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Bridging the Gender Gap in Climate-Resilient Sweet Potato Farming: A Case Study from Goromonzi District, Zimbabwe

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Abstract: This study delves into the gender-specific challenges and opportunities in sweet potato farming in Goromonzi District, Zimbabwe, against the backdrop of escalating droughts. Through a blend of surveys, expert analysis, and high-resolution satellite imagery, the research uncovers critical factors shaping sweet potato production—ranging from land access and cultivation techniques to harvesting and market dynamics. By leveraging the multi-Criteria Decision-Making (MCDM) framework, the study evaluates these factors' importance and presents innovative, gender-inclusive strategies to foster climate resilience. Remote sensing tools map the severity of droughts, while data analysis reveals the interconnected challenges faced by farmers. The findings spotlight the urgent need for equitable resource access and support systems to empower both female farmers, paving the way for sustainable agriculture in an era of climate uncertainty.

Keywords: sweet potato farming; drought impact; gender disparities; climate-resilient strategies; MCDM; remote sensing

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1. Introduction

Over the past two decades, the rise in global carbon emissions has significantly intensified the impacts of climate change, disproportionately affecting low-income countries [1,2]. This has resulted in a surge in climatic extremes, including more frequent and severe floods and droughts, exacerbating vulnerabilities in these regions. Since the year 2000, the African continent has experienced approximately seven hundred floods and more than 120 drought events [3]. In addition to the historical 1992 southern African drought [4,5], Zimbabwe has faced significant national droughts in the 2000s, notably in 2001, 2007, 2010, 2013, and 2017 [6]. Consequently, climate change has emerged as a priority concern for the national government [7–11]. In response, the Zimbabwean government has enacted a series of measures to mitigate the effects of climate change, including the National Climate Change Response Strategy, the National Climate Policy, the National Drought Plan, and the Agricultural Food Systems Transformation Strategy [12]. Collectively, these frameworks

address various aspects of climate change, such as mitigation, adaptation, and the role of financing mechanisms in building resilience among vulnerable communities (ibid).

Historically, sweet potato was classified as an orphan crop due to its perceived absence of formal policy support at the national level. However, the National Development Strategy 1 (NDS1) has since recognized the importance of research and development in enhancing the sweet potato value chain, with a focus on seed production and multiplication [13]. Furthermore, the National Agricultural Policy Framework (2019–2030) emphasizes the role of sweet potato bio-fortification as a strategy for increasing access to micronutrients, particularly vitamin A, in children [13]. Sweet potato is now considered a viable climate change adaptation strategy for poor rural farmers, due to its lower water and chemical fertilizer requirements compared to conventional crops like maize [10,11,14–16]. According to Smith [17], while the average national yield of sweet potatoes is 6 tons per hectare, irrigated sweet potatoes can yield up to 25 tons per hectare. Over the past two decades, Zimbabwe has seen a remarkable increase in sweet potato production. In 2000, national production stood at 6159.17 tons, which increased fourfold to about 24,938.5 tons in 2010, and further tripled to approximately 62,792 tons in 2022 [18]. This increase is largely attributed to the crop's resilience against climate variability [19].

Despite the rising production volumes, sweet potato farmers in Zimbabwe face significant challenges. Historically, before Zimbabwe's independence in 1980, sweet potatoes were primarily cultivated by women in rural areas as a supplementary crop to maize and other staples [20]. While the crop is well-suited to Zimbabwe's climate, there is limited understanding of the gender roles that have contributed to its transformation into a primary food source across the country. Research by Mudombi [14] and Scott et al. [21] highlights sweet potatoes' growing importance in household food security, particularly as a reliable alternative during maize crop failures. However, the historical evolution of land management systems in Zimbabwe has significantly shaped sweet potato production and, by extension, gender dynamics in agriculture. Under colonial-era policies, communal resource-sharing practices were replaced with systems that systematically marginalized women, restricting their access to land and resources [22]. These inequities persist in regions like Domboshava, where men typically control larger plots of land, while women often require permission to access or cultivate even smaller areas [23]. Such gender-biased policies perpetuate unequal rights, limiting women's economic opportunities and exacerbating their vulnerability to poverty [24].

Although legal reforms have been introduced to address these disparities, entrenched cultural norms and patriarchal practices continue to hinder women's ability to own land or participate in agricultural decision-making processes. This exclusion not only reduces women's engagement in productive farming but also restricts the overall potential of Zimbabwe's agricultural sector, undermining efforts to achieve inclusive and sustainable development [25].

The rising transportation and agricultural input costs have also significantly hindered agricultural development in economically disadvantaged areas [26]. Research in KwaZulu-Natal further underscores the impact of extreme weather events, such as drought, on sweet potato production [27–29]. Additionally, challenges such as restricted access to infrastructure, low education and literacy levels, inadequate market information, insecure property rights, poor road networks, long distances to markets, and gender disparities increase transaction costs for farmers [30,31]. The unpredictable nature of data and the rarity of certain events further complicate the creation of accurate mathematical models, rendering conventional statistical data processing techniques largely ineffective [32].

Amidst these adversities, small-scale farmers in Zimbabwe exhibit remarkable resilience and ingenuity, leveraging local knowledge and community networks to navigate

challenges and sustain their livelihoods. Given the increasingly extreme climate events of recent decades, this study aims to explore the impact of these conditions on sweet potato production and supply chains in the Goromonzi district of Zimbabwe. First, the study identifies and analyzes the extreme climate challenges within the sweet potato farming sector in Goromonzi District [33]. Then, it leverages Multi-Criteria Decision-Making (MCDM) to assess the extent to which these climate conditions are perceived as impactful by farmers in sweet potato production. Finally, the study develops and proposes a climate-resilient strategy aimed at fostering sustainable sweet potato farming practices.

After the reviewing of literature, Munyaka et al. [33] conducted a qualitative and quantitative study in the Goromonzi District of Zimbabwe, focusing on the challenges faced by sweet potato farmers. The Focus Group Discussions and the survey findings highlighted significant issues related to planting, harvesting, transportation, and marketability, among others. These results align with broader research on agricultural constraints in Zimbabwe, emphasizing the need for targeted interventions to address these systemic barriers and enhance the sustainability of sweet potato production.

Addressing these challenges requires robust decision-making frameworks to identify and prioritize effective interventions. This is where the multi-Criteria Decision-Making (MCDM) process becomes invaluable. By integrating multiple criteria, MCDM provides a structured and transparent approach to analyzing complex problems, such as those faced in sweet potato production [34]. It allows for a systematic evaluation of factors like harvesting, transportation, and marketability, ensuring that solutions are both comprehensive and effective.

Defined by Triantaphyllou et al. [35], MCDM encompasses a range of methodologies tailored to decision-making needs. For instance, the Analytic Hierarchy Process (AHP) is a widely used MCDM method that involves selecting, weighting, and analyzing criteria [36]. This structured approach enables stakeholders to balance subjective and objective inputs, such as through pairwise comparisons or statistical weighting techniques [37]. Complementary techniques, including TOPSIS and PROMETHEE, further enhance the decision-making process by refining analysis and prioritizing actionable strategies. The versatility of MCDM makes it a valuable tool across various sectors, including agriculture, where it can play a pivotal role in addressing systemic challenges in sweet potato production [38].

2. Methods

2.1. Study Area

Goromonzi, in Mashonaland East, Zimbabwe, lies 32 km southeast of Harare and spans 25,407.2 square kilometers (as shown in Figure 1). It includes 25 wards—13 commercial, 11 communal, and 1 small-scale farming area. The region's fertile soils and altitudes support diverse agriculture. Temperatures range from 15 to 20 °C, with 800–1000 mm of annual rainfall. The land tenure includes freehold, communal, and state ownership, with major uses in large-scale commercial farming, communal lands, and urban zones. Despite a rural majority population of 224,987, urbanization is increasing. Challenges such as limited land access for female farmers, inadequate road infrastructure, and reliance on seasonal water sources are being addressed through initiatives like the proposed Kunzwi Dam, which aims to enhance irrigation and foster agricultural growth.

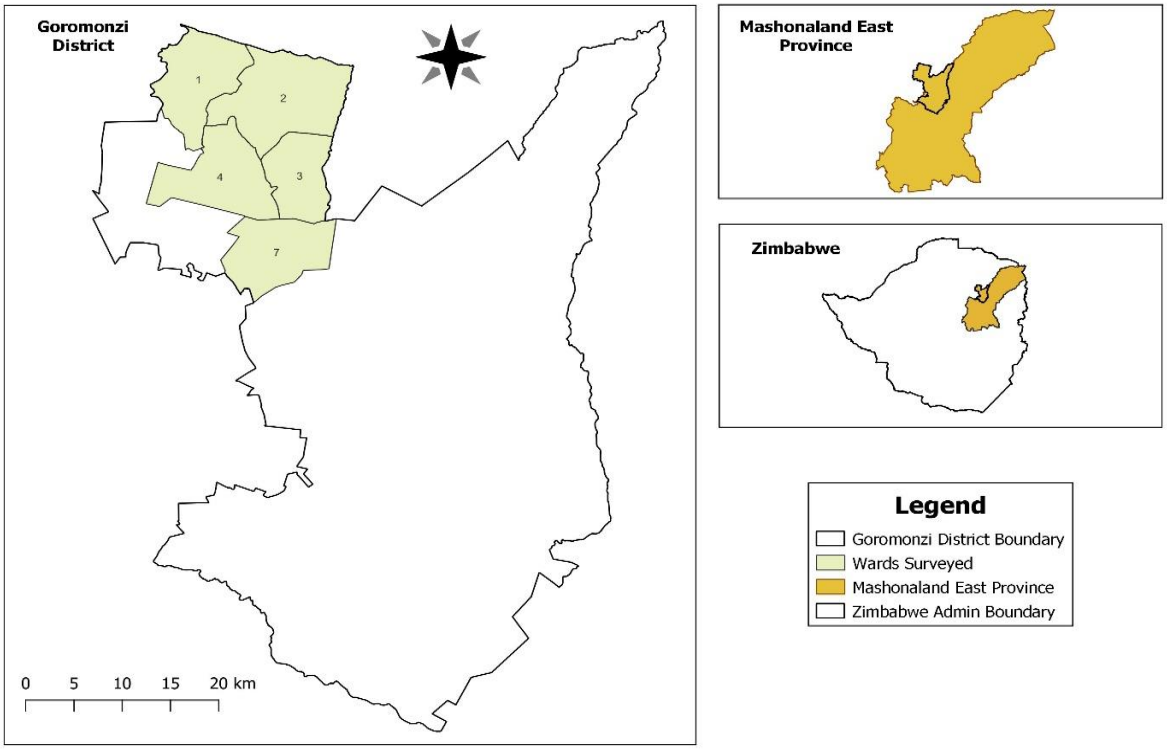


Figure 1. Goromonzi district and selected wards.

2.2. Data Sources

To identify and analyze the extreme climate challenges within the sweet potato farming sector in the Goromonzi District, a combination of reviewed, historical, qualitative and quantitative data was gathered. The study targeted sweet potato farmers, policymakers, and expert opinions from agronomists, economists, and gender specialists in Wards 1, 2, 3, 4, and 7. The Goromonzi District was strategically chosen for its historical association with sweet potato cultivation and its favorable climatic conditions. Specific wards were selected based on accessibility, and a random sampling method at the village level ensured diverse representation.

The reviewed literature on extreme climate challenges in the agricultural sector, particularly in the southern hemisphere, provided critical insights into the interplay of gender, climate resilience, and agricultural practices. These insights were further enriched by historical, qualitative, and quantitative data collected both remotely and onsite. Together, they laid the foundation for identifying and categorizing criteria indices to address challenges in sweet potato farming, with a specific focus on bridging the gender gap in climate-resilient agriculture. Based on this feedback, the study developed a framework comprising two levels of criteria indices.

Historical data were complemented by satellite imagery obtained from sensors such as MODIS and Landsat to generate the Vegetation Health Index (VHI), which monitors drought conditions. The datasets, sourced from the U.S. Department of State/Large Scale International Boundaries [39], included critical information on land surface temperature, vegetation cover, and rainfall patterns—key elements for assessing the impact of drought on agriculture. The analysis focused on a twelve-month period with a spatial resolution of 30 m.

Using Google Earth Engine (GEE), the study employed the VHI to evaluate vegetation health, carefully selecting cloud-free images to ensure accurate land surface depiction [40]. Landsat imagery from four satellites—Landsat 4 and 5 (28 images), Landsat 7 (26 images), and Landsat 8 (11 images)—was imported for analysis [28]. To maintain data integrity,

cloud masking techniques were applied before performing calculations for the Normalized Difference Vegetation Index (NDVI) and VHI. This remote sensing data provided critical insights into the vegetation and climatic conditions affecting sweet potato farming in Goromonzi. The study cross-validated the satellite data with ground-truth data collected during surveys or field visits.

To complement the geospatial data, supplementary datasets from the Humanitarian Exchange were utilized, offering valuable insights into local and regional road networks, transport infrastructure, and populated plateaus. These additional datasets enriched the broader context of the district's agricultural landscape, particularly in understanding the logistical and infrastructural limitations impacting sweet potato farming.

In addition to the satellite imagery and geographical data, Focus Group Discussions (FGDs) with stakeholders, including farmers, policymakers, and extension officers, revealed that sweet potato farmers in Goromonzi primarily face environmental and infrastructural/operational challenges. These challenges are often gender-oriented due to male-biased policies and entrenched cultural norms that disproportionately affect women farmers.

To investigate these issues further, the study identified 201 sweet potato farmers—116 women and 86 men—for a detailed survey. Data were collected using Kobo Collect, with a robust cleaning process to ensure the reliability and accuracy of the findings. Themes extracted from the FGDs, combined with insights from the reviewed literature and survey data, informed the identification of seven secondary challenges, which were analyzed using the Analytical Hierarchy Process (AHP). The identified challenges, depicted as criteria influencing sweet potato farming in Table 1, include:

Table 1. Criteria Definitions for Sweet Potato Production.

Series No.	Criteria	Acronym	Description
C1	Cultivation	C	This refers to the practice of propagating new plants from vine cuttings to develop new storage roots.
C2	Land Use	LU	Soil fertility and access to adequate plots for cultivation.
C3	Harvesting	H	Involves the optimal timing and techniques for harvesting sweet potatoes to maximize yield and quality.
C4	Marketability	M	Challenges in accessing fair markets and achieving competitive pricing for sweet potatoes.
C5	Road	R	The quality of rural roads and their impact on transportation.
C6	Vehicle	V	The availability and efficiency of vehicles for transporting sweet potatoes to markets or storage facilities.
C7	Weather and Climate Condition	WCC	The effect of local weather patterns and climate conditions on the growth and yield of sweet potatoes.

These diverse inputs provided a comprehensive understanding of the environmental, infrastructural, and operational challenges linked to sweet potato farming. The insights gained from both remote sensing and field-based data collection formed the basis for developing a structured framework to address these challenges. Figure 2 illustrates the research framework employed in this study, integrating data from geospatial analysis, FGDs, and surveys. This framework highlights the interconnection between environmental and operational factors, providing actionable insights for improving sweet potato farming systems. By addressing these challenges, the study aims to enhance productivity, bridge gender disparities, and foster resilience in the face of climate variability.

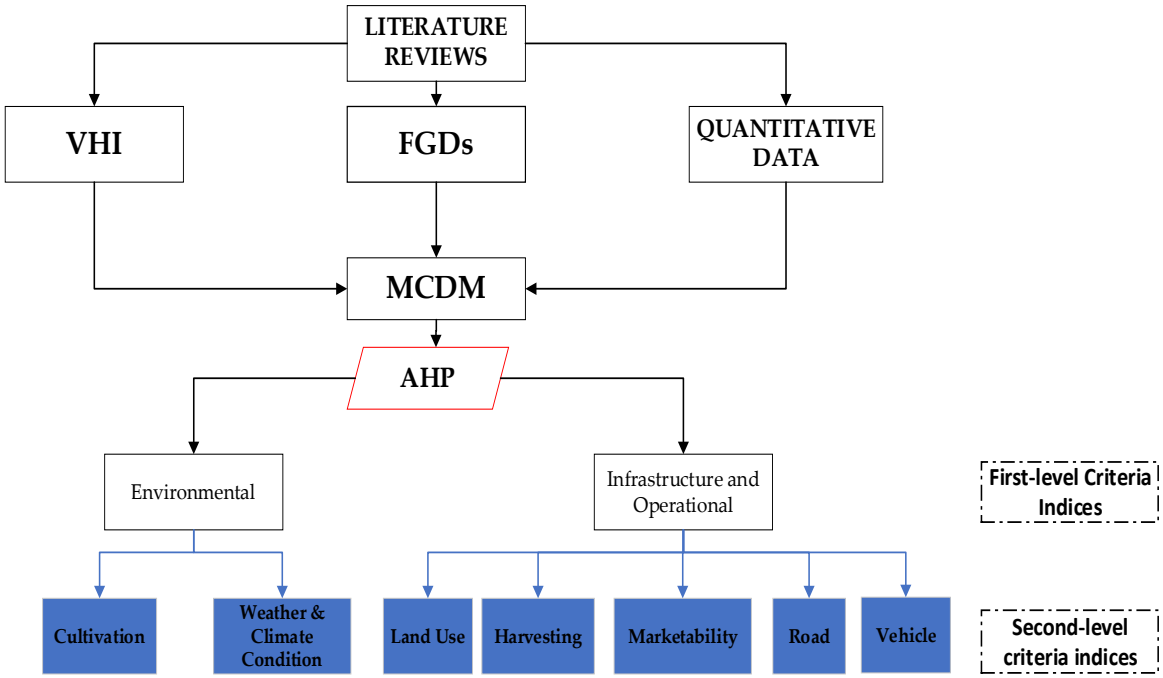


Figure 2. Framework for Evaluating Sweet Potato Production Using MCDM and AHP.

Additionally, the study will address challenges related to the timeliness and efficiency of harvesting, as delays often lead to reduced quality and yields. It will examine the availability of storage and processing infrastructure, critical for managing the bulky and perishable nature of sweet potatoes [14]. Furthermore, the research will assess issues of market access and pricing, identifying ways to empower farmers, especially women, to gain equitable opportunities in local and regional markets.

Key criteria indices impacting sweet potato production in Goromonzi informed the development of a Multi-Criteria Decision-Making (MCDM) framework, incorporating the Analytical Hierarchy Process (AHP) as previously employed by Munyaka and Yadavalli [41]. The approach followed these steps:

- Firstly, it delineated a series of criteria indices relevant to sweet potato production, setting these against alternatives within the context of available resources.
- Subsequently, through a detailed comparison of location-specific criteria using AHP, the study assigned weights (scores) to these criteria.
- Lastly, a comparative analysis was conducted between the sweet potato production criteria indices and their respective scores, utilizing a fuzzy MCDM approach.

MCDM, a methodological approach designed to facilitate decision-making when confronted with numerous, often conflicting criteria, was pivotal in identifying the attributes essential for sweet potato production. To ensure the precision of the model, it was critical that the selected criteria indices comprehensively covered all aspects of sweet potato production, from the identification of suitable soils to considerations of shipment and marketability. Furthermore, the indices were carefully chosen to directly reflect the dynamics of sweet potato production, with each criterion maintaining a degree of independence.

2.3. Data Analysis

The survey targeted 201 participants to analyze sweet potato production, the impact of drought, and community resilience. Data processing and analysis were conducted using Python 3.12, with a focus on frequency distributions to identify missing data and cross-tabulations to explore gender-based responses to drought.

A comprehensive data preprocessing phase ensured data integrity, utilizing Python's Pandas and SciPy libraries for imputation, outlier detection, and validation. Key variables analyzed included vine color, land size, and proximity to water sources.

A Likert scale was employed to quantify the relative importance of criteria such as cultivation techniques, climate conditions, and market access. These criteria were then weighted within the Multi-Criteria Decision-Making (MCDM) process for further analysis.

2.3.1. VHI

The *VHI*, a critical indicator of drought conditions, is computed by combining *NDVI* and Land Surface Temperature (*LST*) values. The *NDVI* calculation utilizes reflectance values from red and near-infrared bands as follows:

$$NDVI = {}^{(Red - NIR)}/_{(Red + NIR)} \quad (1)$$

Here, *NDVI* values range from -1 to 1, indicating the density of plant growth where higher values suggest healthier vegetation. *NDVI* data are derived from the "Landsat Surface Reflectance" of scenes captured by Landsats 4–9, processed into Landsat Level-2 Surface Reflectance products. The infrared data corresponds to band number 4 in Landsats 4, 5, and 7, and band number 5 in Landsat 8.

The *VHI* incorporates measures of vegetation cover, land surface temperature, and rainfall data. Following the methodologies developed by Ghaleb et al. [42] and Bento et al. [43] and applied by Munyaka et al. [40], the Vegetation Condition Index (*VCI*) and the Temperature Condition Index (*TCI*) are calculated and combined to form the *VHI* using these equations:

$$VCI = 100 \times (NDVI - NDVI_{min})/(NDVI_{max} - NDVI_{min}) \quad (2)$$

$$TCI = 100 \times (LST_{max} - LST_c)/(LST_{max} - LST_{min}) \quad (3)$$

$$VHI = 0.5 \times VCI + 0.5 \times TCI \quad (4)$$

where $NDVI$, $NDVI_{min}$, and $NDVI_{max}$ represent the seasonal average of the smoothed weekly $NDVI$, its multiyear absolute minimum, and its maximum, respectively, and LST_c, LST_{min}, and LST_{max} represent similar values for the land surface temperature in Celsius.

These calculations provide a *VHI* value ranging from 0 to 100, where higher scores indicate more robust vegetation health. Annual aggregation of *VHI* values, starting from 1990, was conducted to identify long-term drought trends within the targeted wards. The gathered data were visualized through charts, maps, and time series plots to examine vegetation health trends over time, with subsequent statistical and spatial analysis to interpret these trends.

Land Surface Temperature (*LST*) acts as a gauge for the Earth's surface temperature [44]. For Landsats 4, 5, and 7, thermal band six is used, whereas Landsat 8 utilizes bands 10 and 11, with a preference for band 10 due to calibration issues with band 11. These sensors measure top-of-the-atmosphere radiances, allowing for the calculation of brightness temperatures.

The *VHI* values were then classified into categories representing different levels of drought severity to evaluate agricultural impacts. This classification system, detailed in Table 2, ranges from extreme to no drought, providing a structured framework for assessing drought's effect on agriculture.

Table 2. Drought classification for VHI values.

Drought	Values
Extreme	<10
Severe	≥10, <20
Moderate	≥20, <30
Mild	≥30, <40
No	≥40

2.3.2. Multi Criteria Decision-Making Model

1. Selection of criteria indices

In the quest to identify the key attributes relevant to sweet potato cultivation in Goromonzi, Zimbabwe, the study utilized a combination of literature review and quantitative analysis. Figure 3 offers a detailed depiction of the production system, with first-level criteria indices focusing on environmental, infrastructure, and operational factors. The second-level criteria indices span the entire production process, from cultivation to marketability.

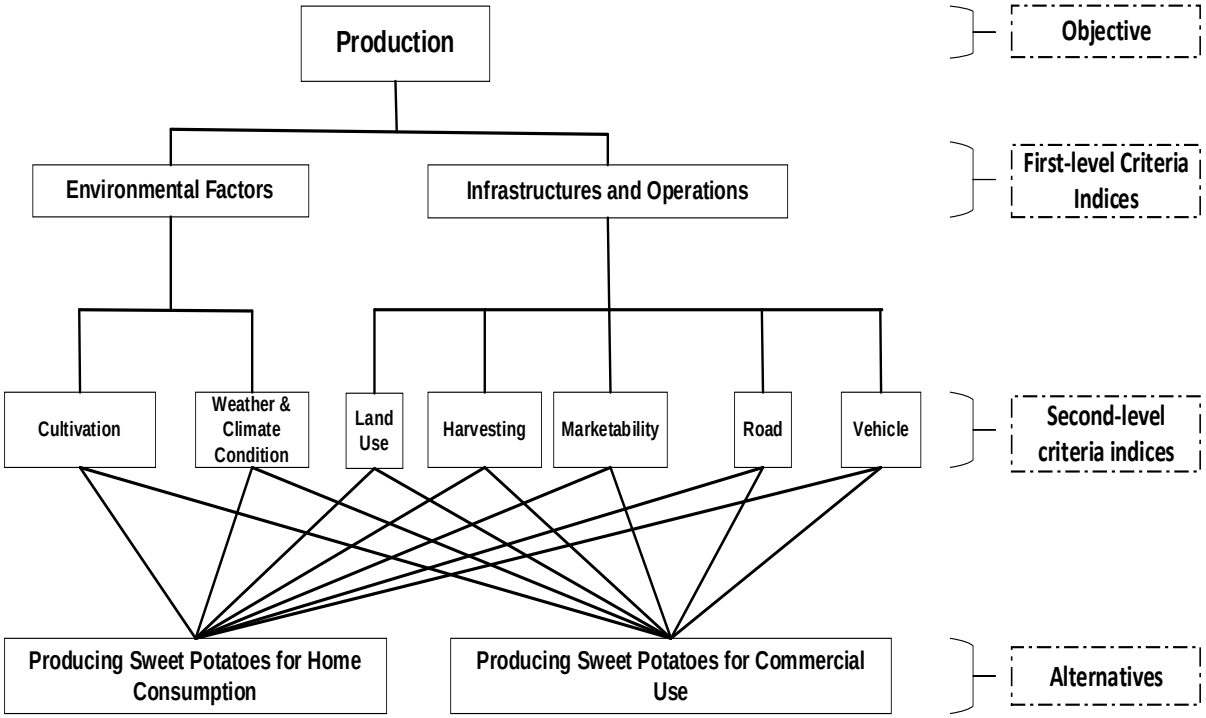


Figure 3. Sweet Potatoes production Criteria and Alternatives.

The first-level criteria indices, mentioned in Figure 2, highlight broad challenges affecting sweet potato production, focusing on environmental and infrastructural/operational factors. Climate change exacerbates extreme weather events such as droughts, erratic rainfall, and rising temperatures, which disrupt planting and harvesting schedules in semi-arid regions like Goromonzi [17,45].

Infrastructural and operational challenges, such as poor road networks and limited transportation options, further hinder the timely delivery of sweet potatoes to markets, particularly during the rainy season. Women farmers, often lacking access to vehicles, face disproportionate disadvantages in accessing markets [46].

The second-level criteria indices delve into specific components of the production process, offering a detailed view of challenges and opportunities. The study will evaluate the availability of high-quality, drought-resistant sweet potato varieties, a crucial factor in improving productivity. Limited access to these improved seeds, particularly for women farmers, remains a significant constraint [33]. It will also explore the role of women in cultivation, focusing on their access to resources and decision-making opportunities.

2. Weighting the criteria indices

In determining the weightage of criteria indices for this study, decision weightage, pivotal in Multi-Criteria Decision-Making (MCDM), was followed by constructing a decision matrix. The application of the fuzzy Analytical Hierarchy Process (f-AHP) was instrumental in computing the weightage of each criterion, translating these criteria into linguistic terms using Triangular Fuzzy Numbers (TFNs) for pairwise comparison matrices.

a. Utilization of Triangular Fuzzy Numbers (TFNs)

TFNs are preferred for their simplicity in calculations, defined by a triplet $(l,\ m,\ u)$ representing the lower, mean, and upper values, respectively [47,48]. The membership function of TFN "A", $\mu_A(x)$, is determined by the Equation (5):

$$\mu_A(x) = \begin{cases} \frac{x-l}{m-l}, & l \le x \le m \\ \frac{u-x}{u-m}, & m \le x \le u \\ 0 \quad otherwise \end{cases} \tag{5}$$

where "x" is the mean value of "A" and $(l,\ m,\ u)$ are real numbers. Two TFNs "A" and "B" are defined by the triplets $A = (l_1, m_1, u_1)$ and $B = (l_2,\ m_2,\ u_2)$ [49].

b. Formulating f-AHP Comparison Matrices

The study adopted a modified synthetic extent approach to f-AHP to address the inherent uncertainties in decision-making, as initially proposed by Chang [48] and further developed by Zhu et al. [50]. Saaty presents the linguistic variables and corresponding TFNs based on a standard 9-unit scale, facilitating the pairwise comparisons essential to f-AHP [51].

This study utilizes modified synthetic extent f-AHP, which was originally introduced by Chang [48] and developed by Zhu et al. [50]. The incompleteness of the synthetic extent f-AHP reflects its suitability in decision problems where uncertainty exists in the decision-making process [49]. The standard 9-unit scale linguistic variables from the Linguistic terms and corresponding TFN was used to make the pairwise comparisons [51]. The values deriving from a pre-defined set of ratio scale values serves to describe the pairwise comparisons [49].

c. Evaluating Fuzzy Synthetic Extent

The value of the fuzzy synthetic extent, S_i, regarding each *ith* criterion is calculated using the fuzzy synthetic extent method in Equation (6). This involves summing the TFNs for each criterion across all decision alternatives and then applying fuzzy arithmetic to find the inverse.

$$S_i = \sum_{j=1}^{m} M^j C_i \left[\sum_{i=1}^{n} \cdot \prod_{j=1}^{m} M^j C_i\right]^{-1} \tag{6}$$

where (.) represents fuzzy multiplication and the superscript (-1) represents the fuzzy inverse [49]. Let $C = \{C_1,\ C_2,\ \ldots,\ C_n\}$ be a N decision criteria set, where n represents the number of criteria and $A = \{A_1,\ A_2,\ \ldots,\ A_m\}$ be a M decision alternative set, where m is the number of decision alternatives. Let M^1C_i, M^2C_i, M^mC_i, $i = 1,\ 2,\ \ldots,\ n$ where all the M^jC_i $(j = 1,\ 2,\ \ldots,\ m)$ are TFNs.

3. Calculating f-AHP Weighted Values

To ascertain the weighted values for each criterion, the study applied principles of fuzzy number comparison, a mathematical approach widely used in decision-making frameworks to handle uncertainty and subjectivity in data. This method evaluates the degree of possibility that one fuzzy number is greater than another, calculated by determining the supremum of the minimum membership functions of the two fuzzy numbers. By considering sets of weight values under each criterion, the fuzzy comparison framework ensures that the analysis remains robust and comprehensive, even when data inputs are imprecise or uncertain [48].

In this study, the weights assigned to each criterion were derived from a diverse range of data sources. These include insights from reviewed literature on agricultural activities relevant to the identified criteria, expert input obtained through focus group discussions (FGDs), historical data such as geospatial and satellite imagery, and quantitative data collected from surveys targeting sweet potato farmers in Goromonzi. This multi-faceted approach ensures that the weighted values are grounded in both empirical evidence and expert judgment, enhancing the reliability of the results.

As an example, for two fuzzy numbers, M_1 and M_2, the degree of possibility that $M_1 \geq M_2$ is defined Equation (7) as follows:

$$V(M_1 \geq M_2) = \underset{x \geq y}{\mathrm{SUP}}[\min(\mu M_1(x),\ \mu M_2(y))] \tag{7}$$

where $\mu M_1(x)$ and $\mu M_2(y)$ represent the membership functions of fuzzy numbers M_1 and M_2, respectively. The supremum, sup, with $V(M_1 \geq M_2) = 1$, identifies the maximum value of the minimum membership functions across the fuzzy set. This approach allows for a systematic and transparent assessment of the relative importance of criteria under varying conditions.

Since M_1 and M_2 is defined by the TFNs (l_1, m_1, u_1) and (l_2, m_2, u_2), respectively, it follows in Equation (8):

$$\begin{gathered} V(M_1 \geq M_2) = 1\ iff\ m_1 \geq m_2 \\ V(M_1 \geq M_2) = hgt(M_1 \cap M_2) = \mu M_1(X_d) \end{gathered} \tag{8}$$

where iff signifies 'if and only if', while d is the ordinate of the highest intersection point between the μM_1 and μM_2 TFNs, and x_d is the point in the domain of μM_1 and μM_2 where the ordinate d is found. The term hgt is the height of fuzzy numbers on the intersection of M_1 and M_2. For $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$, the possible ordinate of their intersection is given by Equation (9). This Equation determines the degree of possibility for a fuzzy number:

$$V(M_1 \geq M_2) = hgt(M_1 \cap M_2) = \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} = d \tag{9}$$

To obtain the degree of possibility for a convex fuzzy number M to be greater than the number of k fuzzy numbers M_i $(i = 1, 2, \ldots, k)$, the use of the operations max and min is needed [52] and is defined in Equation (10) by:

$$\begin{aligned} V(M \geq M_1, M_2, \ldots, M_k & \\ &= V[(M \geq M_1)\ and\ (M \geq M_2) and \ldots and\ (M \geq M_k)] \\ &= \min V(M\ \geq M_i).i \\ & \qquad = 1, 2, \ldots, k \end{aligned} \tag{10}$$

Assuming $d'(A_1) = \min V(S_1 \geq S_k)$, where $k = 1, 2, \ldots, n,\ k \neq i$ and n is the number of criteria. A weight vector in Equation (11) is given by:

$$W' = \left[d'(A_1),\ d'(A_2), \ldots, d'(A_m)\right] \tag{11}$$

where A_i $(i = 1,\ 2, \ldots, m)$ are the m decision alternatives. Each $d'(A_1)$ as illustrated in Equation (12) represents the preference of each decision candidate and W' as vector is nomalised as follows:

$$W' = [d(A_1),\ d(A_2), \ldots, d(A_m)] \tag{12}$$

If two fuzzy numbers, $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$, in a fuzzy comparison matrix satisfy $l_1 - u_2 > 0$, then $V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(x_d)$, where $\mu_{M_2}(x_d)$ is illustrated by Zhu et al., [50] as shown in Equation (13):

$$\mu_{M_2}(x_d) = \begin{cases} \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)},\ l_1 \leq u_2 \\ 0, \quad otherwise \end{cases} \tag{13}$$

By integrating fuzzy number comparison with the data-driven weighting process, as previously outlined by Thokala [53] and Munyaka and Yadavalli [41], the study ensures that each criterion is evaluated, accounting for the complexity and uncertainty inherent in agricultural systems and climate variability. This framework lays the foundation for a decision-making process that supports sustainable sweet potato farming in Goromonzi.

3. Results

3.1. Multi-Criteria Decision-Making Model

3.1.1. Definition of Drought Impacts on Sweet Potato Production in Zimbabwe

Drought significantly disrupts sweet potato growth in Zimbabwe, leading to reduced yields and compromised crop quality, impacting food security and household incomes [14,15]. Recurrent droughts degrade arable land, increasing costs for alternative water sources and drought-resistant varieties, further straining smallholder farmers [8,10]. Integrated drought management strategies, including efficient water use and promotion of drought-tolerant varieties, are essential for sustaining agricultural productivity [6].

3.1.2. Weightage of Sweet Potato Production Criteria

The fuzzy Analytical Hierarchy Process (f-AHP) technique employs pairwise comparisons to evaluate the relative importance of each criterion, offering a systematic way to assign weights based on their significance. This approach is further enhanced by survey results, which provide empirical data to validate and support the assignment of weights. The mixed-methods approach enables an in-depth examination of how various stakeholders—farmers, agricultural experts, and policymakers—perceive the importance of each criterion in the context of drought response in sweet potato production.

By integrating a literature review, expert insights, and survey data, the study showcases the weighted percentages and rankings derived from the f-AHP calculations [37]. This integration not only strengthens the reliability of the findings but also highlights the nuanced differences in stakeholder perspectives. The normalization of the comparison matrix from the f-AHP process, as shown in Figure 4, reveals that "Weather and Climate Conditions" (C7) emerge as the most critical environmental criterion influencing sweet potato production for both male and female farmers. This observation aligns with the findings of Smith et al. [17], which emphasize the profound impact of environmental conditions on agricultural productivity [17].

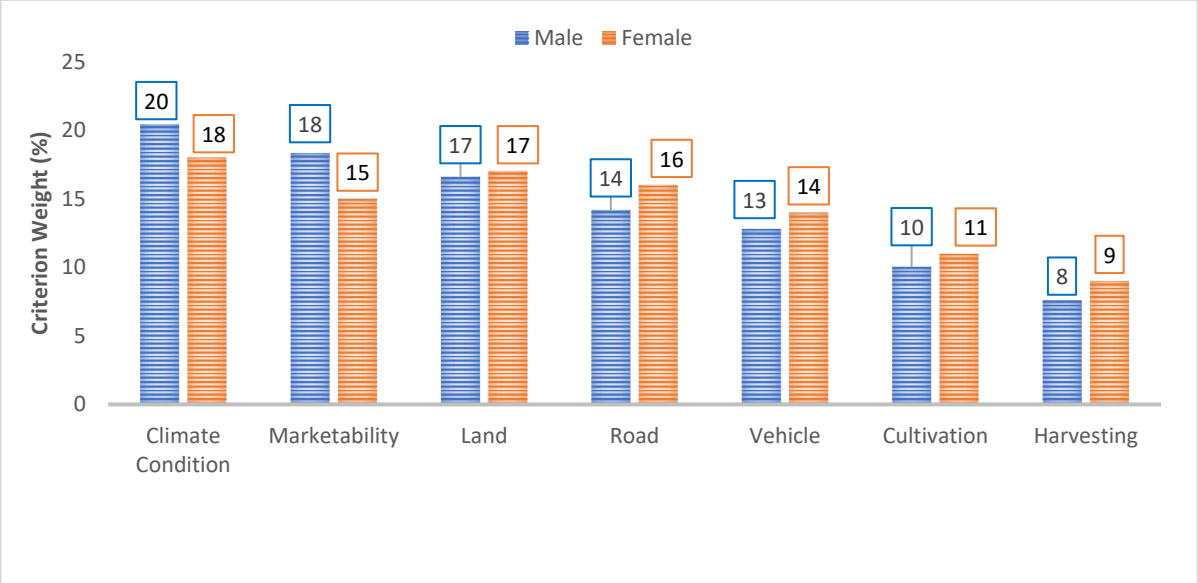


Figure 4. Sweet Potatoes challenges ranking.

The f-AHP analysis also uncovers gender-specific challenges within sweet potato farming. For instance, "Marketability" (C4) ranks as the most significant operational challenge for male farmers, highlighting struggles in accessing fair markets and achieving competitive pricing for their produce. Conversely, for female farmers, "Land Access" (C2) is identified as the most critical infrastructural and operational factor, reflecting the systemic barriers women face due to historical land policies and cultural norms.

3.1.3. Determination of Scores for Sweet Potato Production Criteria

- Environmental Criteria: Cultivation and Weather/Climate Change

Despite Goromonzi's favorable agro-ecological conditions, climate variability remains a significant risk, highlighting the need for sustainable cultivation practices and the adoption of drought-resistant sweet potato varieties to ensure resilience [8,14]. An analysis of satellite imagery using the Vegetation Health Index (VHI) revealed a trend of increasing drought severity between 1990 and 2005 (see Figure 5). The 1992 drought, in particular, had a devastating impact on agriculture, severely affecting crop yields and food security in the region [4].

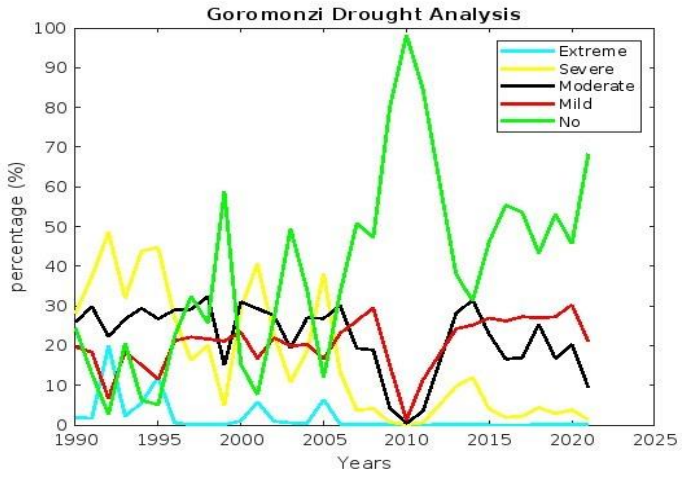


Figure 5. VHI analysis of Drought dataset between 1990 to 2021.

The geographic coordinates of the surveyed farmers were mapped across the targeted wards in Goromonzi District. Symbology was applied to satellite imagery from 1990 to 2020 to classify drought conditions ranging from "no drought" to "extreme drought". Figure 6 illustrates the spatial and temporal distribution of drought severity within the study area, providing a clear visualization of the evolving climatic conditions.

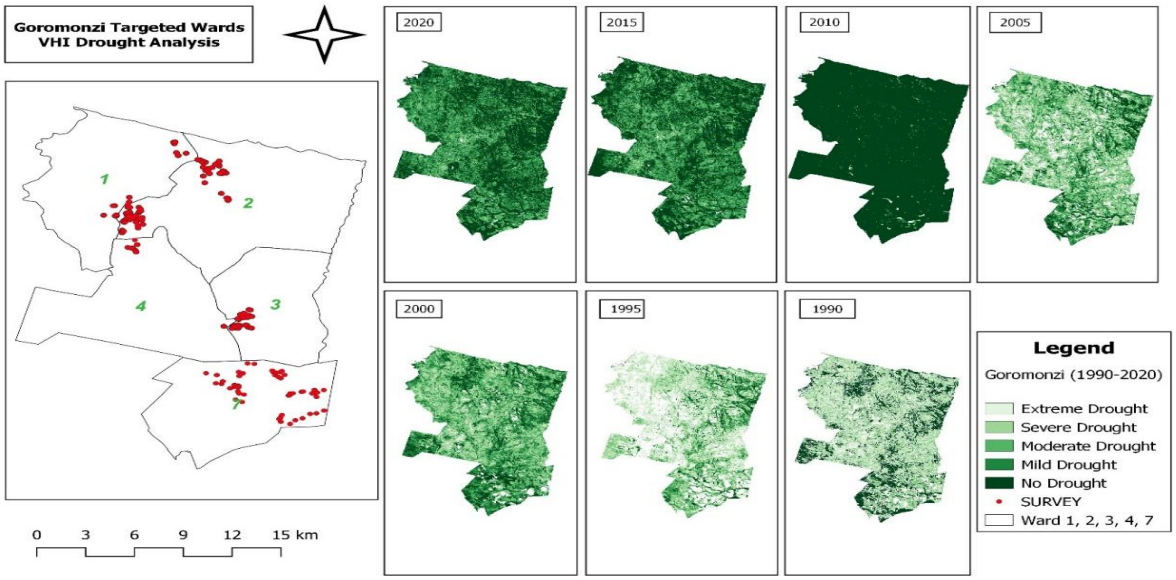


Figure 6. VHI variations in Goromonzi (Ward 1, 2, 3, 4, 7) between 1990–2020.

The analysis confirms that the years 1990 and 2005 experienced the highest severity of drought conditions, with Wards 1, 3, and 4 identified as the most affected. These findings underscore the vulnerability of specific areas within Goromonzi District to climate variability.

Further analysis of sweet potato cultivation from 2021 to 2023 indicated a decrease in instances of extreme (0.03%), severe (1.39%), and moderate (9.29%) drought conditions, alongside an increase in periods without drought (68.3%) (see Figure 7).

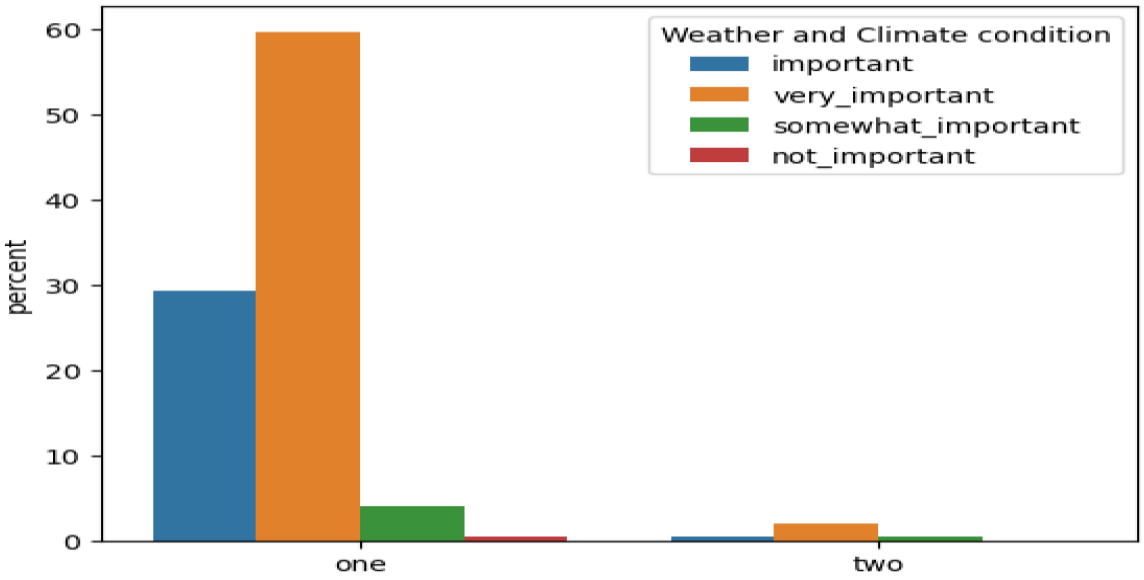


Figure 7. The number of planting seasons for Sweet Potatoes Among Farmers in the last three years.

Furthermore, farmers who identified "Weather and Climate Conditions" as "very important" were surveyed to determine how frequently they plant sweet potatoes each

year. Figure 7 shows that the majority of farmers opt to cultivate sweet potatoes once annually, primarily during the summer months, which coincides with the rainy season.

This preference reflects farmers' reliance on natural rainfall and their concern about insufficient water availability during the dry season. The limited use of irrigation systems and the absence of sustainable farming practices further exacerbate these concerns, leaving farmers vulnerable to unpredictable weather patterns and climate variability.

- Infrastructural and Operational Criteria: Land Use, Harvesting, Road Access, Vehicle Availability, and Marketability

Land access remains a critical challenge, particularly for female farmers who face significant disparities in land ownership and resource access. As a cornerstone of farming, land access is fundamental to agricultural productivity and resilience, with its importance reflected in its high ranking among key challenges [8]. Fair distribution and secure usage rights are essential to enable farmers, particularly women, to maximize their production capacity and contribute to household food security and economic stability.

Having access to land not only allows farmers to produce sufficient quantities for both consumption and sale but also helps them mitigate risks associated with climate variability. However, survey results reveal a pronounced gender disparity in land ownership. Despite women comprising 57.21% of survey participants, compared to 42.78% for men, male farmers hold larger land areas on average (see Figure 8). This imbalance underscores the systemic barriers that limit women's access to agricultural resources, perpetuating inequalities in farming opportunities and outcomes.

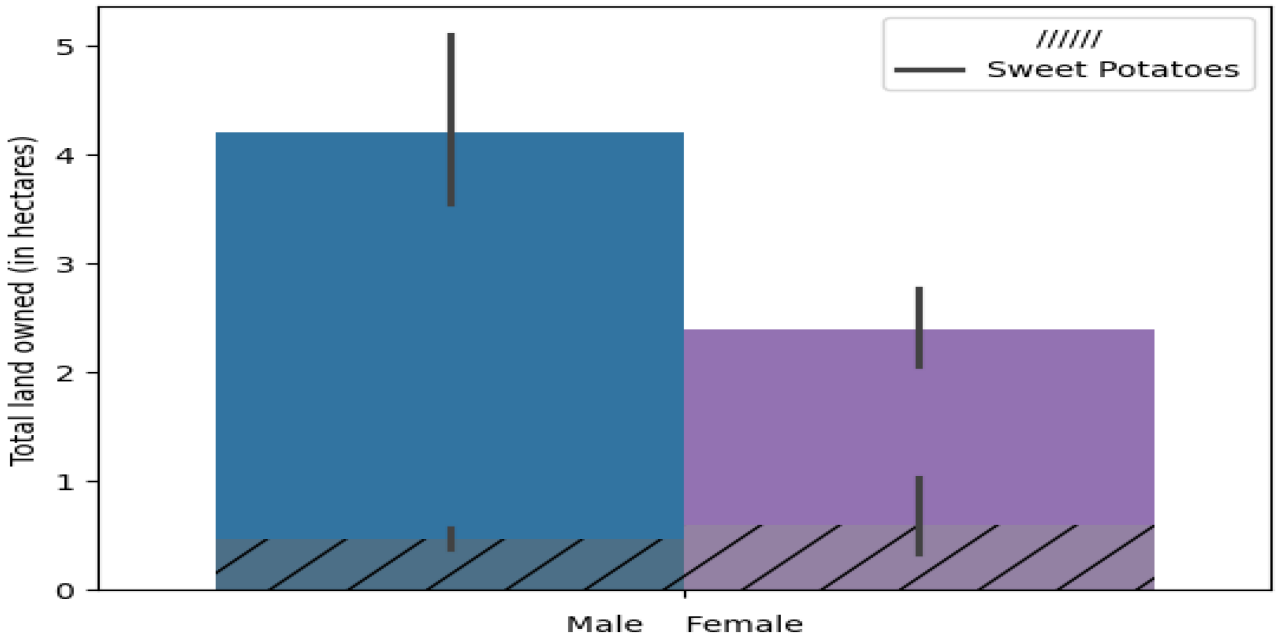


Figure 8. Total land owned (in hectares) by male and female.

Additionally, Figures 9 and 10 indicate that farms operated by women are often located further from water sources than those managed by men, highlighting another layer of disparity in agricultural practices.

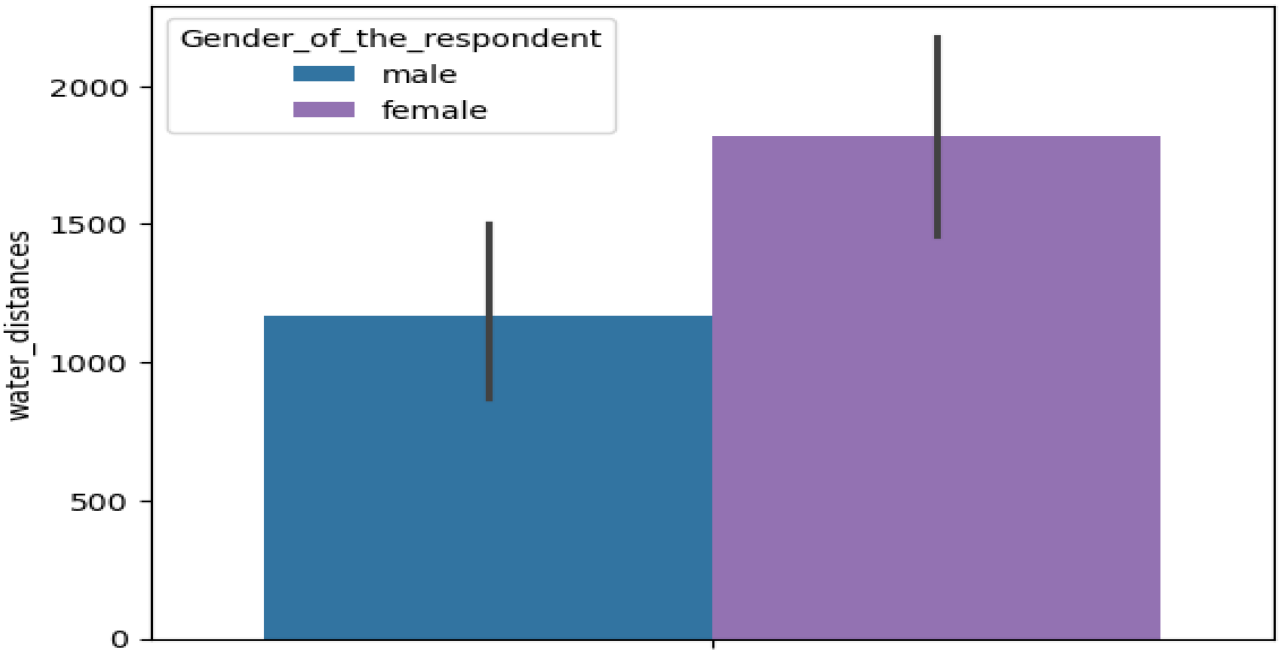


Figure 9. Distance between the Farm and the Water source (in meters).

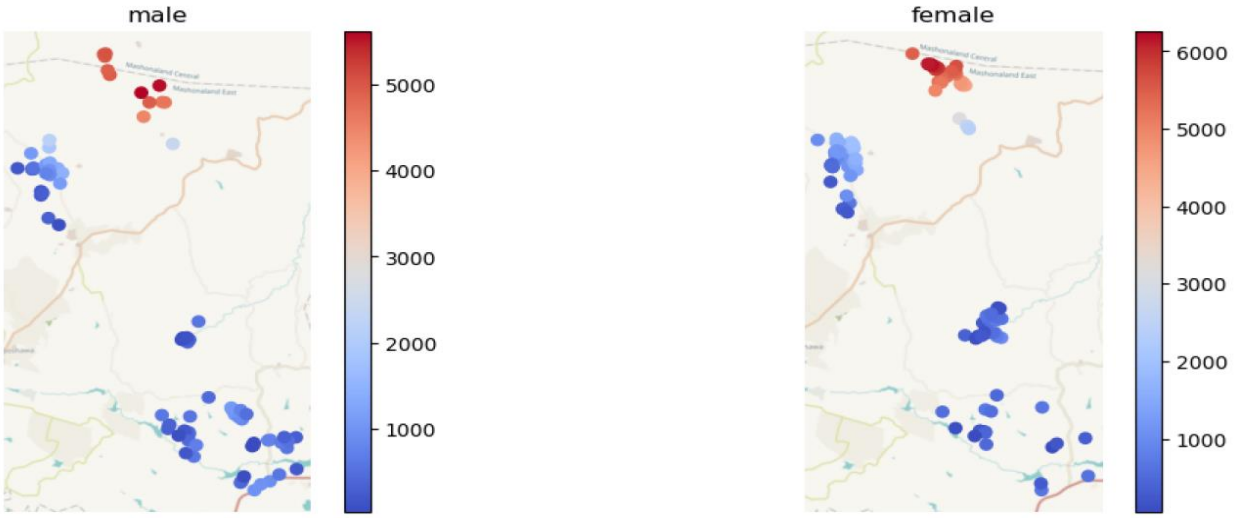


Figure 10. Mapping of the location of Farm and the water source (in meters).

The greater distance from water sources (shown in the increasing orange color in Figure 10) increases the farms' vulnerability to drought, critically limiting irrigation and severely reducing crop yields and productivity. Women who often rely more on rain-fed agriculture face heightened challenges during dry periods, threatening food security and intensifying economic strain on households. This situation highlights the urgent need for targeted interventions to ensure equitable access to essential resources in drought-prone regions [9,14].

Land access presents an additional challenge in harvesting sweet potatoes, with women often constrained to rely on additional labor during extreme climate conditions. Limited access to labor and mechanized tools further exacerbates the difficulty, making the harvesting process significantly more labor-intensive for women farmers [16]. The survey results highlighted a notable difference in access to labor between male and female farmers. Specifically, over 34% of the female farmers surveyed reported having fewer than three individuals available to help with harvesting, while an equivalent percentage of male

farmers reported having the assistance of more than five people, with some having access to up to 20 helpers during the harvest period (see Figure 11). Furthermore, the survey also revealed differences in the types of equipment utilized by farmers for harvesting. While hoes and mattocks are universally used by all farmers, male farmers demonstrated greater access to mechanized tools such as tractors, moldboard plows, and wheelbarrows. Conversely, female farmers in Goromonzi showed a higher usage of Scotch carts, which are considered a more traditional means of harvesting, largely due to financial constraints, lack of ownership, or societal norms that prioritize technological investments for men [16]. These disparities make harvesting more labor-intensive and time-consuming for women.

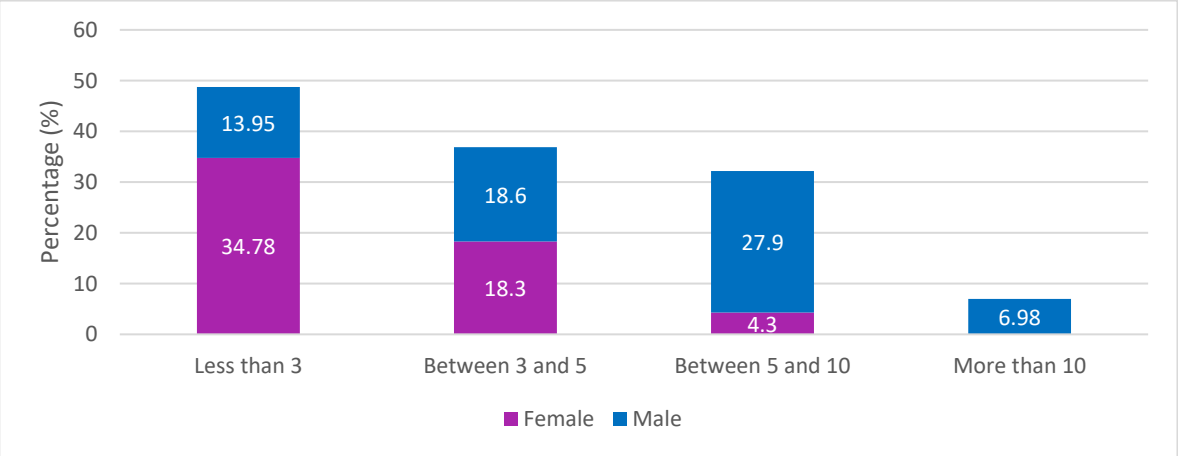


Figure 11. Labor use during Cultivation and Harvesting in Goromonzi district (%).

Storage practices for harvested sweet potatoes also exhibit notable differences between male and female farmers. A significant portion of male farmers (46.51%, compared to 21.73% of female farmers) do not store their sweet potato produce, opting instead to transport it directly to market due to available transportation means. In contrast, female farmers, facing challenges with access to transport services, more frequently adopt traditional storage methods. This includes digging a hole (48.69% of female farmers compared to 30.23% of male farmers) near their homes, treating it with ashes, and then storing sweet potatoes for up to six months.

Road access and vehicle availability also represent a significant barrier, particularly for women, affecting market access and profitability [9]. In Goromonzi, poor infrastructure hinders transportation to markets, disproportionately affecting women who rely on footpaths and tracks. Female farmers face additional barriers, including limited mobility and market access, which widen income disparities. Poor road conditions exacerbate these challenges during droughts, leading to increased spoilage and reduced income, particularly for women [17]. Furthermore, Male farmers have better access to vehicles, giving them an advantage in transporting produce. During droughts, transportation costs rise, further straining small-scale farmers, especially women [15].

Marketability is another key challenge. Gender inequalities in infrastructure and market access favor men [9], forcing women to rely on middlemen, reducing their earnings [6]. Droughts worsen these challenges by lowering yields and increasing transportation costs, particularly for female farmers [17]. Additionally, increased transportation costs during droughts worsen profitability, especially for female farmers who already struggle with access to efficient transport [14].

3.2. Enhancing Gender-Inclusive Strategies for Mitigating Drought Impacts on Sweet Potato Production

3.2.1. Environmental Level

At the environmental level, factors influencing sweet potato production include cultivation practices, climate variability, and drought resilience. To mitigate drought impacts on sweet potato production, gender-inclusive strategies are essential for ensuring equitable access to resources such as climate-resilient farming techniques, quality seeds, and extension services. Empowering women in agriculture not only enhances overall productivity but also fosters resilience in farming communities [54,55]. Sweet potatoes are uniquely suited to diverse soil types, including marginal ones, and are highly adaptable to drought conditions, making them an invaluable crop in regions prone to climate variability [54]. With a relatively short growing season of 3–5 months, they allow for multiple cropping cycles, enabling farmers to diversify production and maximize land use across seasons. Furthermore, the use of sweet potato vines as planting material offers an economical and practical method of propagation, reducing input costs while promoting sustainable practices [56].

Despite advances in sweet potato production in Zimbabwe, particularly with the introduction of improved practices and new varieties, women farmers continue to face systemic barriers. Limited access to resources such as land, quality inputs, and agricultural training often restricts their ability to fully engage in and benefit from sweet potato cultivation. Integrating gender perspectives into national frameworks such as the National Climate Policy and National Adaptation Plan (NAP) is critical to ensuring that adaptation strategies address the needs of all farmers, especially women. Empowering women through targeted training in climate-smart practices and equitable resource distribution strengthens community resilience to climate challenges [57]. Institutional support for gender-sensitive agricultural initiatives is crucial for their effectiveness in addressing climate change impacts. By fostering synergies between gender equality, climate resilience, and sustainable development, Zimbabwe can advance its climate goals while promoting inclusive and sustainable agricultural practices nationwide [58].

A gender-inclusive approach to sustainable sweet potato production significantly contributes to the resilience of farming communities in the face of climate change. By providing equitable access to resources, training, and decision-making opportunities, regardless of gender, the potential of sweet potato cultivation as a climate-smart agricultural solution is maximized [55]. For example, empowering women farmers with knowledge and resources to adopt climate-resilient sweet potato varieties, such as orange-fleshed sweet potatoes, and water-saving techniques not only improves their livelihoods but also enhances the overall resilience of farming systems [59]. Standardizing crop varieties within the community can enhance pest and disease management. By encouraging farmers to grow the same crop varieties, synchronization in planting and harvesting is achieved, allowing for better collective action against pests. Additionally, establishing a community fund for collective pest control purchases can further reduce costs and ensure timely treatments.

In the Goromonzi District, inconsistent rainfall has made sweet potato planting activity vulnerable to drought spells. The reliance on seasonal rainfall makes irrigation infrastructure critical for climate-resilient sweet potato farming. Initiatives like the Kunzwi Dam project aim to address water scarcity, but many smallholder farmers, particularly women, still lack access to irrigation systems [60]. Cooperation among neighbors can extend to essential resources like water. By drilling a borehole for irrigation and domestic purposes, communities can improve their sweet potato agricultural outputs and ensure a reliable water supply. The establishment of demonstration plots on communal land with a reliable

water source allows farmers to experiment with different crops and production techniques, sharing insights and successes.

3.2.2. Infrastructure and Operational Level

Infrastructure and operational challenges significantly affect the scalability and sustainability of sweet potato production in Zimbabwe, particularly in areas such as land use, access, transportation, and market reach. These challenges are compounded by gender disparities and systemic barriers, which hinder equitable participation and productivity in the sector.

Disparities in land ownership play a critical role in limiting sweet potato production. Cultural norms in Zimbabwe have historically limited women's access to land ownership [61]. This marginalization is evident in rural areas, where women's access to land is typically mediated through male relatives, restricting their economic independence and decision-making power [22,61]. Gender-biased policies, coupled with ineffective legal reforms such as the Fast-Track Land Reform Programme (FTLRP) in Zimbabwe, perpetuate unequal rights, leaving women with limited access to arable land [62]. Addressing these barriers requires gender-inclusive strategies that promote equitable land ownership, simplify land registration processes for women, and encourage community-level dialogues to challenge patriarchal norms. Empowering women through education, legal support, and community engagement is essential to overcoming the cultural barriers that hinder their access to land and, by extension, their contributions to agricultural productivity and economic development. These measures are essential for empowering women and ensuring they have equal opportunities to contribute to and benefit from agricultural activities.

Furthermore, improving road infrastructure and transportation services is crucial to enhancing the sweet potato supply chain. The Zimbabwe National Road Administration (ZINARA) oversees the country's extensive road network of approximately 88,100 km, but nearly 70% of these roads are in poor condition, particularly in rural areas. Transportation becomes especially challenging during the rainy season, exacerbating logistical constraints for farmers [63].

Upgrading rural transport systems should be prioritized, with gender-inclusive strategies ensuring women farmers have access to affordable and reliable transportation. Support for women's cooperatives to secure financing for vehicles and shared transport systems can significantly reduce logistical barriers and boost their economic participation. Additionally, targeted interventions in peri-urban areas like Domboshava—where rural communities are transitioning to urban markets—can help facilitate smoother access to both resources and consumers, enhancing the overall efficiency of the supply chain [24].

Gender-specific barriers further hinder women's ability to participate in and benefit from sweet potato production, particularly in accessing markets. Women face challenges such as limited transport options, inadequate infrastructure, and lower bargaining power in market settings. Addressing these issues involves connecting women farmers to market associations, providing training in negotiation skills, and ensuring equitable pricing mechanisms for their produce [64]. Smallholder farmers, especially women, often rely on intermediaries to sell their produce, leading to reduced earnings. Strengthening direct market linkages and establishing cooperatives can empower farmers and ensure fair pricing [64]. Collective selling initiatives can greatly improve women farmers' market access and profitability. Establishing cooperatives allows farmers to pool resources, enhance bargaining power, and lower individual marketing costs. Regular market days and aggregation centers further streamline sales by attracting buyers to central locations, reducing costs, and fostering community among sellers. Group transport to markets also helps farmers share costs, secure discounts, and boost overall profitability.

Systemic challenges also affect all farmers, including the lack of regulations for pesticides, fertilizers, and quality standards, which complicates market access [65]. The bulkiness and perishability of sweet potatoes, coupled with inadequate storage and transport facilities, often force farmers to sell at lower prices through intermediaries, significantly reducing profitability [65,66]. Investments in post-harvest infrastructure—such as cold storage facilities and processing units—are critical to improving the shelf life and market value of sweet potatoes. These investments would allow farmers to retain more value from their produce and reduce post-harvest losses [67,68].

Addressing these interconnected challenges at the infrastructure and operational level is key to ensuring sustainable sweet potato production in Zimbabwe. Prioritizing gender inclusivity in these efforts ensures that advancements benefit all stakeholders, particularly women, who are often underrepresented in the agricultural sector but are essential to its success. By improving land access, transportation, market connectivity, and post-harvest management, sweet potato farming can become a viable pathway to achieving food security, economic equity, and climate resilience in Zimbabwe.

Sweet potatoes are bulky and perishable, and the lack of cold storage facilities leads to significant post-harvest losses. Investments in local processing units, such as those converting sweet potatoes into flour or chips, can enhance marketability and reduce waste [14].

3.2.3. Extension Services

Agricultural extension services are crucial for enhancing the productivity of crops like sweet potatoes, especially in the context of drought. These services provide farmers with essential knowledge, skills, and resources to improve farming practices and optimize yields, which is particularly important during periods of drought [69]. In sweet potato farming in Goromonzi, agricultural extension supports farmers by offering training on various aspects of sweet potato cultivation. This includes land preparation, planting techniques, irrigation methods, pest and disease management, and harvesting practices [70]. By imparting such knowledge and skills, extension services enable farmers to adopt best practices, mitigate the impacts of drought, and enhance sweet potato production [71]. During drought events, agricultural extension agents distribute drought-resilient sweet potato varieties, ensuring better productivity and sustainability even in drought-affected regions [72,73].

4. Conclusions

The study underscores the critical need to address gender disparities in sweet potato farming, particularly during droughts. Women face significant challenges in accessing land, resources, and market opportunities, and these difficulties are exacerbated by climate variability. To enhance resilience and productivity, gender-inclusive strategies that ensure equal access to training, resources, and support systems are essential.

Achieving sustainable agriculture in Goromonzi District requires a holistic approach that integrates modern agricultural techniques with traditional knowledge. The geospatial approach employed in this study enables policymakers and stakeholders to identify the most affected regions, facilitating the development of targeted strategies to enhance climate resilience in sweet potato farming across the district. This holistic approach must also include revising policies to promote women's land ownership rights, addressing cultural barriers, and improving infrastructure such as roads and transportation to boost women's participation in the sweet potato value chain.

Disseminating improved, climate-resilient sweet potato varieties and providing training on best practices through agricultural extension services are also vital. These initiatives ensure that farmers are equipped to cope with climate variability while maximizing productivity. Additionally, improving market access for women is key. This can be achieved

through the creation of gender-inclusive cooperatives, promoting female-led market associations, and training female farmers in negotiation skills to help them secure fair pricing and reduce reliance on intermediaries.

While this study provides valuable insights, it has certain limitations. Firstly, the analysis was restricted to specific wards within Goromonzi District, which may not fully represent the diversity of challenges faced across other regions in Zimbabwe. Secondly, the reliance on self-reported data from farmers introduces potential biases, as participants might underreport or overreport challenges and practices. Lastly, the study primarily focused on sweet potato farming, limiting its applicability to other crops that may have different resilience requirements and challenges. Future research should aim to expand the geographical scope, incorporate additional crops, and explore long-term impacts of the proposed interventions to develop a more comprehensive understanding of gender-inclusive, climate-resilient farming in Zimbabwe.

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