characterized by negative anomalies, reflecting relatively cooler climatic conditions. In contrast, the period from the late 1990s to early 2000s exhibits more frequent and pronounced positive anomalies, signifying a shift toward warmer years. Particularly, the years between 1998 and 2003 recorded notably high positive anomalies, with some exceeding an SAI value of 2.0.

Despite inter-annual fluctuations, the dotted linear trend line demonstrates a modest but clear upward trend, indicating a gradual rise in annual maximum temperature anomalies over the 36-year study period. This warming trend underscores the presence of long-term climate variability and change in the Humbo District, with potential implications for local agriculture, water availability, and household livelihoods.

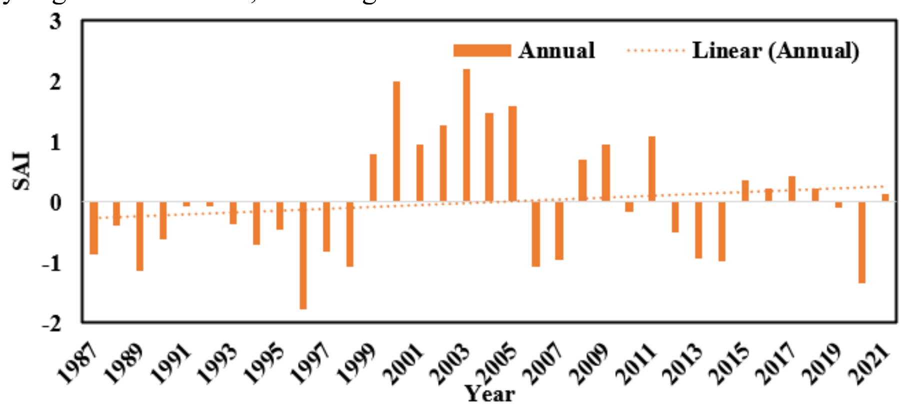

Figure 3. Temporal variations in the annual maximum temperature anomalies of Humbo District (1987–2022)

3.1.3. Temporal Variations in the Seasonal Maximum Temperature Anomalies

Figure 4 illustrates the temporal variations in the seasonal maximum temperature anomalies (SAI) for the Humbo District from 1987 to 2022, focusing on Ethiopia's three primary seasons: Belg (March–May), Kiremt (June–September), and Bega (October–February). Each season is represented by distinct bar plots, with corresponding linear trend lines depicted as dashed lines to highlight the general temperature trends over time.

The Belg season shows a mix of negative and positive anomalies throughout the study period. However, from the mid-1990s onward, there is a discernible shift toward more frequent and pronounced positive anomalies, particularly between the late 1990s and early 2000s. The linear trend line for Belg indicates a gradual warming trend over the 36-year period, reflecting increasing seasonal maximum temperatures.

Similarly, the Kiremt season, which coincides with the main rainy period, displays substantial interannual variability. The years between 1998 and 2003 stand out with pronounced positive anomalies, suggesting exceptionally high maximum temperatures during these summers. The Kiremt trend line also demonstrates a clear upward trajectory, implying a long-term warming tendency during this crucial agricultural season.

The Bega season exhibits a more moderate but still notable warming pattern. Although the anomalies are less extreme than those of Belg and Kiremt, an increasing frequency of above-average temperature years has been evident, particularly from the early 2000s onward. The Bega trend line remains slightly positive, reinforcing the overall warming signal across all seasons. Overall, the results reveal a consistent increase in maximum temperature anomalies across Belg, Kiremt, and Bega seasons during the past three and a half decades. This pervasive warming trend underscores the intensifying influence of climate change on local temperature regimes in the Humbo District, with significant implications for seasonal agricultural productivity, water resource management, and the livelihoods of farming communities in the region.

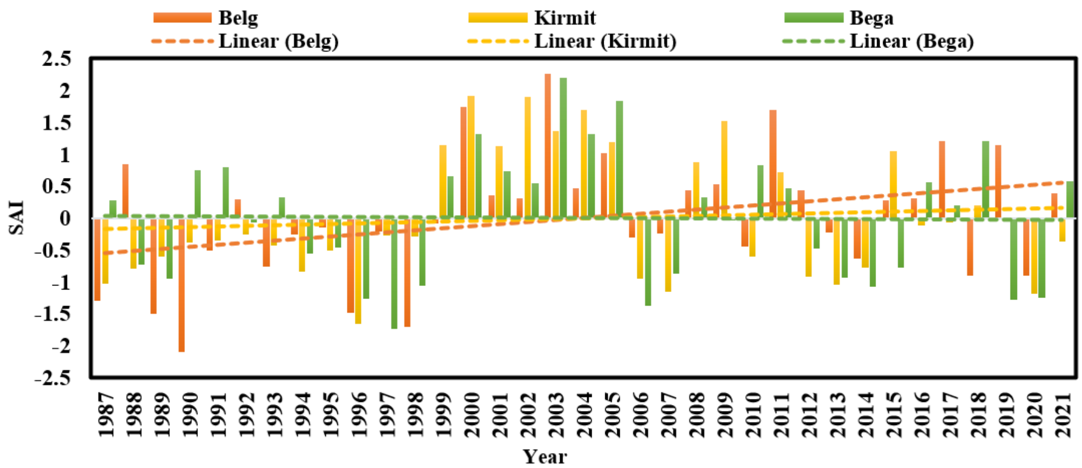

Figure 4. Temporal variations in the sessional maximum temperature anomalies of study area (1987–2022)

3.1.4. Trends in Minimum Temperature of the Study Area (1987–2022)

Figure 5 presents the long-term temporal trends in minimum temperature (Tmin) for the Humbo District between 1987 and 2022, encompassing both annual and seasonal (Belg, Kiremt, and Bega) variations. The solid lines represent smoothed Tmin values, while the dotted lines indicate their respective linear trend lines. Each trend is also accompanied by its regression equation and coefficient of determination (R^2), which quantifies the rate and strength of change over the observation period. The analysis reveals a gradual increase in the annual minimum temperature, represented by the equation $y = 0.0121x + 17.029$ with an R^2 value of 0.0844. Although this indicates a relatively weak relationship, the overall upward trend suggests a slow but persistent warming in minimum temperatures across the district.

Seasonal analysis demonstrates varying magnitudes of change. The Belg season (March–May) exhibits the most pronounced warming trend, with a slope of 0.0265°C per year and an R^2 value of 0.2154. This relatively strong and consistent increase implies a steady rise in nighttime temperatures during the early growing period, potentially influencing crop germination, pest dynamics, and soil moisture retention. The Kiremt season (June–September) also displays a positive trend, with a slope of 0.0084°C per year and an R^2 of 0.0422, reflecting moderate warming but greater internal variability. Conversely, the Bega season (October–February) shows the weakest trend, with an almost flat slope of 0.0014°C per year and a near-zero R^2 value of 0.0003, indicating minimal or no consistent change in minimum temperature during this dry period.

Overall, these findings suggest that minimum temperatures in the Humbo District have been increasing over the past three and a half decades, with the most significant warming observed during the Belg season. Such trends align with broader regional and global warming patterns and have important implications for agricultural productivity, ecosystem functioning, and the overall climate resilience of local communities.

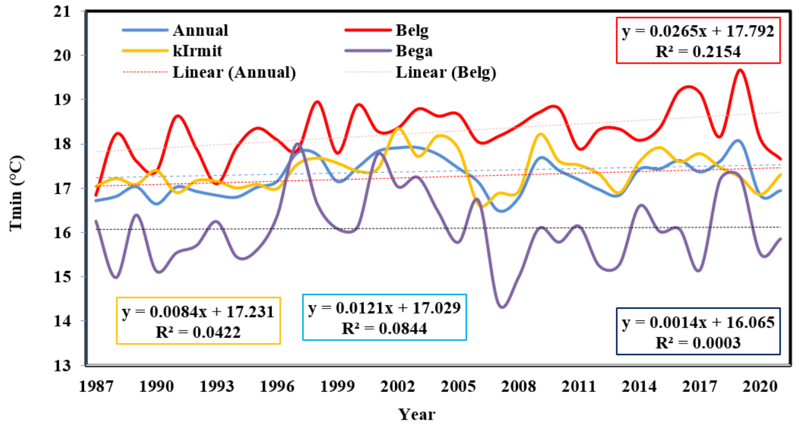

Figure 5. Trends in minimum temperature of study area (1987–2022)

3.1.5. Annual Pattern of the Standardized Anomaly Index (SAI) of Minimum Temperature

Figure 6 illustrates the annual pattern of the Standardized Anomaly Index (SAI) for minimum temperature (Tmin) in the Humbo District from 1987 to 2022. Each bar in the graph represents the annual anomaly of Tmin relative to the long-term mean, where positive values denote warmer-than-average years and negative values indicate cooler-than-average years. The dotted linear trend line reflects the overall direction of temperature change throughout the study period.

The figure reveals that most years prior to the late 1990s were characterized by negative Tmin anomalies, implying that cooler nighttime temperatures were more common during this period. Beginning around 1997, however, a noticeable shift occurs toward predominantly positive anomalies, signaling a gradual increase in minimum temperatures. The years between 1998 and 2003 stand out with several strong positive anomalies, suggesting a phase of pronounced warming. Although subsequent years exhibit fluctuations, the majority of recent years particularly in the 2010s display positive anomalies, indicating persistently warmer minimum temperatures.

The linear trend line further confirms this pattern, showing a gradual upward trend across the 36-year period. This indicates that minimum temperatures in the Humbo District have been rising modestly over time, even though the rate of increase is interspersed with short-term cooling episodes. Overall, the observed warming of Tmin reflects a long-term climatic shift from predominantly cooler conditions in the late 1980s and early 1990s to more frequent warm anomalies in recent decades.

This finding is consistent with broader regional and global climate change patterns, highlighting the progressive warming of nighttime temperatures. Such changes can have substantial implications for agricultural systems, particularly in influencing crop growth cycles, pest dynamics, and evapotranspiration rates, as well as for human comfort and ecosystem functioning within the district.

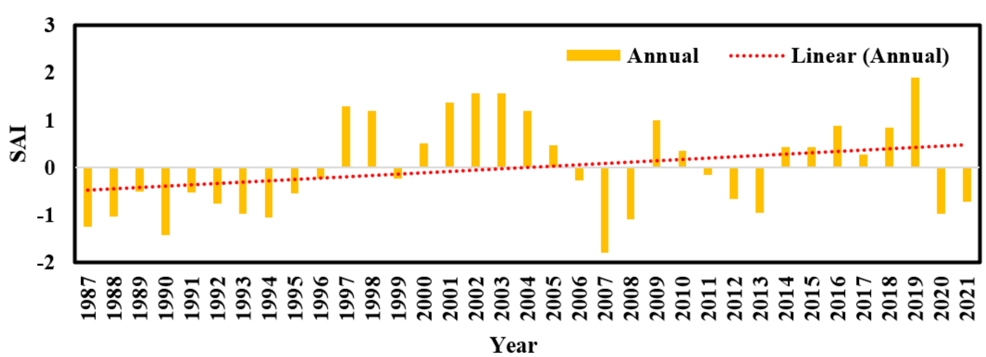

Figure 6. Annual pattern of SAI of minimum temperature in study area

3.1.6. Seasonal Standardized Anomalies of Minimum Temperature

Figure 7 presents the Standardized Anomaly Index (SAI) of minimum temperature (Tmin) for the Humbo District across the Belg, Kiremt, and Bega seasons during the period 1987–2021. The results reveal substantial interannual variability, with alternating positive and negative anomalies around the long-term mean, indicating fluctuating seasonal temperature patterns over the past three and a half decades.

Among the three seasons, Belg and Bega exhibit more pronounced fluctuations, particularly marked by strong warm anomalies during the late 1990s and mid-2010s. In contrast, the Kiremt season shows relatively moderate variability, suggesting that nighttime temperatures during the main rainy season have remained comparatively stable. The dashed linear trend lines for all three seasons indicate a gradual upward trajectory, confirming an overall increase in Tmin across the study period. Notably, the Belg and Bega seasons display slightly steeper trend slopes than Kiremt, implying a stronger warming tendency during these transitional and dry periods.

This persistent rise in minimum temperature across seasons aligns with regional and global climate warming patterns and indicates that nights are becoming progressively warmer in the Humbo District. Such warming can have significant implications for local agricultural systems by altering crop growth cycles, pest and disease proliferation, and evapotranspiration rates. Moreover, increased nighttime temperatures may affect water availability and reduce soil moisture retention, thereby influencing overall ecosystem resilience. These findings underscore the importance of incorporating adaptive agricultural practices and climate-smart management strategies to mitigate the impacts of rising minimum temperatures in the region.

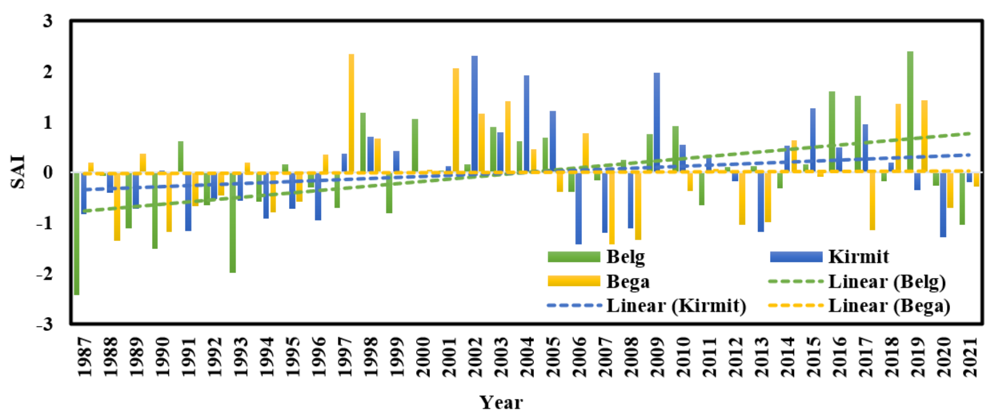

Figure 7. Sessional case standardized rainfall anomalies of the minimum temperature in study area

3.1.7. Temporal Variability and Trends of Average Rainfall in Humbo District

The long-term average annual rainfall in Humbo District was 1302.66 mm, with a coefficient of variation (CV) of 25.44%, indicating moderate interannual variability. Rainfall in the study area exhibits distinct seasonal patterns, with the wettest months occurring in April and May, highlighting the uneven distribution of precipitation throughout the year. Seasonally, Belg contributed 40.72%, Kiremt contributed 36.26%, and Bega accounted for the remaining 23.02% of total annual rainfall. The Bega season, with the lowest contribution, showed relatively high variability (CV = 43.58%) and a minor declining trend (Kendall's Tau = -0.146), although this was not statistically significant ($p = 0.215$).

The annual rainfall trend exhibited a significant positive pattern (Kendall's Tau = 0.344, $p = 0.003$) with a Sen's slope of 4.868 mm per year, suggesting a gradual increase in total rainfall over the study period. The contributions of Belg and Kiremt are critical for agricultural planning and water resource management, as these seasons provide the majority of precipitation. Conversely, the observed decline in Bega rainfall may indicate a shorter or less intense dry season, potentially affecting ecological systems and local livelihoods. The concentration of annual rainfall during the Belg season aligns with findings from previous studies conducted in Ethiopia (Asfaw et al., 2018; Ayalew et al., 2012; Surya Bhagavan, 2016; Gebrehiwot & Veen, 2013).

Figure 8 demonstrates a minor positive trend in annual rainfall, reflecting subtle changes in the hydrological cycle. However, the low R^2 value suggests significant interannual variability, indicating that factors other than the long-term trend contribute to annual totals. For Kiremt rainfall, the R^2 value of 0.0399 indicates that only 3.99% of the variation is explained by the observed trend, which exhibits a negative slope, pointing to a gradual decrease in rainfall during the main rainy season. Similarly, Bega rainfall decreased at a rate of 3.104 mm per year over the study period.

These findings contrast with studies by Wagesho et al. (2013), Asfaw et al. (2018), and Abebe and Arega (2019), which reported significant decreasing trends in annual and Kiremt rainfall. Conversely, the results align with the observations of Conway (2000), Viste et al. (2013), McSweeney et al. (2008), Suryabhagavan (2016), Conway et al. (2004), and Befikadu et al. (2019), who reported statistically non-significant long-term trends in rainfall.

Table 5. M-K Test and Sen's Slope of mean annual rainfall of study area (1987–2022)

Month	Mean RF	Contribution (%)	CV	Kendall's tau	P-Value	Sen's slope
JAN	25.948	1.99	117.30***	-0.108	0.384	0.000
FEB	32.764	2.52	99.41***	-0.160	0.188	-0.620
MAR	86.294	6.62	56.25***	-0.096	0.421	-0.801
APR	212.054	16.28	41.14***	0.221	0.062	2.229
MAY	199.333	15.30	40.87***	0.189	0.111	2.354
JUN	113.496	8.71	53.65***	-0.220	0.064	-1.758
JUL	107.793	8.27	48.63***	-0.189	0.113	-1.055
AUG	124.370	9.55	47.86***	-0.058	0.633	-0.417
SEP	126.735	9.73	48.01***	0.016	0.902	0.000
OCT	150.015	11.52	46.95***	0.163	0.168	1.477
NOV	82.751	6.35	78.33***	0.366	0.002	2.637
DEC	41.111	3.16	106.13***	0.117	0.331	0.504
BELG	530.446	40.72	29.01**	0.070	0.558	3.464
KERMIT	472.394	36.26	38.47***	0.118	0.320	1.992
BEGA	299.825	23.02	43.58***	-0.146	0.215	-3.826
ANNUAL RF	1302.666	100	25.44**	0.344	0.003	4.868

3.1.8. Monthly and Seasonal Rainfall Patterns in Humbo District

Table 5 presents a detailed overview of mean annual rainfall in Humbo District from 1987 to 2022, including monthly distributions, contributions to the annual total, variability, and temporal trends. The wettest months are March, April, May, and June, with April contributing the largest proportion (16.28%) and a mean rainfall of 212.05 mm. Conversely, January and February record the lowest rainfall, each contributing less than 3% of the annual total. The coefficient of variation (CV) values is generally high, particularly in January (117.30%) and February (99.41%), indicating pronounced interannual variability and unpredictability in rainfall during these months. Seasonally, Belg, Kiremt, and Bega periods show notable variability, with Bega exhibiting the lowest CV (43.58%), suggesting relatively more consistent rainfall during the dry season.

Trend analyses using Kendall's tau indicate weak or non-significant trends for most individual months, except for the annual rainfall total (tau = 0.344, p = 0.003), which shows a statistically significant upward trend. The Sen's slope values further confirm the magnitude and direction of change, with the annual rainfall increasing by 4.868 mm per year, while certain months, such as April (2.229 mm/year) and the Bega season (3.826 mm/year), also show upward tendencies, though these are generally not statistically significant. Overall, despite high variability at monthly and seasonal scales, the data indicate a significant long-term increase in total annual rainfall, which is important for water resource management and climate adaptation planning in the region.

3.1.9. Trends in Mean Annual Rainfall

Figure 8 depicts trends in mean annual rainfall for Humbo District between 1987 and 2022, separated into annual totals and the three primary seasons: Belg, Kiremt, and Bega. The figure combines actual yearly rainfall (solid lines) with linear trend lines (dashed lines) to illustrate long-term patterns. Annual rainfall demonstrates substantial interannual variability, with values fluctuating widely from year to year. Nevertheless, the linear trend for annual rainfall ($y = 4.9002x - 8519.8$; $R^2 = 0.0243$) suggests a slight upward trajectory, although the low R^2 indicates that the trend accounts for only a small portion of the variability.

Seasonal trends vary considerably. Belg rainfall exhibits a minor decreasing trend ($y = -3.445x + 7377.9$; $R^2 = 0.0399$), though the slope is weak and actual rainfall remains highly variable. Kiremt shows a modest positive trend ($y = 2.7784x - 5038.8$; $R^2 = 0.0362$), indicating a slight increase, but again with limited explanatory power due to interannual fluctuations. In contrast, the Bega season displays a more pronounced positive trend ($y = 5.5669x - 10859$; $R^2 = 0.2015$), suggesting a relatively stronger increase in rainfall during this dry season.

In summary, while rainfall in Humbo District exhibits high year-to-year variability across months and seasons, there is a statistically significant upward trend in annual totals and Bega rainfall, whereas Belg rainfall shows a slight decline and Kiremt rainfall remains relatively stable. These findings highlight the importance of considering both seasonal and annual patterns in agricultural planning, water resource management, and climate adaptation strategies, as variability appears to exert a greater influence than linear trends, except notably in the Bega season.

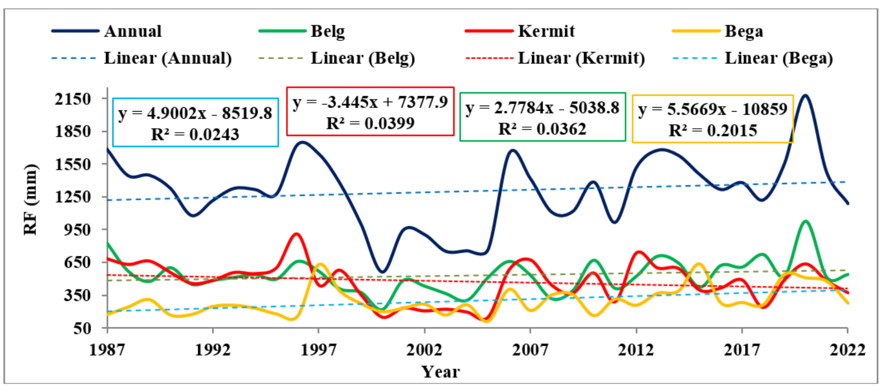

Figure 8. Trends in mean annual rainfall of study area (1987–2022)

3.1.10. Standardized Rainfall Anomalies (SRA)

Figure 9 illustrates the Standardized Rainfall Anomalies (SRA) for mean annual rainfall in the study area. Positive anomalies, represented by upward bars, indicate years with above-average rainfall, while negative anomalies, represented by downward bars, correspond to years with below-average precipitation. Years characterized by negative anomalies reflect periods of reduced rainfall, which have critical implications for rural livelihoods and food security.

Figure 10 further shows that during the study period, 17 years experienced positive annual rainfall anomalies, whereas 15 years exhibited negative anomalies. This indicates that in the majority of years, annual rainfall exceeded the long-term mean, while in fewer years it fell below average.

Focus Group Discussions (FGDs) corroborated these findings. Participants unanimously reported noticeable changes in climatic patterns over the past decade, including irregular rainfall, prolonged dry periods, and rising temperatures. Farmers emphasized that these shifts have disrupted traditional farming calendars, leading to

reduced crop production and, consequently, food shortages.
Inter-seasonal analysis revealed that, similar to annual rainfall, the proportion of positive anomalies exceeded negative anomalies in Belg and Kiremt seasons, whereas Bega showed a higher incidence of negative anomalies. Overall, these results highlight considerable variability in rainfall both across years and seasons, underscoring the need for adaptive agricultural practices to mitigate the impacts of climatic variability on livelihoods in the study area.

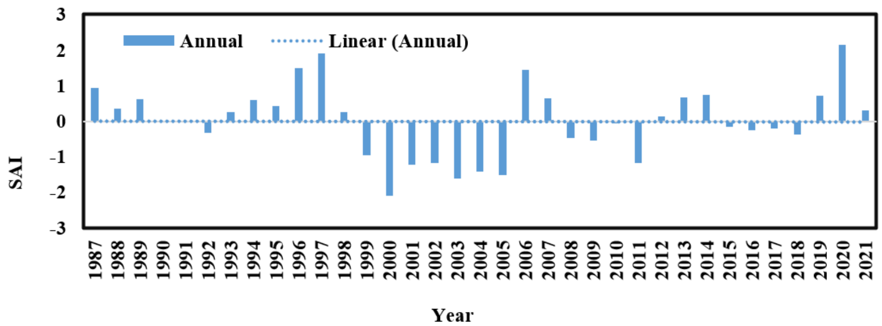

Figure 9. Temporal variations in the annual rainfall anomalies of Humbo District (1987–2022)

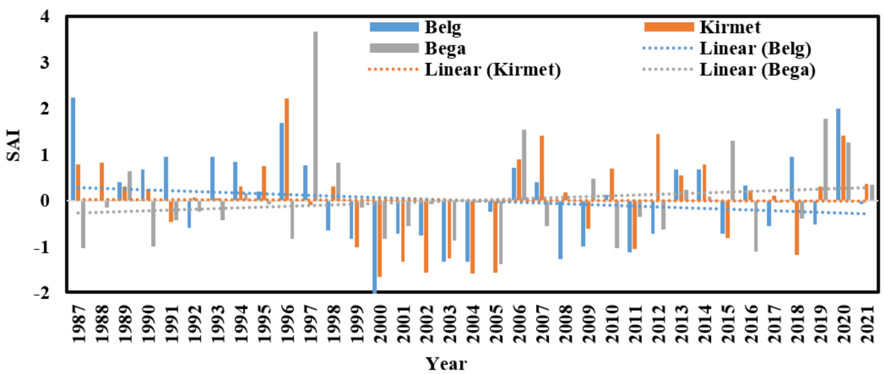

Figure 9. Standardized rainfall anomalies of the rainfall

3.2. Farmers' Vulnerability to Climate Change and Variability

Household vulnerability was assessed using Principal Component Analysis (PCA) based on the three IPCC (2012) dimensions: adaptive capacity, exposure, and sensitivity. Prior to PCA, data suitability was evaluated using the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's test. According to Jamil et al. (2015), PCA is appropriate when the KMO value exceeds 0.5 and Bartlett's test is significant. In this study, the KMO value was 0.78, indicating sampling adequacy, and Bartlett's test was significant ($p < 0.01$), confirming the appropriateness of PCA for factor extraction. Fifteen indicator variables were processed through a correlation matrix and subjected to varimax orthogonal rotation with Kaiser Normalization. Ten observed variables were used to construct the adaptive capacity index of households (Table 6), highlighting the contribution of each variable to the adaptive capacity of irrigation beneficiaries versus non-beneficiaries in coping with climate-related shocks.

3.2.1. Adaptive Capacity Indicators

Household Savings: Irrigation users had a negative index (-0.432), reflecting stronger financial resilience compared to non-users (0.401), enhancing their capacity to manage climate shocks.

Farm Size and Non-Agricultural Income: Lower indices for irrigation users (farm size: -0.631; non-agricultural income: -0.572) indicate better access to land and diversified income sources. Non-users, with positive indices (0.606; 0.546), are more vulnerable due to smaller farms and limited income diversification.

Livestock Ownership and Income Diversity: Irrigation users show lower indices (-0.445; -0.600), signifying more robust adaptive capacity compared to non-users (0.414; 0.582).
Access to Inputs, Healthcare, and Markets: Users benefit from better access to fertilizers and improved seeds (-0.607), healthcare (-0.555), and markets (-0.435), relative to non-users (0.583; 0.534; 0.404).
Irrigation Potential: A substantial difference is observed, with users at 0.645 versus non-users at -0.711, highlighting irrigation's central role in resilience.
Literacy Rates: Negative indices among users (-0.560) correspond to higher awareness and informed decision-making, while non-users (0.533) are limited in accessing knowledge and adaptive strategies. Overall, irrigation users demonstrate consistently stronger adaptive capacity due to financial stability, resource availability, and better access to infrastructure and education. Non-users, constrained by financial limitations, fewer resources, and restricted access to inputs and services, remain highly vulnerable, underscoring the need for targeted policy interventions.

3.2.2. Exposure Indicators

Temperature and Precipitation Changes: Irrigation users had lower exposure indices (-0.515; -0.512) compared to non-users (0.495; 0.489), reflecting their ability to buffer climate stresses via irrigation.
Pest Infestation: Users also exhibited slightly lower pest exposure (-0.503) than non-users (0.479), suggesting better crop protection and management practices.
These findings indicate that irrigation mitigates exposure to climate stressors, whereas non-users are more exposed, emphasizing the importance of expanding irrigation and climate-resilient technologies to reduce vulnerability.

3.2.3. Sensitivity Indicators

Frequency of Drought: Irrigation users show a lower drought sensitivity index (-0.593) compared to non-users (0.579), indicating reduced susceptibility to water scarcity.
Crop Loss During Storage: Lower sensitivity among irrigation users (-0.432) versus non-users (0.401) likely reflects better post-harvest management and financial security. Collectively, these results indicate that irrigation users experience lower sensitivity to climate impacts due to access to resources and adaptive technologies. Non-users face higher sensitivity, highlighting the need for interventions such as drought-resilient crops and improved storage solutions.
Across all dimensions' adaptive capacity, exposure, and sensitivity irrigation users consistently demonstrate lower vulnerability indices, reflecting stronger resilience, reduced exposure, and better coping mechanisms. Conversely, non-irrigation users display higher vulnerability due to reliance on rain-fed agriculture, limited access to resources, and financial constraints. The results reveal that adaptive capacity is highest among irrigation beneficiaries, whereas non-users exhibit the greatest exposure and sensitivity, indicating that their vulnerability is primarily driven by insufficient capacity to cope with climate change and variability.

3.2.4. Overall Vulnerability Status of Households

Figure 11 illustrates the net vulnerability values for both irrigation practitioner and non-irrigation practitioner households in the study area. Overall, vulnerability indices are positive for both groups, indicating susceptibility to climate-related shocks. However, the results in Table 5 show that non-irrigation households are the most vulnerable relative to irrigation practitioners, with a statistically significant difference between the two groups. Irrigation practitioners were categorized as moderately vulnerable, suggesting that these households may require temporary assistance during periods of severe climate stress. Following McCarthy (2001) guidelines and the local context, households were classified based on their vulnerability index (Vi) into three categories: low vulnerability ($0 \leqslant Vi \leqslant 0.45$), medium vulnerability ($0.45 \leqslant Vi \leqslant 0.70$), and high vulnerability ($0.70 \leqslant Vi \leqslant 1.00$). Higher values of Vi indicate greater vulnerability, whereas lower values indicate greater resilience.

Table 6. Vulnerability indices for the study area

Determinants of vulnerability	Description of each indicator	Indices For Irrigation User	Indices For Not user
Adaptive capacity	Saving at HH level	-0.432	0.401
	Enough Farm size of the HHs	-0.631	0.606
	Non-agricultural income	-0.572	0.546
	Ownership of livestock	-0.445	0.414
	Income diversity Gifts and remittances	-0.600	0.582
	Access to farm inputs (Fertilizer supply Improved seeds supply)	-0.607	0.583
	Access to health care	-0.555	0.534
	Access to market	-0.435	0.404
	Irrigation potential at household level	0.645	-0.711
	Literacy rate young and older	-0.560	0.533
Exposure	Increasing Change in temperature	-0.515	0.495
	Decreasing Change in precipitation	-0.512	0.489
	Pest infestation	-0.503	0.479
Sensitivity	Frequency of drought	-0.593	0.579
	Effect of crop loss during storage	-0.432	0.401

*Note: user: Eigenvalue^2 =1.05, percent of variance= 52.5%; Non-user: Eigenvalue^2 =2.94, percent of variance= 67.3%

Frequency distribution of vulnerability indices shows that irrigation practitioner households range from 0 to -0.91, while non-irrigation households range from 0 to 0.75. This pattern highlights that non-irrigation households are more vulnerable, while irrigation practitioners maintain relatively low vulnerability due to greater access to natural and financial capital. Over time, the vulnerability of non-users shows an increasing trend, driven by socio-economic constraints, whereas irrigation users maintain a stable low-vulnerability profile, benefiting from irrigation and financial investments. Policy recommendations to reduce vulnerability include expanding irrigation access and infrastructure for non-users, promoting water-efficient technologies, and integrating climate-smart agricultural practices to sustain and optimize existing irrigation systems. These interventions aim to reduce household susceptibility to climate shocks and enhance long-term resilience. This finding aligns with Kiratu et al. (2015), who reported that farmer-led irrigation marginally improves dietary diversity, reflecting the critical role of irrigation in household livelihood strategies.

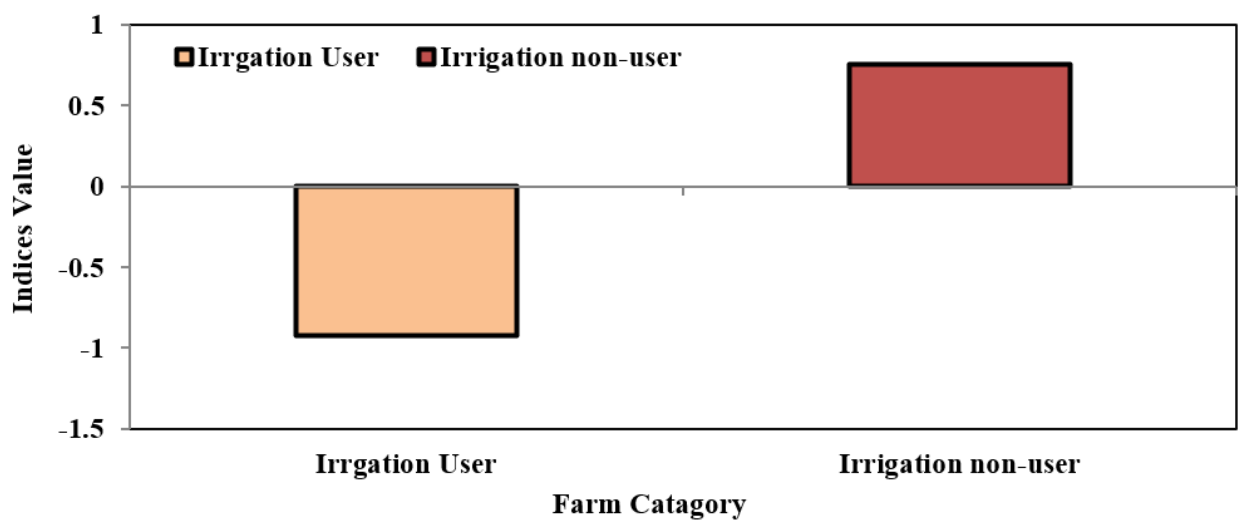

Figure 10. Total vulnerability indices

3.3. Farmers' Perceptions on the Role of Small-Scale Irrigation in Climate Change Adaptation

Key informant interviews and focus group discussions highlighted the significant role of small-scale irrigation (SSI) in reducing farmers' vulnerability to climate change and variability in the study area.

Key Informant Insights: Key Informant 1 noted that farmers utilizing small-scale irrigation experience lower susceptibility to climate change effects, as irrigation allows them to access water even during drought periods, thereby securing higher crop revenues. They emphasized that irrigation mitigates the impacts of inadequate rainfall, enabling cultivation when rain-fed methods fail. In contrast, non-irrigation users largely depend on erratic rainfall, increasing their exposure to climate-related shocks.

Key Informant 2 further explained that without access to water supply or irrigation systems, farmers endure significant crop losses during dry seasons. Many non-irrigation farmers rely on low-productivity varieties, which further heightens their vulnerability to climatic stress.

Key Informant 3 provided a recent example: during the previous prolonged dry season, irrigation users were able to conserve crops and water new plantings, while non-users suffered harvest losses approaching 90%. This disparity significantly affected their livelihoods, highlighting irrigation's critical buffering role.

Focus Group Discussions (FGDs): Participants reinforced these observations. Participant 1 reported that even a small constructed wetland enabled irrigation during dry periods, resulting in better crop yields than those relying solely on rainfall. Participant 2 shared that while his crops failed during the preceding dry season due to lack of irrigation, he observed substantial harvests among friends who practiced irrigation. Participant 3 emphasized the importance of planning and stabilizing incomes, noting persistent food supply challenges for non-irrigation users. Overall, these qualitative insights indicate that small-scale irrigation substantially enhances farmers' resilience to climate variability, safeguards livelihoods during dry spells, and contributes to stable food production. The findings underscore the need for further research, investment, and policy support to expand and upgrade SSI systems, ensuring that more farmers can adapt effectively to changing climatic conditions.

Figure 12. FGD in study area

3.4. Contribution of Small-Scale Irrigation Practices to Reducing Farmers' Vulnerability to Climate Change and Variability

The results indicate that small-scale irrigation (SSI) significantly enhances farmers' adaptive capacity to climate-related risks by increasing household income (Figure 13). Farmers practicing irrigation are better able to cope with and adapt to climate variability, as the additional income generated through irrigated farming provides resources for improving farm management, investing in inputs, and sustaining livelihoods during adverse climatic events.

These findings align with previous studies that highlight the role of irrigation in strengthening climate resilience. Thorlakson and Neufeldt (2012) and Schoeneberger et al. (2017) emphasized that irrigation practices not only improve productivity but also support adaptive strategies by increasing income and reducing farmers' susceptibility to climate shocks. In this study, irrigation users demonstrated enhanced adaptive capacity compared to non-irrigation users, confirming the critical role of SSI in mitigating climate vulnerability and securing rural livelihoods.

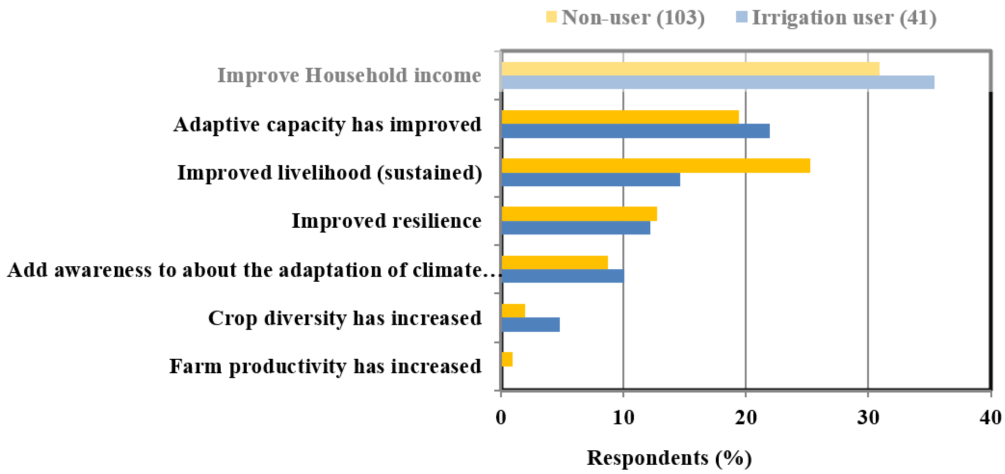

Figure 13. Contribution of SSI household resilience

Adaptive capacity to climate variability refers to the ability of a system or individual to adjust in response to changing climatic conditions in order to minimize potential damages or cope with the associated impacts. It encompasses the planning and implementation of adaptation strategies to moderate the effects of climate variability. The level of adaptive capacity differs among farmers, depending on factors unique to each household, such as access to resources, technology, and knowledge. It is generally assumed that farmers act rationally, adopting measures to reduce the adverse consequences of climate variability. Consequently, some farmers exhibit a greater capacity to adapt than others.

In this study, the adaptive capacity of each household was assessed using a combination of qualitative and quantitative indicators. Table 5 presents the degree of adaptive capacity among household heads and the various strategies employed to cope with climate variability. These strategies include the use of chemical or organic fertilizers, small-scale irrigation, soil and water conservation practices, diversification of crop and livestock types and varieties, adjustment of planting dates, modification of cultivated land size, reduction of livestock numbers, engagement in off-farm activities, utilization of early-maturing crop varieties, cultivation of drought-resistant and low-water-requirement crops, crop rotation, and integration of trees within cropland. The results indicate that irrigation users exhibit higher adaptive capacity than non-irrigators, primarily due to their ability to access and apply appropriate technologies and water for irrigation, allowing them to cultivate their land twice annually. The adaptive capacity of irrigators falls within the range of $0.66 \leqslant AveAdapCapj \leqslant 1.00$. In contrast, non-irrigators demonstrate moderate adaptive capacity, with values ranging from $0.33 \leqslant AveAdapCapj < 0.66$, largely due to limited access to irrigation water, minimal use of modern technologies, and reliance on rain-fed agriculture, which allows only a single annual cropping cycle. This suggests that non-irrigators lack sufficient resources to effectively adapt to climate variability and cope with extreme climatic events.

The study further found that irrigation users are able to cultivate their land twice annually, enhancing productivity, resilience, and, in some cases, transforming livelihoods. These findings are consistent with the studies of Diao Xinshen et al. (2010) and Beyan et al. (2014). Recognizing this, the Government of Ethiopia has identified small-scale irrigation as a key adaptation strategy. Table 5 shows that all irrigation users employed a variety of adaptation measures compared to non-users. However, Table 7 highlights the main constraints limiting household adaptation, including limited access to irrigation water, shortages of agricultural inputs, insufficient labor, lack of credit or capital, and inadequate access to information. As a result, non-irrigators are more severely affected by climate variability and extreme events.

Table 7. Degree of adaptive capacities and adaptation strategies of households

Adaptation strategies	Irrigation user			Irrigation non-user		
	AC (Adapj)	Rank	Degree of AC	AC (Adapj)	Rank	Degree of AC
Application of organic fertilizer	0.602	9	Moderate AC	0.311	11	Low AC
Use early maturing crop varieties.	0.621	8	Moderate AC	0.524	6	Moderate AC
Use drought-resistant and water-efficient agricultural varieties	0.806	2	High AC	0.738	2	High AC
Utilization of Soil and water conservation measures	0.748	6	High AC	0.408	9	Low AC
Small scale irrigation	0.825	1	High AC	0.204	12	Low AC
Reduce numbers of Livestock	0.553	11	Moderate AC	0.476	8	Low AC
Integration of tree within crops	0.583	10	Moderate AC	0.379	10	Low AC
Diversify from farming to off-farming activities	0.291	12	Low AC	0.757	1	High AC
Diversification of crop and livestock types and varieties	0.796	3	High AC	0.515	7	Moderate AC
Crop rotation	0.631	7	Moderate AC	0.699	3	Moderate AC
Changing the size of land under cultivation	0.767	4	High AC	0.553	4	Moderate AC
Changing planting dates	0.757	5	High AC	0.544	5	Moderate AC
Total	0.665		High AC	0.509		Moderate AC

Note: AC: Adaptive Capacity.

Key Informant Interview (KII) Insights: Q1: Impacts of small-scale irrigation on farmer resilience to climate change: According to the key informants, small-scale irrigation practices have substantially improved farmers' resilience to climate variability. By providing a reliable water supply during dry periods, these systems reduce reliance on increasingly unpredictable rainfall, enabling farmers to cultivate crops even during the dry season. This, in turn, enhances food security and ensures a more stable household income.

Q2: Challenges in implementing small-scale irrigation practices

The main constraints reported by farmers include the high initial costs of infrastructure, limited technical knowledge, and inadequate access to maintenance services. Many farmers face difficulties investing in irrigation systems due to delayed financial returns. Consequently, education and training initiatives are critical to improve farmers' understanding of the benefits, operation, and maintenance of small-scale irrigation systems.

Figure 14. Focus Group Discussion (FGD)

During data collection farmers reported notable improvements in crop productivity following the adoption of small-scale irrigation. One farmer highlighted that prior to implementing irrigation, cultivation was limited to the rainy season, whereas now, double cropping is possible, generating surplus produce for sale. Participants emphasized that irrigation has enabled them to sustain food supplies even during drought periods. As one farmer noted, “Last year, despite inadequate rainfall, we had sufficient food due to irrigation.”

Small-scale irrigation has also facilitated crop diversification, which has enhanced household income. A participant remarked that growing high-value vegetables now contributes significantly to improving family livelihoods.

Despite these benefits, farmers identified key challenges, including high initial costs and a lack of technical knowledge. One farmer stated the desire to adopt a drip irrigation system but noted difficulties with installation and sourcing materials. The group underscored the importance of community-based training programs, suggesting that workshops and knowledge-sharing sessions would empower farmers and promote mutual support. Additionally, farmers expressed the need for improved access to financial resources and technical assistance, emphasizing that such support would allow them to expand irrigation infrastructure and further strengthen their resilience to climate variability.

4. Conclusion

This study demonstrates the critical role of small-scale irrigation (SSI) in mitigating the adverse impacts of climate change and variability on rural communities in Humbo District, South Ethiopia. Analysis of long-term climate data revealed substantial variability and shifts in both rainfall and temperature, posing significant challenges to rain-fed agriculture and rural livelihoods. The observed seasonal and annual patterns, along with pronounced trends, underscore the importance of strategic water resource management to enhance agricultural productivity and resilience under changing climatic conditions. The study further showed that a majority of both SSI participants and non-participants perceived changes in climate, particularly regarding temperature and rainfall. Mann-Kendall trend analysis confirmed a significant upward trajectory in long-term average monthly temperatures, with maximum temperatures rising most prominently during the Belg and Kiremt seasons. Seasonal rainfall variability was observed across Kiremt, Belg, and Bega, as well as in annual totals. Positive rainfall anomalies predominated in most seasons, except during Bega, further illustrating the region’s climatic variability.

The findings highlight SSI as an effective adaptive strategy to counter climate variability. Farmers practicing irrigation exhibited lower vulnerability compared to non-users, benefiting from improved access to water infrastructure, financial resources, diversified income streams, and agricultural inputs. These advantages collectively enhance adaptive capacity, reduce exposure and sensitivity to climate risks, and strengthen resilience to climate-related shocks. In contrast, non-irrigation households remain highly vulnerable due to reliance on rain-fed farming and limited adaptive capacities. This disparity underscores the urgent need for targeted interventions, including expanded SSI access, capacity-building initiatives, and equitable resource distribution. Overall, small-scale irrigation emerges as a transformative tool for enhancing rural resilience and sustaining livelihoods under climate variability.

Recommendations

- Smallholder farmers should adopt selective adaptation strategies, including the use of early-maturing crop varieties, drought-resistant and low-water-requirement crops, diversification of crop and livestock types, and adjustment of planting dates, to enhance their adaptive capacity to climate variability.
- Promotion of small-scale irrigation practices, which have proven potential for climate change adaptation and mitigation, is essential. Farmers should be empowered to take a leading role in the management and operation of these irrigation systems.
- Awareness-raising and education initiatives are needed to strengthen farmers’ understanding of the linkage between climate

change and irrigation, thereby encouraging wider adoption of irrigation practices.

- Further research should focus on developing robust proxy indicators to identify and support the most vulnerable households, enabling targeted interventions at the household level.
- Integrating rural development schemes that enhance adaptive capacity to climate variability and change is recommended, with particular attention to the range of climate extremes experienced by local communities.

Data Availability

No datasets were generated or analyzed during the current study.

Authors Contribution

Abraham Woru Borku: Conceptualization, visualization, resources and manuscript editing.
Thomas Toma Tora: Conceptualization, supervision, formal analysis and investigation.
Mamush Masha: Conceptualization, methodology, formal analysis and investigation, writing-original draft preparation

Competing Interests

The authors declare no competing interests.

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