NAMIBIA UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Pearl Millet (*Pennisetum glaucum* [L.] R. Br.) Water Use Efficiency and Productivity in Semi-Arid Conditions of Namibia

By

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Dissertation submitted in fulfilment of the requirements for the Doctorate degree in Natural Resources Science (10DNRS) at the Namibia University of Science and Technology

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Declaration

I, Ofentse Moseki, declare that the work contained in the thesis entitled **'Assessment of Pearl Millet Water Use Efficiency and Productivity in Semi-arid Conditions of Namibia'** is my original work and that I have not previously submitted its entirety or any part to any university or higher education institution for the award of a qualification.

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Disclaimer

I declare that this thesis is my work, except where the other authors are acknowledged. No part of this thesis has been submitted for any degree or examination to any other university.

Signature Mseki

Date 20/08/25

Dedication

This work was dedicated to my family.

Table of Contents

List of Figures

List of Tables

Abbreviations and Acronyms

ABA: Abscisic Acid

AWC: Available Water Content

CAM: Crassulacean Acid Metabolism

CAT: Catalase

CK: Cytokinin

CMIP: Coupled Model Intercomparison Project

CWR: Crop Water Requirements

DNA: Deoxyribonucleic Acid

EC: Electrical Conductivity

ET_c: Actual evapotranspiration

ET_o: Reference evapotranspiration

FAO: Food and Agriculture Organisation

FC: Field Capacity

GA: Gibberellins

GCWM: Global Crop Water Model

GDP: Gross Domestic Product

GPX: Guaiacol Peroxidase

GR: Glutathione Reductase

HI: Harvest Index

IAAs: Auxins

ICRISAT: International Crops Research Institute for the Semi-Arid Tropics

K_c: Crop Factor

LAI: Leaf Area Index

OM: Organic Matter

PCA: Principal Component Analysis

PWP: Permanent wilting point

ROS: Reactive Oxygen Species

SL: Strigolactones

SOD: Superoxide Dismutase

SSA: Sub-Saharan Africa

SSPs: Shared Socioeconomic Pathways

t/ha: tons per hectare

WP: Water Productivity

WUE: Water use efficiency

WUEinst: Instantaneous water use efficiency

WUEi: Intrinsic water use efficiency

Thesis Outline

This thesis is presented as a compilation of chapters. Chapters are prepared as manuscripts for scientific publication; therefore, a certain amount of repetition is unavoidable. Some chapters are already published articles. The thesis is structured as follows:

Chapter 1: This chapter provides a general introduction, problem statement, objectives, and the significance of the study.

Chapter 2: This chapter provides a literature review on the importance of pearl millet, water use efficiency, and morphophysiological plasticity of pearl millet in response to drought and heat stress.

Chapter 3: This chapter provides results on physiological and vegetative changes of Okashana 2 and Kangara pearl millet in response to different irrigation regimes.

Chapter 4: This chapter provides results on the effects of water regimes on water use efficiency and drought tolerance indices of pearl millet varieties in semi-arid Namibia.

Chapter 5: This chapter provides results on the effects of water regimes on the nutritional quality of pearl millet grains cultivated in semi-arid conditions in Namibia.

Chapter 6: This chapter presents findings on the potential effects of climate change on the productivity of pearl millet, using shared socioeconomic pathway (SSP) scenario tests under various projected future climatic conditions.

Chapter 7: This chapter presents the synthesis and outcomes of the research as well as its implications and Future Work.

ABSTRACT

Pearl millet (Pennisetum glaucum (L.) R. Br.) is a C4 crop that is well adapted to semi-arid climates and is a staple food in Namibia. However, declining yields due to climate variability and changes have raised concerns regarding its sustainability and its ability to drive food security. In this study, the responses of two local pearl millet cultivars, Kangara and Okashana 2, to different water regimes (100%, 75%, and 50% crop evapotranspiration [ETc]) at the Mannheim Crop Research Station, Tsumeb, Namibia, during the 2023 and 2024 cropping seasons were investigated. A split-plot factorial design was employed to assess morpho-physiological, yield, nutritional responses and water use efficiency (WUE) of pearl millet. Additionally, the projected climatic conditions were used to estimate pearl millet yield and water productivity under various climate change and planting date scenarios. Water stress significantly affected plant height, leaf number, tillering, chlorophyll content, stomatal conductance, leaf temperature, panicle traits, biomass, grain yield, and 1000-seed weight ($p < 0.001$). The 50% ETc regime significantly reduced the growth and yield parameters, whereas the 75% ETc regime maintained acceptable productivity, suggesting that it is an optimal irrigation strategy under water-limited conditions. Biomass yield (BY) varied between 5.54 and 1.14 tons/ha in Season 1 and between 3.81 and 1.50 tons/ha in Season 2, while grain yield (GY) ranged from 1.23 to 0.38 tons/ha in Season 1 and from 1.02 to 0.58 tons/ha in Season 2. The highest yields were observed at 100% ETc, with a decline under increasing water stress. Okashana 2 exhibited a significantly higher harvest index under 50% ETc ($p = 0.003$), suggesting its ability to allocate resources effectively under water stress. WUE for BY varied from 0.78 to 1.74 kg. ha/m^3, whereas that of GY ranged from 0.28 to 0.47 kg. ha/m^3, with strong positive correlations between GY and BY ($r = 0.88$, $p \leq 0.01$), and between WUE-GY and GY ($r = 0.80$, $p \leq 0.01$). The nutritional composition was minimally influenced by water stress. Although the moisture content remained unaffected in the first season, significant differences were observed in the second season ($p < 0.001$), with the highest levels at 75% ETc (6.63%) and the lowest at 50% ETc (2.10%). In the second season, the fat content varied significantly ($p < 0.001$), with the highest content at 50% ETc (4.99%) and the lowest at 100% ETc (2.11%). Several mineral elements, including acid detergent fiber, calcium, potassium, magnesium, phosphorus, and iron (Fe), were significantly affected by irrigation regimes ($p < 0.05$), with the highest Fe (76.61 mg/kg) recorded at 50%

ETc. Principal component analysis revealed distinct correlations under different water regimes, highlighting the nutritional resilience of pearl millet.

To assess future climatic effects, the AquaCrop model was used under historical (1995–2014) and projected (2020–2059) climate scenarios for two planting dates (15 December and 15 January). Future projections indicate a decline in rainfall, rising temperatures, and higher reference evapotranspiration (ETo). Water productivity is projected to decline by 22-35%, with dry yields decreasing from 0.94 to 0.81 tons per hectare in December and from 1.83 to 1.21 tons per hectare in January between 2020 and 2039. The 15th of January is recommended as the planting date to maintain crop yield under future climate conditions. These findings underscore the importance of optimising irrigation and planting strategies to enhance pearl millet production and resilience under water-limited conditions. Therefore, this study recommends adopting water-saving strategies such as deficit irrigation management to ensure the sustainability and production of pearl millet, thereby promoting food security in water-scarce environments. This study contributes to the scientific understanding of how water use and pearl millet performance are affected by moisture levels. In addition, this study contributes to the development of climate-resilient cropping systems suitable for dryland agriculture in Southern Africa.

Keywords: *AquaCrop model, Agricultural water management, Climate change adaptation, Pearl millet, Semi-arid Namibia, Water use efficiency, Water productivity*

1 GENERAL INTRODUCTION

1.1 Background

Climate change and population growth have significantly affected water availability worldwide, particularly in regions with limited water resources. Water scarcity occurs when the available water resources do not meet human or environmental demands (Lautze, 2014; UN-Water, 2024). This phenomenon has become a significant concern in areas where rainfall is highly variable, leading to competition among various water-using sectors. Moreover, climate change is projected to result in higher temperatures and decreased precipitation in some regions, with varying impacts on water resources and livelihoods (Maliva & Maliva, 2021), while in other regions, it will result in increased rainfall. The impacts of climate change have been observed in sub-Saharan Africa (SSA), including reductions in crop yield quality and quantity, with more significant impacts on smallholder farmers (Ayanlade et al., 2022).

Water scarcity poses a significant challenge to agricultural systems, particularly in SSA, where most rely on rainfed agriculture. This issue arises because a substantial proportion of the received precipitation is lost through surface runoff, deep percolation, and evaporation, leaving insufficient water available for plant use (Soil Science Glossary Terms Committee, 2008; Rockström & Falkenmark, 2015). Although little can be done to prevent the effects of climate change, adaptation and mitigation strategies can be employed to mitigate these impacts, particularly concerning the limited water resources required for global crop production, which is crucial for maintaining the food supply chain for humans and healthy ecosystems. Effective irrigation water management strategies are necessary to counteract the effects of limited rainfall and to enhance the productivity of various agroecosystems. Without proper water management practices, allocations between sectors may conflict. To address the water scarcity crisis, researchers and governments of various nations have invested substantial resources in investigating ways to ensure proper water allocation, thereby reducing the impact of water scarcity while maintaining food security in water-scarce environments. Comprehending and quantifying water demand and usage across sectors in these areas is crucial for effective water resource management. Cultivating drought-tolerant and resilient crop species, such as pearl millet, in drought-prone areas under climate change conditions constitutes a potential mitigation strategy (Raut et al., 2023).

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is one of the staple foods in most sub-Saharan African (SSA) countries (Upadhyaya et al., 2007; Pattanashetti et al., 2016; Zhang et al., 2021). Pearl millet offers several health benefits, including a higher energy and fibre content than sorghum (Nambiar et al., 2011). Additionally, it is higher in protein, has the potential to act as a probiotic when fermented, possesses antioxidant, anti-aging, and anti-carcinogenic properties, and prevents non-communicable diseases (Dias-Martins et al., 2018; Kaur et al., 2021; Rotela et al., 2021). India, China, and Nigeria are the largest producers of pearl millet globally, highlighting its significance (Khairwal et al., 2007; FAOSTAT, 2022). In terms of cultivation in the southern region, it is primarily grown in Botswana, Namibia, South Africa, Zambia, and Zimbabwe (Upadhyaya et al., 2007). Pearl millet employs various morphological and physiological mechanisms to resist drought, including osmotic adjustment, stomatal regulation, and developmental plasticity during tillering and root growth (Merga, 2020). Although the crop is drought-tolerant, studies have shown that low moisture levels hamper its productivity (Azare et al., 2020). Appropriate water management through irrigation can enhance pearl millet productivity even in areas that undergo drought (Kumar & Kumar, 2021).

Water use efficiency (WUE) and irrigation water management practices are key metrics for evaluating crop efficiency in terms of water utilisation, addressing future demands, and promoting water conservation in agriculture (Yuan et al., 2021). WUE is critical for agricultural productivity, particularly in semi-arid regions with limited water resources. WUE is defined as the ratio of biomass produced or yield to the quantity of water utilised (Hatfield & Dold, 2019). Three levels determine crop water use efficiency: leaf water use efficiency, whole-plant water use efficiency, and yield water use efficiency (Medrano et al., 2015). In this study, WUE was assessed at the whole plant level. Research on WUE and productivity of crops in semi-arid regions has garnered substantial attention in recent years owing to the increasing impact of climate change on agricultural productivity.

Numerous studies have shown that water stress circumstances frequently result in higher crop water use efficiency (WUE), even though the yield is reduced (Farooq et al., 2019). Adaptive management strategies such as irrigation water management, soil management, intercropping, and appropriate cultivar selection can help increase WUE (Farooq et al., 2019). In assessing pearl millet WUE, previous studies assessed these at the seedling stage, intercropping pearl millet with other crops, and the effect of planting density (Shirzad et al., 2020; Bani Hani et al., 2022; Pilloni et al., 2022; Bana et al., 2023). Furthermore, previous studies have shown that irrigation practices such as varying the amount of plants given to pearl millet can significantly influence plant growth, development, and yield in different environments, and consequently WUE (Farooq et al., 2019; Lira et al., 2020; El-Tigani, 2022; Yadav et al., 2022). These studies highlight that the agro-physiological and morphological such as plant height, leaf numbers, stomatal conductance, chlorophyll content and yield responses of crops to irrigation, can differ depending on variety and environmental conditions. These studies were conducted in different environmental conditions, which affect the generalization of findings, thus necessitating crop evaluation in different environments, particularly local cultivars under specific location environments.

In Namibia, pearl millet, locally known as Mahangu, is primarily cultivated in northern regions and is a staple crop of significant socioeconomic importance. Pearl millet is the primary staple food for over 50% of the population (Namibian Agronomic Board, 2021). This suggests that this crop holds a significant value for communities in the country. There are two primary indigenous varieties, namely Okashana 2 (SDMV 93032) and Kangara (SDMV 92040) (Ipinge, 1998), which are primarily cultivated under rainfed conditions under the highly vulnerable to variations in the weather patterns. Despite its inherent resilience, pearl millet productivity in Namibia is often hampered by suboptimal water management practices, poor soil fertility, and limited access to modern agricultural inputs and technologies. Irrigation is required for optimal pearl millet production (Ausiku et al., 2020). To alleviate food insecurity, sustainable agricultural production must be ensured while minimising the use of irrigation water in water-stressed environments. Namibia is a semi-arid country with an annual rainfall of 250 mm (Liu & Zhou, 2021).

Previous studies have shown that Namibia is not an exception, as climate projections indicate a similar trend of higher temperatures accompanied by low rainfall (Dirkx et al., 2008; Davis & Vincent, 2017). The rainfall distribution in this country is highly variable in space and time, with the northern part receiving approximately 650 mm per year, and the southern part receiving approximately 50 mm per year.

According to Namibia Hydrological Services, approximately 83% of water is lost through evaporation, 14% is lost through transpiration, 2% is absorbed into the river system, and only 1% is absorbed underground, which is later abstracted for livelihood activities. Approximately 80% of the country's water supply is derived from unevenly distributed groundwater, with some areas having high water volumes and others having low water volumes. Additionally, this water availability does not guarantee good water quality for human activities such as agriculture.

Given the importance of pearl millet in ensuring food security and supporting rural livelihoods in Namibia, it is imperative to understand its productivity and sustainability, and devise strategies to optimise its production under changing climatic conditions. By assessing pearl millet WUE, this study intends to inform and thus enable actions to maximise yield with minimum water input, which can be achieved by regulating the amount of water administered to crops. This is particularly pertinent in Namibia, where frequent droughts and unpredictable rainfall substantially affect agricultural productivity. Understanding these responses can help optimise irrigation practices to enhance crop performance and resilience under varying water availability conditions. Therefore, this study aimed to assess the water-use efficiency and productivity of pearl millet under semi-arid conditions in Namibia.

1.2 Problem Statement

Food security and environmental sustainability are pressing challenges in the 21st century, particularly in water-scarce regions such as sub-Saharan Africa (SSA). In these areas, limited rainfall and high temperatures constrain water availability, making efficient water use in agriculture essential for sustaining crop production (Moroke et al., 2010). In Namibia, where semi-arid conditions dominate, rainfall is highly variable and temperatures are frequently high, further limiting the water resources and crop productivity. Agriculture accounts for nearly half of national water withdrawals (Ihemba & Esterhuyse, 2020), while rural households depend heavily on pearl millet (Pennisetum glaucum L.Br), locally known as Mahangu, which is one of the staple foods.

Despite its importance, pearl millet production remains highly variable because of erratic rainfall. For example, only 111 tons were produced locally in 2015/2016, compared to 2000 tons in 2021/2022, with substantial imports required in both seasons (Namibia Agronomic Board, 2021, https://www.nab.com.na/agronomy/grain-statistics/#1657790629327-608520af-da3f, accessed 30 June 2025). Simultaneously, Namibia's population has grown by over 43% since 2011 (Namibia Statistics Agency, 2023), intensifying the demand for food and water resources. Vision 2030 identifies food security and sustainable resource use as national priorities (Dubbeling, 2016), underscoring the urgency of improving crop productivity without compromising water sustainability in semi-arid regions.

However, research on how different irrigation regimes affect the growth, yield, nutritional quality, and water-use efficiency of Namibia's local pearl millet cultivars (Kangara and Okashana 2) remains limited. In addition, little is known about how future climate scenarios may influence the water productivity of pearl millet. Addressing these knowledge gaps is critical for developing climate-resilient strategies to enhance pearl millet yields and secure food production under Namibia's increasingly variable climatic conditions.

1.3 Research Objectives

1.4.1 General Objective

To assess the influence of irrigation regimes on water use efficiency and productivity of pearl millet cultivars under semi-arid conditions in Namibia.

1.4.2 Specific Objectives

1. To analyse the effects of irrigation regimes (100%ETc, 75%ETc and 50%ETc) on the agro-physiological (stomatal conductance and chlorophyll content) and morphological (plant height, leaf area, tiller number, panicle length, and total biomass) responses of two pearl millet cultivars (Kangara and Okashana 2) under semi-arid conditions of Namibia.
2. To evaluate the drought tolerance indices and water use efficiency of pearl millet varieties in the semi-arid conditions of Namibia.

3. To determine the effect of irrigation regimes on the nutritional quality of Okashana 2 and Kangara pearl millet.
4. To assess the potential effects of climate change on the water productivity of pearl millet using Shared Socioeconomic Pathways (SSPs) scenario tests under different projected future climatic conditions.

1.4 Hypotheses

1. Irrigation regimes significantly influence the agro-physiological and morphological responses of Kangara and Okashana 2 pearl millet cultivars under semi-arid conditions.
2. Drought tolerance indices and water use efficiency of pearl millet are significantly affected by varying water regimes in the semi-arid environment of Namibia.
3. Irrigation regimes have a significant effect on the nutritional quality of Okashana 2 and Kangara pearl millet cultivars.
4. Projected future climate conditions based on Shared Socioeconomic Pathways (SSPs) scenarios will significantly alter the water productivity of pearl millet in semi-arid Namibia.

1.5 Significance of the Study

In recent years, the effects of unpredictable climatic conditions exacerbated by climate change on crop production and water scarcity have become a growing concern in semi-arid environments, including Namibia. In these environments, farmers often experience highly variable yields as the majority rely on a rainfed system to cultivate crops such as pearl millet. Understanding how different irrigation regimes affect the water use efficiency (WUE) and productivity of pearl millet under semi-arid conditions of Namibia is crucial. This study offers insights into cultivar-specific responses to irrigation regimes, thereby enhancing our scientific understanding of drought-tolerant crops and informing strategies for adapting to and mitigating the effects of climate change. The findings of this study will help farmers in semi-arid regions, particularly Namibia, to optimise their irrigation practices, improve crop yields, and conserve water, ultimately leading to more sustainable agricultural practices. Furthermore, the results of this study will inform policies aimed at achieving some of the Sustainable Development Goals (SDGs), including Zero Hunger (SDG 2), Responsible Food Production and Consumption (SDG 12), and Climate Action (SDG 13). Moreover, policymakers can use this study to inform the development of science-based policies that support sustainable agriculture and water use for optimal pearl millet production in Namibia. It is in this light that this thesis contributes both theoretically and practically to the ongoing discourse on sustainable agriculture production in water-limited environments and the face of climate change by comprehensively exploring water use efficiency in pearl millet production.

1.6 Justification of the Study

Given its adaptability and importance, pearl millet is well-suited for improving and promoting water use efficiency (WUE) in Namibia, but there is little known about the crop's performance, particularly the local cultivars (Okashana 2 and Kangara) in real water-stress situations. This lack of knowledge on basic agro-morphological and physiological, yield, and nutritional responses to water stress has limited the strategic and practical options for addressing pearl millet productivity in Namibia. It is therefore important to assess pearl millet water use efficiency and productivity, and nutritional security, without compromising the future.

1.7 Limitations of the Study

This study was conducted under field conditions over a limited period, and the climatic conditions during the experiment may not fully reflect long-term averages. A two-season approach (September to December 2023 and January to April 2024) was employed to capture seasonal variability within a single cropping year. However, financial and logistical constraints prevented seasonal replication of the experiment. Despite these limitations, the study employed rigorous methodologies and comprehensive data analyses to ensure the reliability and validity of the findings.

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2 THE IMPORTANCE AND MORPHO-PHYSIOLOGICAL PLASTICITY OF PEARL MILLET UNDER DROUGHT AND HEAT STRESS: LITERATURE REVIEW

2.1 Introduction

Pearl millet (*Pennisetum glaucum* [L.] R. Br.) is a hardy and drought-tolerant cereal crop cultivated for the production of food, feed, and raw industrial materials in arid and semi-arid regions worldwide (Burgarella et al., 2018). Globally, pearl millet is ranked as the sixth most widely cultivated cereal crop following maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), barley (*Hordeum vulgare* L.), and sorghum (*Sorghum bicolor* L.) (Satyavathi et al., 2021; FAOSTAT 2022). It is gluten-free and a rich source of essential nutrients, such as folic acid (46 mg/100 g), iron (75 mg/kg), zinc (43 mg/kg), tannins, phenolic acids, and flavonoids, with health benefits to humans in the fight against cancer, diabetes, and heart diseases (Hassan et al., 2021). It has a higher energy content (363.0 kcal/100 g) and crude fiber content (2.3/100g) than sorghum, which has 329.0 kcal/100 g and 2.0g/100 g of energy and crude fiber, respectively (Ullah et al., 2017; Nambiar et al., 2011; Pujar et al., 2020). Pearl millet has a higher protein content of 11.6 g/100 g (Pujar et al., 2020) and exhibits probiotic, antioxidant, anti-aging, and anti-carcinogenic properties, which may help reduce the risk of non-communicable diseases (Dias-Martins et al., 2018; Kaur et al., 2021; Rotela et al., 2021).

Pearl millet is widely produced under poor soil fertility, elevated temperatures, and highly variable rainfall conditions in arid and semi-arid environments. This crop is extensively grown in countries such as India, China, Mexico, and Russia (Moreta et al., 2015). It is also cultivated in Nigeria, Niger, Mali, Senegal, Burkina Faso, Uganda, Zambia, Angola, Namibia, and Botswana. Drought (DS) and heat stress (HS) are significant constraints on crop production and quality, despite its well-established adaptation to dry environments (Khairwal et al., 2007; Faye et al., 2019; Ozturk et al., 2021; Kapoor et al., 2022). Therefore, agricultural water management is critical in water-stressed environments. Coincident drought and high-temperature events frequently affect plants at any stage of growth. DS and HS alter plant physiological functions and biochemical pathways, leading to crop failure and poor crop productivity (Ndlovu et al., 2021). DS and HS (≥40 °C) during the reproductive stage reduce pollen viability, which consequently decreases fertility and grain yield (Halilou et al., 2020; Sharma et al., 2021; Bani Hani et al., 2022). Additionally, DS and HS at the post-flowering stage significantly reduce the height and yield of pearl millet (Narasimhulu et al., 2023) although the effects of DS and HS vary based on the variety, and growth stage (Dietz et al., 2021) and some pearl millet genotypes can restore grain yield under drought stress (Ghatak et al., 2021).

DS and HS adaptations are categorised as avoidance, tolerance, escape, and recovery (Shrestha et al., 2023). Pearl millet has morpho-physiological plasticity traits that help to sustain cellular metabolism, water absorption, reduced evapotranspiration, and oxidative stress under both DS and HS conditions (Serba et al., 2020). However, the morpho-physiological plasticity of crops requires a comprehensive understanding to develop effective crop management practices, including the development of supplemental irrigation schemes to improve water management for stable production under fluctuating environmental conditions (Yadav et al., 2012; Reddy et al., 2013). Complementary climate-smart strategies, such as irrigation water management, are necessary to enhance the production and productivity of pearl millet in a changing climate. Effective agricultural strategies include the integration of the cultivation of climate-resilient varieties and improved agronomic practices such as intercropping, efficient water management, soil improvement technologies, and weed and pest management (Varshney et al., 2017; Debieu et al., 2018; Ausiku et al., 2020; Huang et al., 2021).

2.2 Methodology

A systematic review was employed to aggregate and assess information from a set of studies using standardised techniques, including structured search methods, critical appraisal, and synthesis of selected information (Kitchenham, 2004). Searches were performed using electronic databases, including the Web of Science, Scopus, ScienceDirect, PubMed, and Google Scholar. The search only included articles published in English. Boolean operators (AND, OR) were used to refine the results, and truncation (*) was applied when appropriate. Search terms included keywords such as semi-arid conditions, drought resistance mechanisms, pearl millet productivity, irrigation management schemes, stress avoidance, stress tolerance, stress escape, and stress recovery mechanisms and combinations of keywords such as, "pearl millet" AND ("drought stress" OR "heat stress"), "Pennisetum glaucum" AND ("morphological traits" OR "physiological traits"), Pearl millet" AND ("plasticity" OR "adaptation").

2.3 Pearl Millet Cultivation and Productivity

According to the World Bank, approximately 304,290 hectares of land were under cereal production in Namibia in 2018 (World Bank 2018). The primary crops cultivated included white maize, pearl millet, and wheat. A report prepared by the Agronomy and Horticulture Market Development Division under the Namibian Agronomic Board indicated that the total domestic demand for grain (white maize, wheat, and pearl millet) was 318,530 tons between April 2021 and February 2022, resulting in a total value of N$1.5 billion. Of the 318,530 tons, 110,380 tons were accounted for by local production, whereas 208,151 tons were imported (Namibian Agronomic Board, 2022). Namibia, therefore, remains a net importer of staple grain crops, thereby rendering the country's food supply insecure.

Pearl millet belongs to the Poaceae family. This crop is cultivated in arid and semi-arid environments, as it is vital for providing a climate-resilient and healthy meal option for humans (Pattanashetti et al., 2016; Dias-Martins et al., 2018; Baby et al., 2020). It offers many benefits to communities, as more by-products can be derived from it, such as bread, beverages, and snacks (Balasubramanian et al., 2012; Siroha et al., 2016; Dias-Martins et al., 2018). Crop residues can also be used as fodder. Pearl millet can grow in a wide range of soil conditions, particularly in arid and semi-arid regions (Satyavathi et al., 2021). It thrives in low-nutrient soils and has a deep root system that allows it to survive water scarcity (Satyavathi et al., 2021). However, waterlogged conditions can negatively affect pearl millet growth, particularly during seed setting (Hirooka et al., 2021).

Drought-tolerant crops, such as pearl millet, exhibit specific physiological and biochemical properties that enable them to cope with water stress. Previous studies on pearl millet have focused on the combined effects of fertilisation, salt stress, and water on various aspects of the crop in different agroecosystems (Azare et al., 2020; Halilou et al., 2020; Lira et al., 2020; de Có et al., 2023). Management practices also influence pearl millet productivity in terms of yield. Intercropping was carried out to determine the effect of irrigation regimes on field crops (including pearl millet) in Pakistan, and it was found that intercropping reduced the yield of crops compared with sole cropping (Khalid & Khalil, 2020). In addition, technologies have been widely developed and utilised as tools for technology transfer and decision support in agricultural practices. For example, Ausiku et al. (2020) modeled and parameterised a crop model to improve water use and yield. They recommended determining crop parameters for other pearl millet varieties for irrigation management, long-term yield projections, and planning purposes. Pearl millet undergoes different developmental stages before maturity, taking approximately 105-140 days to reach maturity (Brouwer & Heibloem, 1986). The entire growth cycle is divided into four developmental stages. The initial stage was defined as the period from sowing or transplanting to when the canopy covered approximately 10% of the ground surface. Secondly, vegetative growth begins when the canopy partially covers the ground and lasts until the full canopy cover reaches approximately 70-80%. The mid-season or reproductive stage follows the end of the vegetative stage and lasts until maturity, encompassing stages of blossoming and grain setting. Finally, the late-season stage begins once the mid-season stage ends and continues until the last day of ripening and harvest (Brouwer & Heibloem, 1986). These stages on average last 15, 25, 40, and 25 days, respectively (Allen et al., 1998).

2.4 Plant Water Relations

Plant-water relations encompass the processes by which plants extract water from the soil, utilise it within their cells, and ultimately, lose water through their leaves (Passioura, 2010). The plant-water relationship is influenced by the environmental evaporative demand and the physiology of the crop. Transpiration pulls aid plant water movement. Transpiration pull is a biological process in which water is forced to pass through xylem cells in response to evaporative demands (Chavarria & dos Santos, 2012; Lambers & Oliveira, 2019). Similar to how plants in their natural habitats have adapted to water stress (Basu et al., 2016), many crop species can adapt to or survive varying evaporative demands, depending on factors such as the cultivation area, type of soil, prevailing weather conditions, and seasons (Zivcak et al., 2016). Soil water is often categorised into field capacity (FC), permanent wilting point (PWP), and available water content (AWC). Field capacity refers to the amount of water remaining in the soil after it has been fully saturated and undergone deep percolation. The permanent wilting point occurs when plants wilt due to a lack of soil moisture and fail to recover after being provided with water. Available water content is the quantity of water that the soil can store and is typically available for plant use (Assi et al., 2019). During transpiration, water movement from the soil is facilitated by the stomata. Under soil moisture deficit conditions, plants lose more water from their leaves and eventually wilt (Passioura 2010). Under water-stressed conditions, plants significantly reduce transpiration by reducing leaf number, leaf size, and stomatal size, as well as by shedding leaves, depending on the species, as an adaptation strategy to stress (Anjum et al., 2011). All these adaptation strategies exhibited by plants mitigate the negative impacts of water stress on the photosynthetic rate, thereby positively affecting water use efficiency (WUE) and, in some instances, increasing yield potential (Blum, 2005; Basu et al., 2016). Stomata also control gaseous exchange between the interior and exterior parts of the leaf (Lawson & Vialet-Chabrand, 2019).

2.5 Water Use Efficiency

Water-use efficiency (WUE) quantifies the effectiveness of crops in utilising available water to produce biomass or yield per unit of water consumed (Sinclair et al., 1984; Sharma et al., 2015). Three levels determine crop water use efficiency: leaf water use efficiency, whole-plant water use efficiency, and yield water use efficiency. Leaf water use efficiency reflects the balance between carbon gain (photosynthesis) and water loss (transpiration) at the leaf level, and is often measured as the ratio of CO_2 assimilation rate to transpiration rate or stomatal conductance (Hatfield & Dold, 2019; Petrík et al., 2023). Leaf water-use efficiency is classified into two categories: intrinsic water-use efficiency (WUEi) and instantaneous water-use efficiency (WUEinst). Intrinsic WUE (WUEi) is defined as the ratio between leaf net carbon assimilation rate (A) and stomatal conductance to water vapour (gs), *i.e.,* A/gs. WUEi is a commonly used technique for selecting water-efficient plants (Pimentel, 2022). In contrast, instantaneous WUE (WUEinst) is defined as the ratio of the leaf net carbon assimilation rate (A) to the rate of leaf transpiration (E), that is, A/E

(Flexas et al., 2010; Gago et al., 2014). These factors are influenced by the prevailing environmental conditions surrounding leaves. For instance, increasing CO_2 levels can enhance leaf WUE, but this effect diminishes under heat stress (Hatfield & Dold, 2019). Whole-plant-level WUE considers the ratio of total biomass produced to total water transpired by the entire plant, encompassing all photosynthetic and non-photosynthetic parts of the plant. Yield WUE is typically calculated as crop yield per hectare divided by total transpiration or evapotranspiration (Hatfield & Dold, 2019).

Calculating the crop water demand is crucial for implementing effective water resource management strategies in agriculture. Researchers can estimate the amount of water required at various stages in the field and through modeling. The latter is used to overcome the challenges associated with the direct field measurements of reference evapotranspiration (ETo) rates and potential evapotranspiration rates (ETc), also known as crop water requirements (CWR), which is the quantity of water lost to the environment by a specific crop. This depends on specific crop, climate, and soil data (Smith et al., 1998). These measurements can be obtained using micrometeorological methods, such as Eddy Covariance (carbon and water fluxes), cylindrical micro-lysimeters, weighing lysimeters, heat-pulse velocity, and the Penman-Monteith method. Several computer models incorporating these methods have been developed and used to determine the ETo, ETc, and CWR of different crops. Some commonly used models include the CROPWAT model, Global Crop Water Model (GCWM) (Siebert & Döll, 2008), Water Requirements Satisfaction Index (GeoWRSI) developed by the Food and Agriculture Organization of the United Nations (Frere & Popov, 1979), and Decision Support System for Agrotechnology Transfer (DSSAT). Studies have been conducted to determine the WUE of various crops globally (Gebrehiwot & Gebrewahid, 2016; Wang et al., 2017; Kadigi et al., 2019; Leite et al., 2021; Onyango et al., 2021; Santiago-Arenas et al., 2021). While numerous studies have been done in different agroecological zones, WUE assessments specific to the climatic conditions of Namibia are required.

2.6 Factors Affecting Crop Water Use Efficiency

2.6.1 Meteorological Factors

Climatic factors comprise several variables, including temperature, rainfall, humidity, wind speed and direction, solar radiation, and carbon dioxide concentrations, that affect crop water needs in a particular location. WUE tends to be higher in tropical and subtropical zones due to high relative humidity in these conditions than in drier conditions (Mbava et al., 2020). Additionally, wind influences atmospheric water vapour flux, gas exchange, and leaf temperature, which are dependent on the aerodynamic properties of a crop, such as leaf area index (LAI), roughness, canopy structure, and density (Jones, 1999; Alekseychik et al., 2017). Areas with hot, dry, windy, and sunny climates tend to use more water than those cultivated in cool and humid climates (Allen et al., 1998). Furthermore, demand for irrigation tends to decrease during rainfall events (Martello et al.,2015).

2.6.2 Edaphic Factors

The soil is the most important part of the terrestrial biosphere. It underpins species distribution, productivity, and water and biogeochemical cycling processes (Rounsevell et al., 1999). Owing to the varying properties of different soil types, WUE is correlated with the type of soil on which the crops are cultivated. Mbava et al. (2020) highlighted that the amount of soil organic matter and soil bulk density were positively correlated with WUE. Water percolates more easily in sandy soils than in clayey soils (Allen et al., 1998; Easton & Bock, 2016). Therefore, crops cultivated in sandy soils require more water than those in clay soils because of their higher infiltration rates. Ismail and Ozawa (2007) reported higher WUE in clay soil crops than in sandy soil. The same trend has been observed in rice cultivated in clay and sandy loam soils (Dou et al., 2016). Soil fertility also affects the quantity of water required by plants. Soils with low fertility tend to have higher evaporation rates than those with high fertility (Allen et al., 1998). Prudat et al. (2022) also highlighted that both sandy topsoil and shallow fragipans have positive effects on plant-available water during dry periods in Namibia.

2.6.3 Agronomic practices

Agronomic factors influencing crop water use efficiency include the growing season, water quality, available irrigation water, pests, and diseases. The growing season and length affect crop water requirements; crops grown during the rainy season require less irrigation water than those grown during the dry season (Allen et al., 1998; Huang, 2008; Cao et al., 2021). The choice of irrigation system also affects the water use in production. When the water supply is limited, drip irrigation is preferred because of its high water application efficiency, with approximately 90 % taken up by plants compared with surface irrigation (approximately 60 %) (Brouwer et al., 2001). Drip irrigation is typically used for row-planted crops, such as trees and vineyards. This saves water because only the area around the plant root zone is watered, unlike the sprinkler system. Additionally, tillage management has been found to affect WUE, with tilled soil exhibiting greater WUE for pearl millet than no-till (Crookston et al., 2020).

2.7 Stress resistance mechanisms

2.7.1 Stress avoidance mechanism

Drought avoidance involves maintaining an elevated plant water potential even in the face of water scarcity. This leads to changes in both the physical structure of plants and their internal biochemical processes, such as changes in photosynthesis and stomatal conductance patterns (Anjum et al., 2011), as well as modifications in leaf morphology and structure, and the development of deeper root systems.

2.7.1.1 Stomatal Control

Drought and heat stress, which are often inextricably linked, affect the rates of photosynthesis and stomatal conductance in plants. Drought is a significant abiotic stressor that has detrimental effects on both plant growth and crop productivity (Shivhare & Lata, 2019). Plant photosynthesis and stomatal conductance are affected by various environmental factors and crop genotypes (Lawson et al., 2011; Martínez-Goñi et al., 2023). Stomata facilitate photosynthesis (Blatt et al., 2022; Bassham & Lambers, 2024). Stomata are tiny openings on the leaf surface that regulate the exchange of gases such as water vapour and carbon dioxide (Harrison et al., 2020). The number of stomata per unit area of the leaf is known as the stomatal density (Miyazawa et al., 2006; Bertolino et al., 2019). Under drought conditions, plants generally adjust their stomatal pore apertures to minimise water loss, while maintaining optimal CO_2 uptake for photosynthesis (Bertolino et al., 2019; Shrestha et al., 2023). As soil moisture decreases, stomata tend to close, thereby reducing water loss through transpiration (Xu et al., 2023). Reduced stomatal conductance represses the entry of CO_2 into the leaves, thus impairing photosynthesis (Kusumi et al., 2012; Shrestha et al., 2023). Furthermore, plants generally respond differently to drought stress depending on the photosynthetic pathway employed (Pearcy & Ehleringer, 1984; Hamim, 2005). Genetic variations among pearl millet cultivars may also influence their ability to avoid water stress and the subsequent photosynthetic and stomatal responses (Iwuala et al.,2020). An adequate water supply through irrigation can enhance the chlorophyll content of pearl millet leaves, leading to a greener appearance and increased photosynthetic efficiency. Additionally, under prolonged water stress, pearl millet leaves may undergo premature senescence (aging) and drop (Sade et al., 2018; Ruehr et al., 2019; Seleiman et al., 2021).

2.7.1.2 Leaf Morphology and Structure

Under water-deficit conditions, plants employ various strategies to reduce transpiration loss, including several where the leaf's structure is changed in order to limit water loss or to respond to increases in water availability (Seleiman et al., 2021). Leaves are the fundamental parts essential for photosynthesis, and any changes in moisture availability can directly affect their development (Lawson & Milliken, 2023). Adequate soil moisture promotes larger leaf size and greater leaf area in pearl millet (Crookston et al., 2020). However, during drought stress, plants tend to reduce leaf expansion, thus reducing cell expansion rates to conserve water and adapt to the stress (Hasanuzzaman et al., 2022; Laskari et al., 2022). A study conducted on maize, sorghum, and pearl millet at ICRISAT, India, indicated that these crops might restrict transpiration by reducing leaf area expansion rate (Choudhary et al., 2020). Leaf area shows the potential of a plant's photosynthetic capacity and overall growth potential (Pallardy, 2010; Weraduwage et al., 2015).

2.7.1.3 Plant Height and Growth Rate

Previous research has shown that moisture stress significantly affects pearl millet development and growth. This was evidenced by various vegetative changes, including plant height, growth rate, and early growth stages. Lira et al. (2020) found a positive correlation between the amount of water irrigated (100% ET) and the height of pearl millet; the plant achieved higher heights with increased water supply. This could be due to elongation of the internodes and an increase in plant height. A similar response in terms of growth in response to moisture availability was observed in other cereal crops like maize and sorghum. In Iraq, Al-Naily and Ibraheem (2020) evaluated the response of sorghum to water stress, and their results showed a significant decrease in vegetative growth of sorghum under 50% irrigation. Vegetative characteristics, such as plant height, stem height at the midpoint of the lower internode, and the number of internodes, decreased in response to water supply. Sufficient moisture during maize germination and seedling development is crucial because this stage promotes rapid germination and early root development, thereby laying the foundation for a robust plant (Khaeim et al., 2022). The adverse effects of heat stress on germinating pearl millet seeds were found to be intensified when imbibition occurred at elevated temperatures (Yadav et al., 2016). Inadequate irrigation during this phase can lead to delayed emergence, poor root establishment, and reduced growth rates (Li et al., 2022), consequently affecting yield formation. Appropriate irrigation during the reproductive stage is crucial for optimal grain formation and filling. Wang et al. (2023) found that water refill of maize under heat stress improved canopy temperature, grain formation, and filling capabilities. Water stress at this stage can result in a reduced grain set and a smaller grain size, negatively impacting the overall yield.

2.7.1.4 Tiller Production and Panicle Development

Tiller production refers to the formation of new shoots or branches from the base of the main stem, whereas panicle development refers to the formation and growth of inflorescences (flowering structures) that eventually bear the grain (Maiti & Bidinger, 1981; Ali et al., 2019; Lin et al., 2023). Water availability has a direct impact on these processes, which are crucial for determining the crop yield and overall performance. During drought stress, pearl millet and its wild ancestors exhibit plasticity characterised by the asynchronous development of tillers (Vadez et al., 2012). Primary tillers tend to emerge from the leaf axils of the main stem, whereas secondary tillers originate from buds located in the leaf axils of the primary tillers (Shrestha et al., 2023). Furthermore, insufficient water during flowering and grain-filling periods can lead to poor pollination, lower seed formation, and reduced grain weight. Additionally, during the DS and HS phases, pearl millet has been observed to optimise flower opening during cooler early morning or late evening hours, thereby avoiding or reducing the effects of heat stress damage during this period (Jagadish, 2020). Previous studies have concluded that water stress during panicle development reduces the yield of the main panicle of pearl millet (Mahalakshmi & Bidinger, 1986; Addisie & Yemane, 2011; Kapoor et al., 2022). Adotey et al. (2021) found that a water deficit negatively affected the grain numbers obtained at different positions within the sorghum panicle. Enough soil moisture supports healthy panicle development, and grain filling can improve the harvest index by increasing the biomass allocated to grains rather than stems and leaves. The harvest index is the ratio of grain yield to total aboveground biomass (Hütsch & Schubert, 2023).

2.7.1.5 Root Morphology and Development

Root morphology and development are integral to pearl millet establishment and survival (Passot et al., 2016). Different irrigation strategies can have varying effects on root growth and architecture, which, in turn, influence the overall performance and productivity of the pearl millet crop. Pearl millet lateral roots form on both primary and crown roots, contributing to the plant's ability to acquire water and nutrients in arid regions (Passot et al., 2016). Compared to maize and sorghum, pearl millet displays a smaller root system with thin roots (Rao & Ito, 1998). A significant positive correlation was observed between the development of a deep root system and leaf relative water content, grain weight, and yield in winter wheat under drought stress in the Great Plains of the United States (Awad et al., 2018). A modeling study conducted by Faye et al. (2019) found that pearl millet redirects root growth toward deeper soil layers, where more water is retained during drought conditions, while maize and sorghum develop steeper root angles and deeper root systems under water deficit (Hostetler et al., 2024). Furthermore, a study conducted in Mali showed that the pearl millet variety developed a good root system under drought conditions and exhibited good root growth under more favorable conditions (Sanogo et al., 2022). Increased root branching and root hair development enable better exploitation of the soil volume, enhancing overall water and nutrient uptake efficiency (Kohli et al., 2022). Root hairs are delicate, elongated structures that emerge from the root epidermis, thereby increasing the root surface area and improving its ability to absorb water and nutrients (Wei & Li, 2016).

2.7.2 Stress tolerance mechanism

Drought tolerance is the ability of a plant to maintain its physiological functions even under extreme drought stress. This is achieved by adjusting the osmotic pressure, antioxidant defense system and hormonal regulation to either minimise or restore the damage caused by stress (Yordanov et al., 2003; Haghpanah et al., 2024).

2.7.2.1 Osmotic Adjustment

Osmotic adjustment is a physiological process that helps plants, including pearl millet, cope with water stress caused by drought or inadequate irrigation (Chen & Jiang, 2010; Shrestha et al., 2023). It involves the accumulation of osmolytes, such as soluble sugars and specific amino acids, within plant cells in response to water deficits (Turner, 2018; Bhutto et al., 2023). Osmolytes are small organic compounds that help to maintain cell turgor and cellular hydration, allowing plants to endure periods of water scarcity (Sharma et al., 2019; Singh et al., 2015). When pearl millet is subjected to water stress, it experiences a decrease in soil water availability, which is subsequently reflected within the plant. In response, pearl millet initiates osmotic adjustment to maintain cellular water balance (Bani Hani et al., 2022; Shrestha et al., 2023). In cells, it synthesises and accumulates osmolytes, such as proline, betaine, and soluble sugars, to increase osmotic potential (Cattivelli et al., 2008; Bani Hani et al., 2022). Osmotic adjustment helps prevent cellular dehydration during water stress, thereby reducing leaf senescence (Mahmood et al., 2020). By accumulating osmolytes, pearl millet can maintain a higher osmotic potential than that of the surrounding soil or environment. This reduces the gradient of water movement from plant cells, thereby minimising water loss and preventing cellular dehydration. Osmotic adjustment also helps to protect cell structures by accumulating proline during water stress (Yang et al., 2021). Accumulated osmolytes can be rapidly metabolised during stress injury, and cellular hydration is restored more efficiently (Yang et al., 2021).

The extent of osmotic adjustment in pearl millet can vary based on genetic factors, environmental conditions, and severity and duration of water stress. Some pearl millet varieties may exhibit better osmotic adjustment capabilities, allowing them to more effectively tolerate water stress. Determining how various cultivars or varieties respond to water stress conditions is pivotal for tailor-made decisions or solutions for each case. For example, in a study conducted by Wasaya et al. (2022) on YBS-98 and BY-18 pearl millet cultivars grown under full irrigation, regular irrigation, and drought stress at the flowering stage, altered physiological responses were observed. Additionally, 0, 2, 4, and 6 mg L^{-1} silicon (Si) levels were applied to the leaves of pearl millet. During the 2018 and 2019 field studies conducted during the Kharif season in Punjab, Pakistan, different physiological (proline content, SPAD-chlorophyll value, and membrane stability index) and yield attributes were measured. The results indicated that terminal drought stress decreased all agronomic attributes of pearl millet, except proline content. Proline content increased under drought-stressed conditions. They concluded that foliar application of 6 mg L − 1 Si could be the best option for attaining a sustainable millet yield under terminal drought conditions (Wasaya et al., 2022).

2.7.2.2 Antioxidant Defense System

The antioxidant defense system is a complex network of enzymatic and non-enzymatic components that protects plants from oxidative stress (Hasanuzzaman et al., 2020). Oxidative stress occurs when the production of reactive oxygen species (ROS) exceeds the ability of the plant to neutralise and detoxify them. ROS are highly reactive molecules that, when in high concentrations, can damage cellular components, including proteins, lipids, and DNA, leading to cellular dysfunction and even cell death (Hasanuzzaman et al., 2020; Raja et al., 2017). Many genes encoding ROS-scavenging enzymes are activated in pearl millet in response to heat stress (Singh et al.,2024), suggesting that ROS production increases during stress in general. For example, many genes encoding ROS-scavenging enzymes are activated in pearl millet in response to heat stress (Huang et al., 2021).

Water stress can lead to the accumulation of ROS in plant cells, especially in chloroplasts and mitochondria (Das & Roychoudhury, 2014), which are generated as by-products of photosynthesis and respiration, respectively. Choudhury et al. (2022) found that drought stress elevates reactive oxygen species (ROS) levels in the roots and shoots of pearl millet seedlings. In response, pearl millet activates various antioxidant enzymes to counteract and neutralise these harmful molecules. However, after exposure to drought stress, key antioxidant enzymes such as catalase (CAT), guaiacol peroxidase (GPX), superoxide dismutase (SOD), and glutathione reductase (GR) were suppressed, suggesting a breakdown in the plant's antioxidant defense system. Their study concluded that pearl millet was highly vulnerable to drought stress during the early seedling stage (Choudhury et al., 2022). Water availability also influences the concentration of non-enzymatic antioxidants in pearl millet. Compounds such as ascorbic acid (vitamin C), glutathione, and tocopherols (vitamin E), serve as ROS scavengers and play a vital role in safeguarding cellular structures from oxidative damage. Photosynthesis is a significant source of ROS in plants, and maintaining a functional antioxidant defense system is essential to protect the photosynthetic machinery from oxidative damage (Foyer, 2018; Hasanuzzaman et al., 2020). Water stress-induced oxidative damage can negatively affect the growth and productivity of pearl millet (Choudhury et al., 2022).

2.7.2.3 Hormonal Regulation

Hormonal regulation of pearl millet plays an important role in plant growth, development, and adaptation to environmental stress. Hormones are chemical messengers that control various physiological processes in plants (El-Esawi, 2017). These hormones are auxins (IAA), cytokinins (CKs), abscisic acid (ABA), gibberellins (GAs), and ethylene (ET) (El-Esawi, 2017). Changes in water availability can affect the synthesis, transport, and signaling of different hormones in pearl millet. Abscisic Acid (ABA) is a crucial hormone in the response of plants to water stress (Wani et al., 2016). When different pearl millet species experience water deficit, it triggers the production and build-up of abscisic acid (ABA) (Qazi et al.,2025). Elevated ABA levels facilitate stomatal closure, reduce water loss through transpiration, and conserve water within the plant, thereby helping plants survive under water-stressed conditions (Wilkinson et al., 2012). Gibberellins (GA) are growth-promoting hormones that influence stem elongation and flowering (Wani et al., 2016). Just like other cereal crops, pearl millet may exhibit lower levels of gibberellins, contributing to decreased plant height, tillering, and overall growth under water stress conditions.

Cytokinins (CK) are hormones that promote cell division and lateral bud growth (Sosnowski et al., 2023). Ethylene is a hormone involved in plant growth and development, including fruit ripening, leaf abscission, and responses to environmental stresses (Groen & Whiteman, 2014; Wani et al., 2016). Under water stress, ethylene production may increase, leading to premature senescence (aging) in leaves and other plant tissues (Zia et al., 2021). Jasmonates regulate plant defense mechanisms against biotic and abiotic stressors (Wani et al., 2016). Exogenous ABA and JA improve drought tolerance in pearl millet by enhancing antioxidative enzyme activities (Awan et al., 2021). A study conducted by Javadipour et al. (2021) on wheat revealed that drought stress affected certain physiological traits. Applying methyl jasmonate (MeJA) to wheat leaves may enhance grain yield and help offset the losses caused by drought stress. They recommended using MeJA to reduce the effects of water stress on drought-tolerant cultivars. Similarly, under water stress, jasmonate levels may increase in pearl millet, activating stress-related defense mechanisms to protect the plant from damage. Auxins are hormones that influence root growth, stem elongation, and tropic responses (Woodward & Bartel, 2005). Strigolactones (SLs) have been found to regulate plant architecture, including shoot branching and tiller formation (Wu et al., 2022). Zhuang et al. (2017) highlighted that axillary buds are affected by drought stress and could be associated with SL signaling, leading to drought inhibition of tillering in perennial grass species.

2.7.3 Stress escape mechanism

Drought escape involves coordinating the timing of a plant's growth stage, life cycle, or planting to avoid drought during the growing season (Yadav & Sharma, 2016). Because pearl millet evolved from its wild progenitors under semi-desert conditions, it often has a shorter crop cycle than other cereals. This is because it has a "built-in" drought escape mechanism, such as early flowering, acquired from its wild progenitors, which results in a short grain-filling stage and small seeds (Vadez et al., 2012). In most crops, the response to drought depends heavily on matching the plant phenology with the stress environment. The primary mechanism by which pearl millet escapes drought stress involves changes in flowering plasticity (Vadez et al., 2012; Shrestha et al., 2023). Thus, the ability of pearl millet to flower early is crucial for escaping drought. The characteristics of asynchronous tiller development in pearl millet serve a dual purpose: it serves both as a means of escaping drought conditions and as a recovery mechanism during irregular drought stress in the vegetative phase (Craufurd & Bidinger, 1988; Vadez et al., 2012). This trait enables plants to produce tillers and undergo flowering at distinct times, thereby assisting in effectively mitigating mid-season droughts (Mahalakshmi & Bidinger, 1986). Moreover, pearl millet has adapted its flowering period to occur during the cooler periods of the early morning or late evening, aiming to minimise the potential damage from heat stress that may occur during the flowering stage (Jagadish, 2020). Plasticity in tillering and flowering is a valuable attribute that can be harnessed to adapt to evolving climates.

2.7.4 Stress recovery mechanism

Drought recovery refers to the ability of a plant to rejuvenate its metabolic processes once severe drought has ended (Zheng et al., 2023). Moderate or partial water stress, in which pearl millet experiences an intermittent water deficit followed by rehydration, can have complex effects on photosynthesis and stomatal conductance. During the water deficit phase, the stomata partially close to reduce transpiration losses. However, when water becomes available again, stomatal reopening, photosynthesis, and conductance can recover to some extent, depending on the degree of drought (Xu et al., 2010). Kusaka et al. (2005) found that drought-induced leaf folding 21 days after germination occurred in a pearl millet accession known for its drought resilience (IP8210), but it recovered after rewatering. Pearl millet also uses asynchronous tillering as a drought recovery mechanism (Shivhare et al., 2020; Shrestha et al., 2023). Subramanian and Maheswari (1989) compared the physiological responses of pearl millet and sorghum to water stress. Their study found that after rewatering, the stomatal conductance and transpiration rates of pearl millet recovered more quickly than those of sorghum.

2.8 Effective irrigation schemes for pearl millet water use efficiency

Irrigation is crucial for pearl millet cultivation, particularly in areas with insufficient or unreliable rainfall. Effective irrigation schemes can help optimise water use, enhance crop growth, and improve yield. Several effective irrigation schemes are widely used, such as drip irrigation, sprinkler irrigation, subsurface drip irrigation, furrow irrigation, wetting front detector systems, and scheduled irrigation.

Sustainable water management in pearl millet cultivation is crucial, particularly for implementing deficit irrigation strategies. Irrigation regimes refer to the frequency, amount, and timing of water application to plants to improve crop water use efficiency (WUE) by reducing the volume of water applied or the number of irrigation cycles (Tura & Tolossa, 2020). Several studies have highlighted the significance of drip irrigation in pearl millet systems (Bhattarai et al., 2020; Crookston et al., 2020; Hiekal & Hossam, 2022).

Previous studies on drip irrigation assessment have found a noticeable increase in yield characteristics, including seed production, straw yield, and overall biological yield, at higher irrigation levels (Bhunia & Verma, 2016; Salem & Shoman, 2021. Pearl millet hybrids, when grown as a summer crop with irrigation in the regions of Rajasthan, Gujarat, and Uttar Pradesh in India, have been documented to produce grain yields of up to 4000–5000 kg per hectare in just 80–85 days of maturation, whereas under harsh environmental conditions, only 300–400 kg ha per of grain is harvested (Khairwal et al., 2007). However, under these conditions, deficit irrigation, which involves purposefully delivering less water to the crop than required, is vital for efficient water use while minimising water wastage (Fereres & Soriano, 2007; Montazar et al., 2020).

The low productivity of pearl millet is primarily because of its cultivation under dry conditions and inadequate water management under irrigation conditions (Kumar & Kumar, 2021). Deficit irrigation strategies aim to optimise water-use efficiency by providing water when needed and reducing irrigation during less critical growth stages (Fereres & Soriano, 2007). Adopting efficient irrigation techniques, such as drip or sprinkler irrigation, can enhance the water-use efficiency in pearl millet cultivation. Additionally, understanding the crop's growth stage and phenology enables informed decisions regarding when and how much water to apply, ultimately saving water. Monitoring soil moisture levels and weather conditions can also help adjust irrigation schedules. By optimising water-use efficiency and applying water strategically, farmers can achieve both economic and environmental benefits, thereby safeguarding the long-term sustainability of pearl millet cultivation.

2.9 Conclusion

Pearl millet is a highly resilient cereal crop with significant potential to enhance food and nutritional security in arid and semi-arid regions. Its adaptability to harsh environments is underpinned by diverse morpho-physiological, biochemical, and genetic mechanisms that enable survival during drought and heat stress. However, despite its inherent resilience, climate variability, prolonged drought episodes, and poor agronomic practices continue to constrain productivity. Understanding the stress resistance mechanisms employed by pearl millet, such as drought avoidance, tolerance, escape, and recovery, is essential for optimising crop performance under water-limited conditions. Previous studies have shown that improved irrigation regimes, soil fertility management, and the integration of stress-resilient cultivars can significantly enhance water-use efficiency and yield stability. Moreover, physiological traits such as stomatal regulation, osmotic adjustment, antioxidant defense, and hormonal signalling are valuable for breeding and agronomic interventions. To ensure sustainable pearl millet production, climate-smart agricultural strategies such as deficit irrigation, intercropping, and the use of improved crop varieties must be promoted. Future research should integrate field experimentation, crop modelling, and genomics to refine irrigation scheduling, identify high-performing cultivars, and analyse the responses of pearl millet to climate change under varying environmental conditions. Ultimately, strengthening pearl millet systems is crucial for sustaining livelihoods and building resilience in semi-arid farming communities.

2.10 References

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3 AGRO-PHYSIOLOGICAL AND MORPHOLOGICAL RESPONSES OF PEARL MILLET TO VARYING WATER REGIMES IN THE SEMI-ARID CONDITIONS OF NAMIBIA

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Abstract: Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is a C4 plant adapted to semi-arid climates and is one of the primary staple foods in Sub-Saharan Africa, including in Namibia. The decline in yields associated with water scarcity over the years has been a national concern in the country. An experimental field trial was conducted at the Mannheim Crop Research Station, Namibia, during the 2023 and 2024 cropping seasons to investigate the response of two local pearl millet cultivars (Kangara and Okashana 2) to different water regimes (100%, 75%, and 50% crop evapotranspiration [ETc]) according to morpho-physiological and yield parameters. Pearl millet was planted in a split-plot factorial design with four rows per plot under the three water regimes, and the genotypes were planted in subplots. The results revealed that the water regime had a significant effect on plant height, number of leaves, tillers, chlorophyll content, stomatal conductance, leaf temperature, stem thickness, number of productive tillers, panicle diameter, panicle length, dry panicle weight, biomass, grain weight, and 1000-seed weight of the two pearl millet cultivars ($p < 0.001$). At 50% ETc, the water regime significantly reduced the growth and yield parameters compared with the 75% ETc and 100% ETc water regimes, highlighting the significance of water in plant development and growth. The findings highlighted that both cultivars responded similarly to water stress. This research has significant implications for the planning and production of pearl millet under water-limited environments under changing climatic conditions.

Keywords: *crop physiology; evapotranspiration; Namibia; pearl millet; water scarcity*

3.1 Introduction

In recent decades, water availability has been declining owing to climate change and population growth, particularly in arid and semi-arid regions, posing significant challenges to sustainable crop production (Emediegwu et al., 2022; UN-Water, 2024). These challenges are acute in Sub-Saharan Africa (SSA), where unpredictable rainfall patterns and high temperatures limit agricultural productivity (Emediegwu et al., 2022). This is reflected in declining crop yields across the region due to drought stress. Drought stress occurs when available soil water is limited for crop utilisation, whereas atmospheric conditions, such as high temperatures, cause continuous water loss by transpiration or evaporation (Farooq et al., 2012). Drought stress negatively affects key physiological, morphological, biochemical, and molecular processes in crops, including growth phenology, water and nutrient uptake, and photosynthesis (Salehi-Lisar & Bakhshayeshan-Agdam, 2016).

Pearl millet (*Pennisetum glaucum* (L.) R. BR.), a drought-tolerant crop, is promising for sustaining food production under these challenging conditions because of its low water requirement compared to other cereal crops. Millions of people in Sub-Saharan Africa and Asia consume millet as a staple diet (FAO, 2023). However, pearl millet is susceptible to water stress at critical stages of development (Choudhury et al., 2022; Emediegwu et al., 2022). Globally, crop production is frequently constrained by moisture stress during the growing season in dryland environments, leading to significant reductions in economic yields (Kapoor et al., 2022). Despite its resilience to arid environments compared with crops such as maize, rice, and wheat, pearl millet faces the risk of yield loss due to frequent drought and heat stress (Kapoor et al., 2022). For example, in Nigeria, erratic rainfall and poor crop management have reduced yields, leading to crop failure in pearl millet production (Azare et al., 2020).

The benefits of pearl millet extend beyond its role as a source of food. Its by-products, including fodder, porridge, and snacks, contribute to food security and economic resilience (Siroha et al., 2016. It is cultivated in several countries in Southern Africa, including Botswana, Namibia, South Africa, Zambia, and Zimbabwe (Upadhyaya et al., 2007). Despite its importance, the physiological and agronomic responses of local pearl millet cultivars under water deficit conditions remain underexplored, particularly in Namibia. Given the sensitivity of crops to water stress, understanding how different water regimes affect their physiological and yield traits is critical for improving productivity under semi-arid conditions.

Studies investigating drought tolerance in pearl millet and the effects of water relations on physiological and biochemical traits under different environments have found that drought stress affects the growth traits of pearl millet (Bello et al., 2019; Choudhury et al., 2022; Ateeq et al., 2024). Assessing crop performance across diverse agroecological systems is crucial for optimising agricultural practices. Lincoln et al. (2023) highlighted that agroecological niches and associated cropping systems are essential for realising the potential of underutilised crops. Darmaun et al. (2023) highlighted the importance of multidimensional and multiscale assessments in evaluating agroecological transitions, emphasising adaptability to local conditions and social interactions. Considering the differences brought about by agroecological zones, there is a dearth of information regarding the responses of different local cultivars, such as Okashana 2 and Kangara, to varying irrigation treatments in Namibia, where both genetic and environmental factors significantly influence crop yields. This is critical for ensuring food security under the changing environmental conditions in Namibia.

In light of these gaps, this study sought to evaluate the effects of different water regimes on the physiological and yield parameters of two pearl millet cultivars, Okashana 2 and Kangara, cultivated in Namibia. We determined (i) the effect of different water regimes on pearl millet height, number of tillers, number of leaves, chlorophyll content, stomatal conductance, and leaf temperature of pearl millet in Tsumeb, Namibia, and (ii) the impact of the growing season, water regime, and variety on morpho-physiological characteristics. We hypothesized that higher irrigation levels would enhance the agro-morphological and physiological traits of both cultivars. Furthermore, it was anticipated that, owing to their genetic differences, Okashana 2 and Kangara would exhibit distinct responses to different water regimes for pearl millet in Namibia.

3.2 Materials and Methods

3.2.1 Study Area

Namibia is a semi-arid country in Sub-Saharan Africa (SSA) (Byers, 1997; Lange, 1998). This study was conducted at Mannheim Research Station experimental field sites in the Oshikoto Region, Namibia (Lat. −19.168611 and Lon. 17.763056). Both crop production and livestock farming are practised in this area. Namibia is characterised by highly variable rainfall and temperature in space and time (Figure 3.1), recurrent droughts, and water scarcity. According to Namibia Water Corporation, Ltd. (NamWater) (Namibia Water Corporation Ltd [NamWater], 2022), the annual rainfall varies between 550 mm and 600 mm in the north and 250 mm and 300 mm in the south. Nearly 80% of the country is supplied by underground water, mainly because it is naturally protected from evaporation; hence, it depends on this source. Evapotranspiration rates vary from 2600 mm per annum in the northeast to 3700 mm per annum in the south. Higher evapotranspiration rates were observed between October and December. During the September to December 2023 cropping season, the monthly maximum temperature ranged between 38 °C and 36 °C; the average temperature ranged between 28 °C and 25 °C, and minimum monthly temperatures ranged between 18 °C and 12 °C, which were obtained from the synoptic station of Tsumeb. The corresponding rainfall measured during that period was in November and December with 7.2 mm and 33.6 mm, respectively. Conversely, during the January to April 2024 cropping season, the maximum monthly temperature ranged between 36 °C and 32 °C; the average monthly temperature ranged between 25 °C and 22 °C, and minimum monthly temperatures ranged between 18 °C and 14 °C, while the rainfall received during that period ranged from 63.3 mm to 18.8 mm.

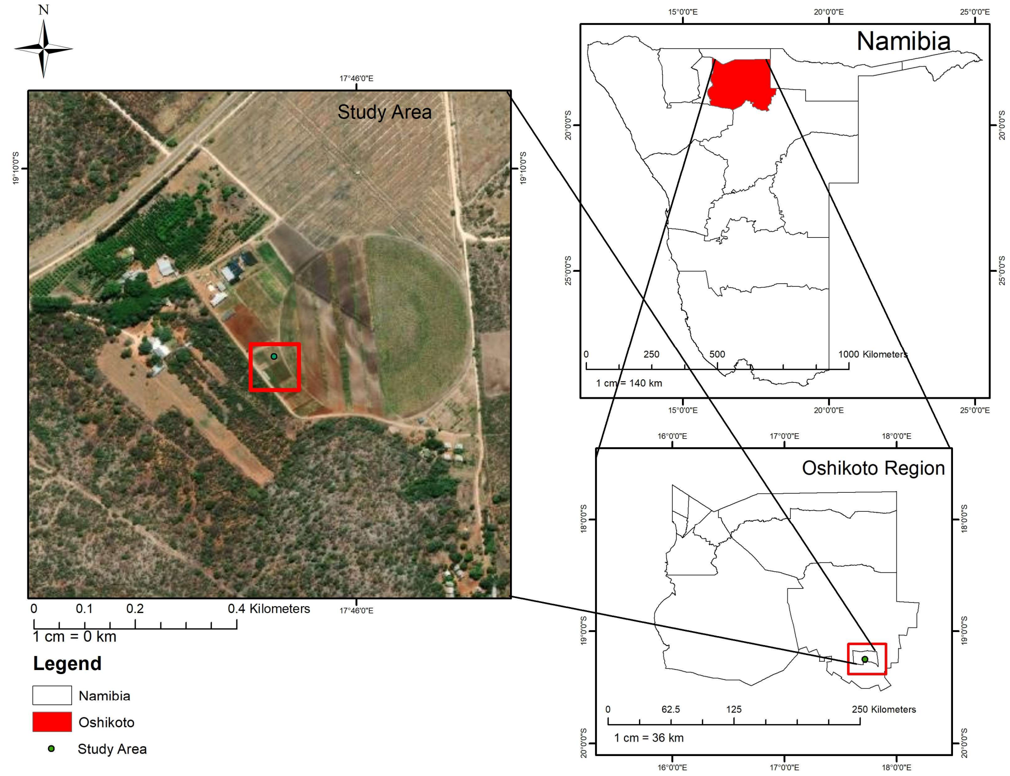


Figure 3-1. Map showing the study area at Mannheim Crop Research Station, Tsumeb, Oshikoto region, Namibia.

3.2.2 Methodology

3.2.3 Experimental Design

First, the land was prepared by clearing debris, followed by the placement of the irrigation system. The experiment was then laid out in a blocked split-plot design, with three irrigation treatments as the main plot factor and crop cultivars (Kangara and Okashana 2) as the subplot factor, with four replicates. Before sowing, soil samples were taken to make a composite sample that was analysed in the lab for fertility and classification according to a previously described method (Walworth, 2011). Soil samples were collected from five locations on each plot to create a composite. Polyethylene drip laterals (20 mm inside diameter) were installed before planting in every plot, with emitters (rated at 1 L/h discharge) spaced every 0.2 m on the laterals. Each plot was 3 m by 3 m, and a buffer zone with 1.0 m and 2.0 m spacing was provided between the plots and blocks (Figure 3.2). After irrigation, observations of emitter wetting patterns showed complete closure between adjacent emitters on the same lateral side, and more than 85% between rows, which ensured uniform wetting within the plots. Each plot consisted of four rows spaced at 0.75 m; only the two middle rows were used for monitoring, while the other two were used as borders. Several seeds were planted in each hole at a spacing of 0.15 m, and thinning was performed after emergence to achieve a population of 30 plants, with one plant in each stand. The first trial season was conducted from September to December 2023, and the second from January to April 2024.

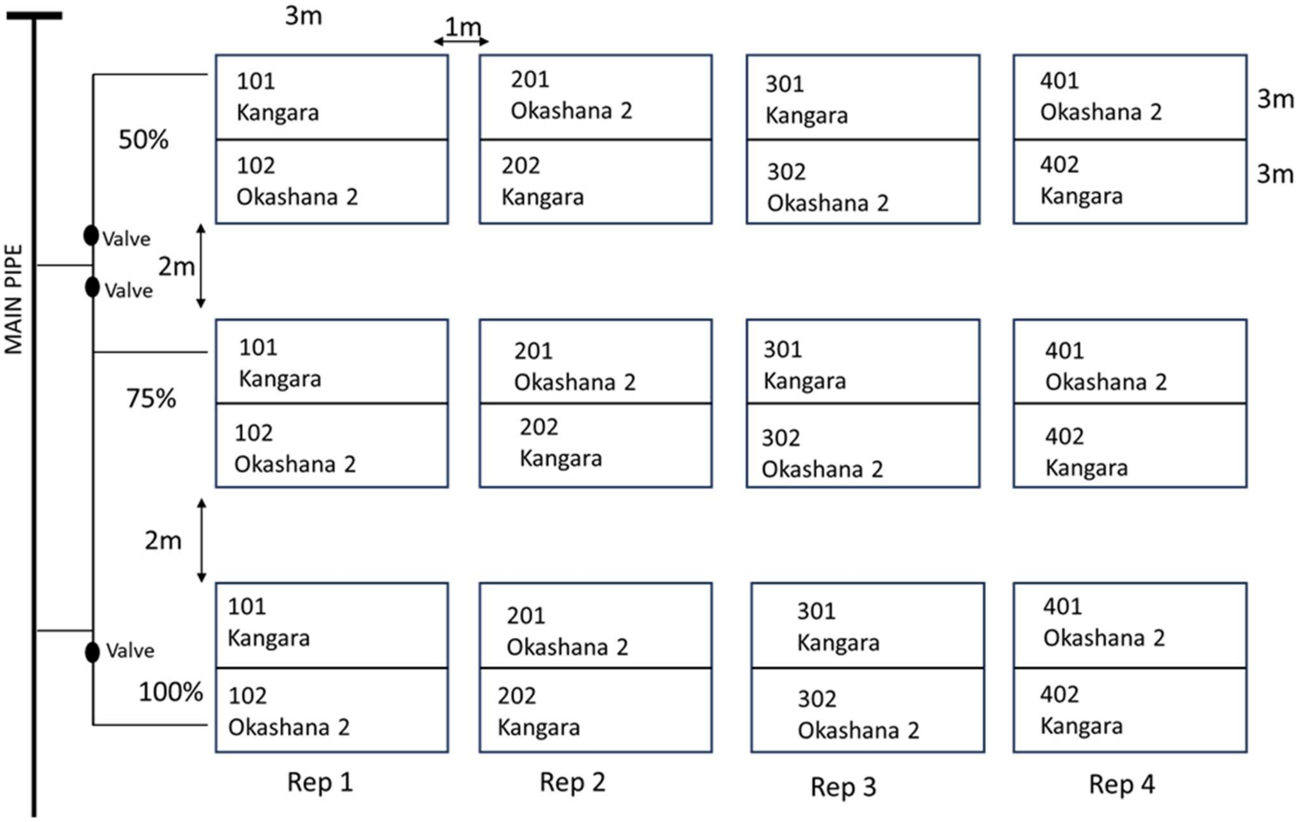


Figure 3-2. Experimental design for the September–December 2023 and January–April 2024 growing seasons. Numbers above the variety in each plot represent the plot number.

3.2.4 Treatments Determination

The crop evapotranspiration rate was computed using the CROPWAT 8.0 model (Smith et al., 1998), which uses meteorological, soil, and crop factors as the inputs for the study area. Long-term monthly climate averages for the Oshikoto region were obtained from the National Aeronautics and Space Administration (NASA) for 1991–2022 (https://power.larc.nasa.gov/data-access-viewer/, accessed on 15 August 2023) (National Aeronautics and Space Administration (NASA), 2023). The data acquired were the mean monthly minimum and maximum temperatures (°C), relative humidity (%), solar radiation/sunshine hours, rainfall (mm), and wind speed (m/s). Crop data were obtained from existing databases and the literature, such as the FAO database (Allen et al., 1998; Smith, 1993). These data were input into CROPWAT 8.0 model to determine the potential evapotranspiration rate (ET_o) of the area. The actual crop evapotranspiration (ET_c) was derived by multiplying the potential evapotranspiration (ET_o) by the crop factor (K_c), based on both growth stages and soil water measurements. A total of 75% and 50% of the ETc from CROPWAT 8.0 computation were used to determine the crop response to different percentages of water supplied in addition to the control (100 ETc) (Table 3.1).

Table 3-1. The total amount of irrigation water supplied to Pearl Millet.

Treatment (ETc)	**Total Water Applied (mm)— Season 1 (September to December 2023)**	**Total Water Applied (mm)— Season 2 (January to December 2024)**
50%	304.77	239.34
75%	457.16	359.02
100%	609.55	478.69

3.2.5 Data Collection

Agronomic trait data were collected using the pearl millet descriptor methods described by the International Board for Plant Genetic Resources (IBPGR) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) (IBPGR and ICRISAT, 1993).

3.2.5.1 Morphological Traits Data

Quantitative data were acquired through biometric parameter measurements, including plant height (PH), stem thickness, number of leaves, and tillers. These data were collected at physiological maturity from five plants in each plot, selected randomly. The plant height (PH) was measured from the base of the plant to the tip of the panicle. The number of physiologically active leaves and tillers was counted and recorded accordingly.

3.2.5.2 Stomatal Conductance Measurements

Stomatal conductance was measured using the Decagon Leaf Porometer (SC-1; Decagon Devices Inc., Pullman, WA, USA). Readings were taken from the abaxial surfaces of the fully expanded and exposed leaves. In each plot, three plants were randomly selected to take conductance measurements, which were later averaged to get the conductance for each treatment. These readings were taken just before physiological maturity at 83 days after planting.

3.2.5.3 Chlorophyll Content Measurements

Using a digital SPAD-502 Plus chlorophyll meter (Konica Minolta Sensing, Inc. Tokyo, Japan), the SPAD values were determined (Minolta, 2009). The chlorophyll meter is a spectral instrument that measures the difference in transmittance between red (650 nm) and infrared (940 nm) light passing through the leaf, generating a 3-digit SPAD value. This value was used to take chlorophyll content readings from the three uppermost, fully expanded leaves from each plot. Three SPAD values per leaf, including one value around the midpoint of the leaf blade and two values 3 cm apart from the midpoint, were averaged to give the mean SPAD value of the leaf as outlined by a previous study (Zhang et al., 2019). Readings were taken just before physiological maturity at 83 days after planting.

3.2.5.4 Leaf Temperature Measurements

Leaf temperature measurements were taken using a non-contact laser infrared digital thermometer (EC-Technology, N10IT001–5, Woodridge, IL, USA) between 1200 and 1300 hours when the plants were exposed to concentrated sunlight radiation. Three plants were selected from each plot for the measurements. Upper-top leaves fully exposed to the sun's radiation were targeted. These readings were taken just before physiological maturity at 83 days after planting.

3.2.5.5 Yield and Yield Attributes Measurements

At physiological maturity, several data were collected from the main stem. Stem thickness (ST) and panicle diameter (PD) (cm) were measured using a Vernier caliper. Panicle length (PL) in centimeters was measured from the lower panicle branch to the tip of the panicle. Aboveground biomass (B) and panicles were harvested and air-dried for two weeks before weighing. The dry panicle weight (DPW) in grams was measured and recorded after drying before hand-threshing them. Grain weight (GW) was measured in grams by weighing the grains per panicle, which was recorded after threshing. The grains were then weighed using a balance scale, and thousand-grain weight (1000-GW) seeds were counted using an electronic seed counter (Pfeuffer Contador GmbH, Kitzingen, Germany).

3.2.6 Data Analysis

The effects of the cropping season, water regime, and variety on morpho-physiological traits, including plant height, number of leaves, number of tillers, leaf temperature, chlorophyll content, stomatal conductance, and yield attributes of pearl millet, were analysed using a two-way factorial design with analysis of variance (ANOVA) in R version 4.4.0 (R Core Team, 2021) (Equation (1)). Model assumptions were tested by evaluating the normality of error distributions for each dependent variable using the Shapiro–Wilk test ($p < 0.05$) and assessing the homoscedasticity of variances using the Levene test ($p < 0.05$). When a significant F-test was detected, a post-hoc analysis using Tukey's Honestly Significant Difference (Tukey's HSD) at a 5% significance level was performed to identify the groups that showed significant differences. Akaike information criteria (AIC) were used to compare potential models, with the model with the lowest AIC score considered the best fit for describing the relationships between season, water regime, variety, and their interactions with the morpho-physiological and yield traits studied (R Core Team, 2021) (Sakamoto et al., 1986).

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \tag{1}$$

where Y_{ijk} is the dependent variable; μ is the overall mean of the dependent variable; α_i is the effect of the i-th level of the main effect A; β_j is the effect of the j-th level of the main effect B; $(\alpha\beta)_{ij}$ is the interaction effect of A and B, and ε_{ijk} is the residual error (Martınez, 2015).

3.3 Results

3.3.1 Effects of Water Regime, Variety, Season, and Their Interactions on the Morpho-Physiological Traits of Pearl Millet Varieties

The results analysing the water regime had a statistically significant effect ($p < 0.001$) on plant height, number of leaves, number of tillers, chlorophyll content, stomatal conductance, and leaf temperature(Table 3.2). The variety had a statistically significant effect on plant height ($p < 0.05$). The season had a statistically significant effect ($p < 0.001$) on plant height, number of leaves, tillers, and chlorophyll content. Furthermore, there was a statistically significant interaction between the water regime and season on plant height ($p < 0.001$) and number of tillers ($p < 0.001$). However, there was no statistically significant difference in the interaction of the water regime by season on the other measured plant parameters. There was a clear positive response between the water regime, season, and the dependent variables, while with variety, there was no distinct difference for most of the measured parameters.

Table 3-2. Analysis of variance (mean squares) for physiological and vegetative traits of pearl millet.

Model Term	**DF**	**Plant Height (cm)**	**No. of Leaves**	**No. of Tillers**	**Chlorophyll Content (SPAD value)**	**Stomatal Conductance (mmol_m_2_s_)**	**Leaf Temperature (°C)**
Water Regime (WR)	2	3078.48 (<0.001)	131.94 (<0.001)	81.39 (<0.001)	687.61 (<0.001)	90,047.00 (<0.001)	398.58 (<0.001)
Variety (V)	1	349.25(0.05)	0.15 (0.807)	0.18 (0.72)	0.47 (0.88)	4178.00 (0.26)	0.25 (0.84)
Season (S)	1	1333.47 (<0.001)	234.53 (<0.001)	201.38 (<0.001)	1021.36 (<0.0010)	2346.00 (0.40)	47.73 (0.005)
WR × V	2	71.67 (0.43)	0.26 (0.90)	0.08 (0.94)	24.75 (0.27)	2068.00 (0.53)	0.15 (0.97)
WR × S	2	1199.87 (<0.001)	4.63 (0.172)	13.47 (<0.001)	35.35 (0.16)	2300.00 (0.49)	21.66 (0.03)
V × S	1	191.82 (0.13)	1.02 (0.53)	2.12 (0.21)	0.02 (0.93)	1100.00 (0.56)	0.43 (0.78)
WR × V × S	2	76.71 (0.40)	1.61(0.53)	0.17 (0.88)	0.75 (0.96)	334.00 (0.90)	0.92 (0.85)
Residual	36	81.94	2.51	1.32	18.42	3201.00	5.56
Grand Mean		149.18	10.97	5.43	44.45	297.61	34.27
CV (%)		6.1	14.4	21.1	9.7	19.0	6.9
S.E±		9.05	1.58	1.15	4.29	56.58	2.36

Note: DF: degrees of freedom brackets (*p*-values). Means were separated using Tukey's Honestly Significant Difference (Tukey's HSD) test at *p* = 0.05.

3.3.1.1 Interaction of Water Regime by Season on Pearl Millet Morpho-Physiological Characteristics

Figure 3.3a,b shows the interaction effect of water regime and season on pearl millet growth and development. The seasonal effect model had the lowest AIC compared to other model terms. Graph (a) shows the relationship between plant length and the water regime across the two seasons. Statistically significant differences in plant length were observed between the different water regimes in September–December 2023 and January–April 2024. Plants under the 50% ETc treatment, September–December 2023, showed the shortest length, and from January to April 2024, plants showed similar height to those in September–December 2023. It can be seen from the graphs that the 100% ETc treatment resulted in longer plants, and September–December 2023 plants tended to be longer than January–April 2024 plants in each water regime. Under the 75% ETc treatment in September–December 2023, plants were slightly shorter than under the 100% ETc treatment, similar to the treatment with 100% ETc in January–April 2024. Under the 100% ETc treatment, plant lengths were statistically different from those under 50% ETc in September–December 2023. Plants have the highest mean length under 100% ETc in September–December 2023 compared to January–April 2024. These results show the influence of water availability on plant height. Higher water availability resulted in taller plants.

Graph (b) shows the relationship between the number of tillers (presented on a logarithmic scale) and different water regimes across the two seasons. Under 50% ETc in September–December 2023, plants showed a moderate number of tillers, whereas in January–April 2024, plants had the lowest number. Higher water availability (100% and 75% ETc) resulted in a more significant number of tillers, as there were no statistically significant differences between the two water regimes in either season. Under 75% ETc in September–December 2023, plants also showed a higher number of tillers than in January–April 2024 plants under the same treatment. September–December 2023 plants had the highest number of tillers, whereas in January–April 2024, plants had fewer tillers under the same treatment of 100% ETc. There was a statistically significant difference between the seasons in this water regime, as indicated by the different letters. However, September–December 2023 generally produced more tillers than January–April 2024 across all water regimes.

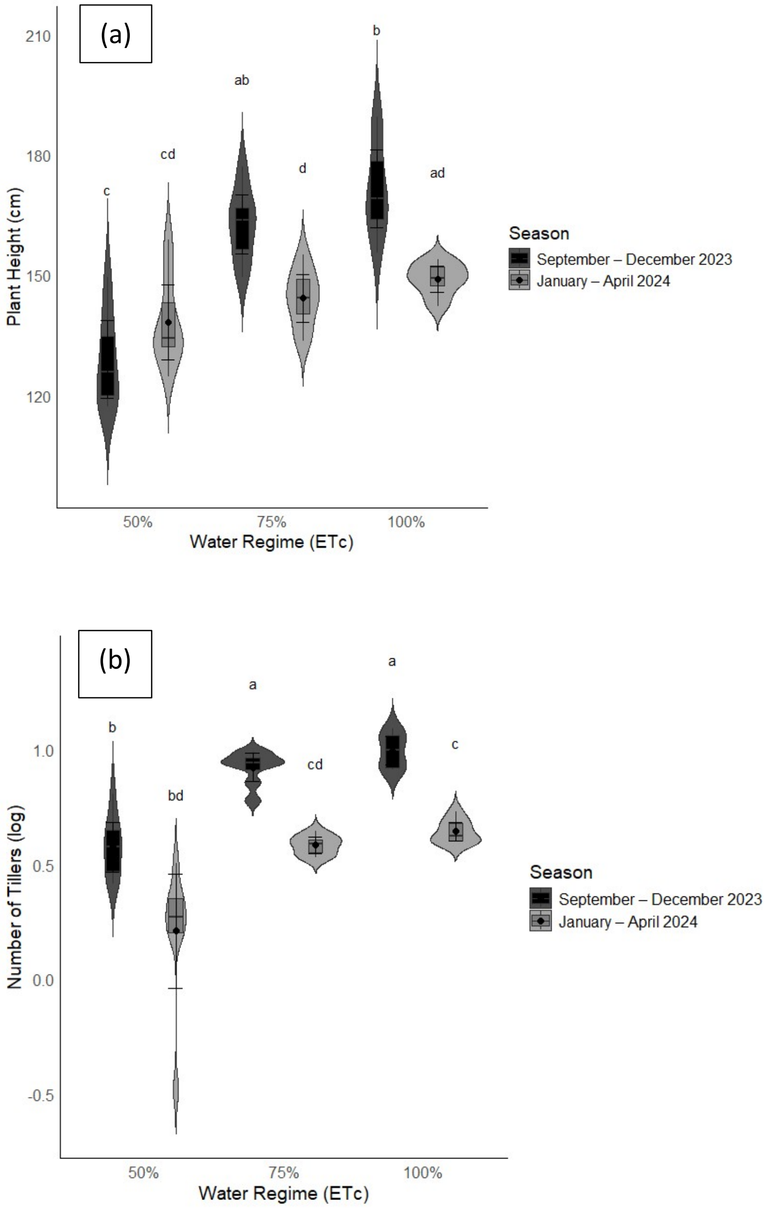


Figure 3-3. Interaction effect of water regime by season on pearl millet length (a) and number of tillers (b). Means are separated by Tukey's Honestly Significant Difference (Tukey's HSD) test at p = 0.05. Different superscript letters explain mean differences. Season 1 is September–December 2023, and Season 2 is January–April 2024. Whiskers represent standard errors.

3.3.2 Effects of Water Regime, Variety, Season, and Their Interactions on the Yield and Yield Attributes Response of Pearl Millet to Water Regimes

Table 3.3 shows that there was a statistically significant difference in the effect of the water regime on stem thickness (F (2) = 16.215, $p < 0.001$), and there was no statistically significant interaction between the water regime and season on stem thickness. There was a statistically significant interaction between the water regime and season (F (2) = 12.228, $p < 0.001$) on the number of productive tillers. There was a statistically significant difference in water regime (F (2) = 20.273, $p < 0.001$) and a statistically significant difference in season (F (1) = 35.018, $p < 0.001$) on panicle diameter, and there was no statistically significant interaction effect of water regime by season on panicle diameter; however, there was no statistically significant interaction difference of water regime by season on panicle length. There was a statistically significant difference (F (2) = 2.791, $p < 0.05$) in the length of the panicles. There was also a statistically significant difference in the panicle length (F (1) = 17.774, $p < 0.001$). There was a statistically significant difference (F (2) = 31.240, $p < 0.001$) between the water regimes and panicle weight; however, there was no statistically significant difference in the water regime by season on the dry panicle weight. There was a statistically significant interaction effect of the water regime and season on biomass (F (2) = 9.626, $p < 0.001$). There was also a statistically significant interaction effect of the water regime and season on grain weight (F (2) = 3.536, $p < 0.05$). There was no statistically significant interaction effect of water regime on the 1000-grain weight by season; however, there was a statistically significant effect of water regime (F (2) = 62.411, $p < 0.001$), variety (F (1) = 5.404, $p < 0.05$), and season (F (1) = 37.208, $p < 0.001$). Overall, the water regime influenced all measured parameters; the variety affected panicle length and 1000-seed weight; the season affected the number of productive tillers, panicle diameter, biomass, and 1000-seed weight; and the interaction between water regime and season affected the number of productive tillers, biomass, and grain weight of pearl millet.

Table 3-3. Analysis of variance (mean square) of yield and yield attributes of pearl millet varieties evaluated at different water regimes in the 2023 and 2024 seasons.

Model Term	**DF**	**ST (cm)**	**NP**	**PD (cm)**	**PL (cm)**	**DPW (g)**	**BM (g)**	**GW (g)**	**1000-SW (g)**
Water Regime (WR)	2	0.12 (<0.001)	18.51 (<0.001)	0.34 (<0.001)	5.71(0.07)	10,043.0 (<0.001)	99,558 (<0.001)	4521.0 (<0.001)	80.58 (0.001)
Variety (V)	1	0.01(0.28)	0.81 (0.15)	0.01 (0.46)	36.38 (<0.001)	109.0 (0.56)	2576 (0.25)	21.0 (0.71)	6.98 (0.03)
Season (S)	1	0.0008(0.76)	7.32 (<0.001)	0.58 (<0.001)	1.08 (0.47)	391.0 (0.28)	41,167 (<0.001)	169.0 (0.30)	48.04 (<0.001)
WR × V	2	0.004 (0.64)	0.60 (0.22)	0.002(0.91)	0.50 (0.78)	80.0 (0.78)	4814 (0.08)	72.0 (0.63)	3.24 (0.10)
WR × S	2	0.009 (0.31)	4.67 (<0.001)	0.020.32	5.36(0.09)	681.0 (0.14)	17863 (<0.001)	533.0(0.04)	0.39 (0.74)
V×S	1	0.01 (0.22)	0.03(0.79)	0.04(0.13)	2.05(0.32)	196.0 (0.44)	68 (0.85)	26.0 (0.68)	1.67 (0.26)
WR × V × S	2	0.001 (0.88)	0.34 (0.42)	0.02(0.40)	0.26(0.88)	416.0 (0.29)	90 (0.95)	138.0(0.41)	0.37 (0.75)
Residual	36	0.008	0.38	0.02	2.05	321.0	1856	151.0	1.29
Grand Mean		0.58	2.95	2.51	20.71	70.75	164.17	48.88	9.72
CV (%)		15.0	21.0	5.1	6.9	25.3	26.2	25.2	11.7
S.E ±		0.09	0.62	0.13	1.43	17.93	43.08	12.30	1.14

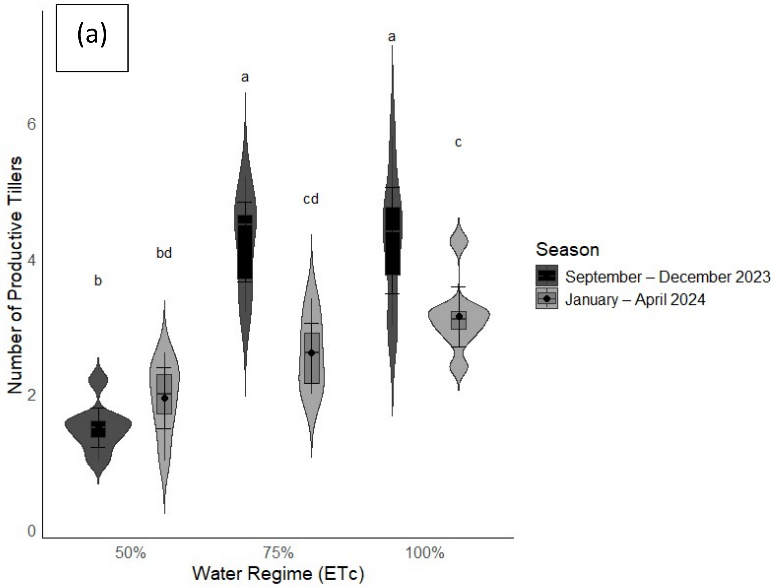
Note: DF, degrees of freedom; ST, stem thickness; NP, number of productive tillers; PD, panicle diameter; PL, panicle length; DPW, dry panicle weight; BM, biomass; GW, grain weight; SW, seed weight; brackets (*p*-values). Means were separated using Tukey's Honestly Significant Difference (Tukey SD) test at $p = 0.05$.

3.3.2.1 Interaction of Water Regime by Season on Pearl Millet Yield and Yield Characteristics

Figure 3.4 shows the interaction effect of the water regime by season on yield and yield attributes. The seasonal effect model had the lowest AIC compared to other model terms. (a) illustrates the interaction between water regime (ETc) and season on the number of productive tillers in pearl millet. At 50% ETc, both seasons had significantly fewer productive tillers than those under the higher water regime. September–December 2023 showed more productive tillers than January–April 2024 under the 100% and 75% ETc regimes, highlighting that conditions in September–December 2023 favour tiller productivity. Under 75% ETc, there was a similar trend to the 100% ETc regime, with September–December 2023 having more productive tillers than January–April 2024. However, the overall number of tillers was slightly lower than that at 100% ETc. Under 100% ETc, Tukey's post-hoc test revealed that September to December 2023 had a significantly higher number of productive tillers than January to April 2024. The number of productive tillers increased with a higher water regime, indicating a positive relationship between water availability and pearl millet productivity.

(b) shows the relationship between the water regimes by season and biomass. Both seasons had the lowest biomass at 50% ETc. The seasonal means were not statistically different in this water regime. The biomass decreased as the water regime decreased from 100% to 50% ETc in both seasons. September–December 2023 showed higher biomass than January–April 2024 across all water regimes, but the difference diminished in the 50% ETc water regimes. Under 75% ETc, September–December 2023 biomass was not statistically significantly different from biomass at 100% ETc. The January–April 2024 biomass was statistically different from that of September—December 2023 at 75% ETc. Under 100% ETc, September—December 2023 had the highest biomass compared to January–April 2024. The results show that biomass increased with increased water availability across the two seasons. Additionally, the seasonal effect was observed, which indicates the importance of seasons in evaluating pearl millet productivity.

(c) illustrates the relationship between water regime, season, and grain weight (in grams) for the two seasons. September–December 2023 had a lower grain weight under 50% ETc, whereas January–April 2024 had a slightly higher grain weight. However, the difference between the two seasons was not statistically significant. Grain weight decreased as the water regime decreased from 100% to 50% ETc in both seasons. September–December 2023 maintains a high grain weight at 100% and 75% ETc but significantly drops at 50% ETc. A similar pattern was observed between January and April 2024. Under 75% ETc, the mean was higher in September–December 2023 than in January–April 2024; however, the difference was not statistically significant. Under 100% ETc, September–December 2023 and January–April 2024 had high grain weights, but the results were not statistically different. The results show that grain weight increased with higher water regimes, indicating a positive relationship between water availability and grain weight.



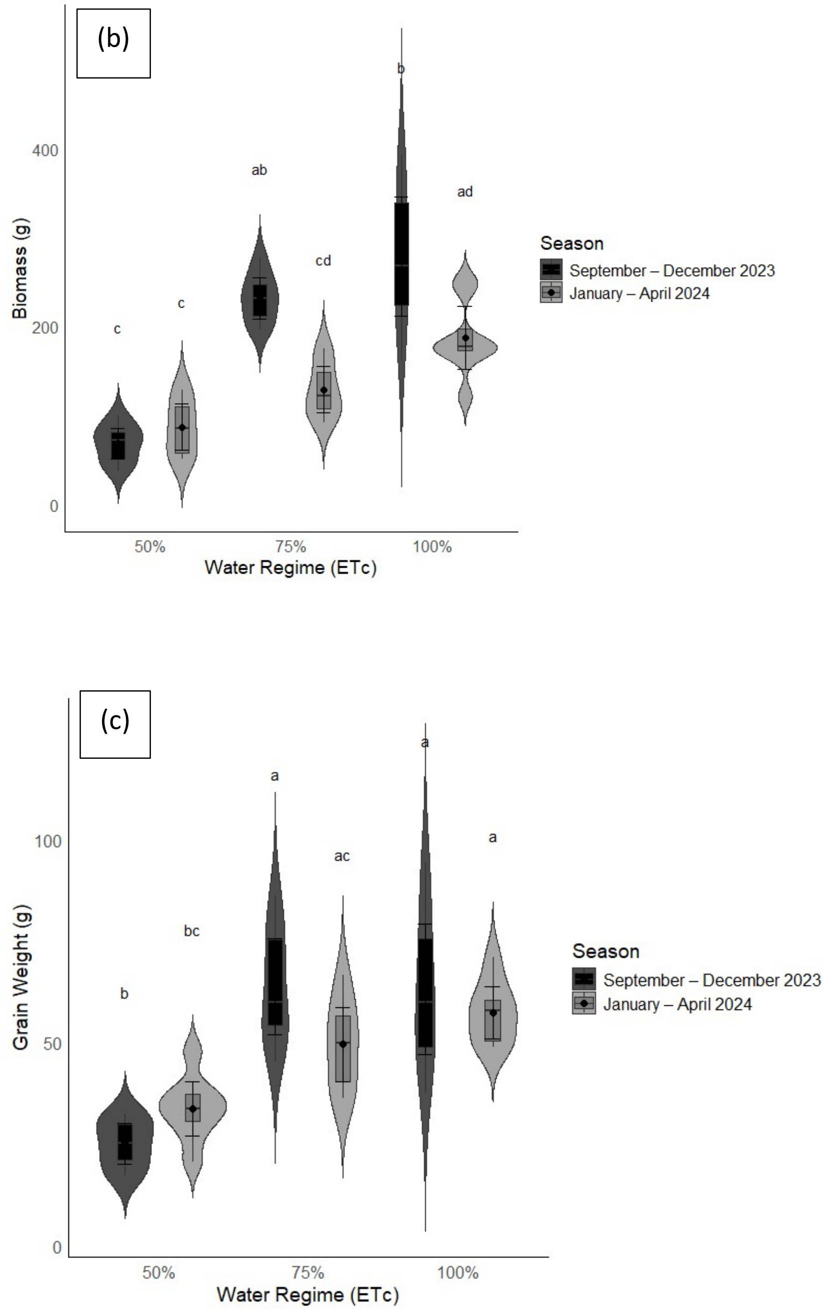


Figure 3-4. Effect of water regime by season on pearl millet's (a) number of productive tillers, (b) biomass, and (c) grain weight. Means are separated by Tukey's Honestly Significant Difference (Tukey HSD) test at p = 0.05. Means with the same letters are not significantly different. Season 1 is September–December 2023, and Season 2 is January–April 2024. Whiskers represent standard errors.

3.3.3 Changes in Yield and Yield Attributes of Pearl Millet Cultivars During the Two Studied Seasons

Table 3.4 presents the data on the effect of different water regimes on the yield and yield attributes of the two pearl millet cultivars (Kangara and Okashana 2) across the two seasons (2023 and 2024). Stem thickness decreased with reduced water availability in both seasons; the number of productive tillers was highest at 100% ETc and significantly lower at 50% ETc; and panicle diameter was highest at 100% ETc and decreased with reduced water availability. Panicle length also decreased with reduced water availability at 50% ETc. However, this difference was not statistically significant during the January to April 2024 season. Kangara had significantly shorter panicles than Okashana 2 in both seasons. The dry panicle weight was significantly lower at 50% ETc than at 75% and 100% ETc. Both seasons showed highly significant differences in biomass, with lower biomass observed in reduced water levels. Grain weight was significantly reduced at 50% ETc compared with the higher water regimes. Both seasons showed significant differences, with highly significant differences and significant differences between September and December 2023 and January and April 2024. The 1000-seed weight decreased with reduced water application. Both seasons show significant differences, with highly significant differences between January and April 2024 and significant differences between September and December 2023. Furthermore, there were no significant interactions between water regime and cultivar for yield and yield attributes in either season.

Table 3-4. Effect of water regime on pearl millet cultivars and their interaction on yield and yield attributes during the two studied seasons.

Parameter	**Stem Thickness (cm)**		**Number of Productive Tillers**		**Panicle Diameter (cm)**		**Panicle Length (cm)**	
Season	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
A. Water Regime (ETc)								
100	0.69 ^{b}	0.66 ^{b}	4.27 ^{b}	3.14 ^{b}	2.57 ^{b}	2.75 ^{b}	21.27 ^{b}	20.71
75	0.55 ^{a}	0.59 ^{b}	4.24 ^{b}	2.60 ^{ab}	2.37 ^{a}	2.67 ^{b}	21.19 ^{b}	21.03
50	0.52 ^{a}	0.48 ^{a}	1.50 ^{a}	1.93 ^{a}	2.28 ^{a}	2.46 ^{a}	19.21 ^{a}	20.83
F-test	0.004	<0.001	<0.001	0.002	0.003	<0.001	0.02	0.90
B. Cultivar								
Kangara	0.56	0.58	3.49	2.66	2.42	2.58	19.48	20.19
Okashana 2	0.62	0.58	3.18	2.45	2.39	2.67	21.64	21.52
F-test	0.15	0.91	0.28	0.36	0.63	0.08	0.002	0.04
C. Interaction								
A × B	0.66	0.92	0.16	0.88	0.80	0.38	0.89	0.78

Parameter	Dry Panicles Weight (g)		Biomass (g)		Grain Weight (g)		1000-Seed Weight (g)	
Season	1	2	1	2	1	2	1	2
A. Water Regime (ETc)								
100	89.65 ^{b}	88.89 ^{b}	278.90 ^{b}	187.59 ^{b}	63.16 ^{b}	57.52 ^{b}	10.26 ^{b}	12.04 ^{b}
75	90.98 ^{b}	70.48 ^{b}	232.40 ^{b}	129.68 ^{a}	63.83 ^{b}	49.61 ^{b}	9.69 ^{b}	12.05 ^{b}
50	40.16 ^{a}	44.31 ^{a}	69.1 ^{a}	87.38 ^{a}	25.27 ^{a}	33.90 ^{a}	6.19 ^{a}	8.07 ^{a}

F-test	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001
B. Cultivar								
Kangara	74.11	64.36	184.94	128.75	52.16	46.93	9.28	10.91
Okashana 2	73.09	71.42	201.98	141.02	49.35	47.08	8.15	10.52
F-test	0.90	0.30	0.42	0.38	0.64	0.97	0.02	0.42
C. Interaction								
A × B	0.35	0.78	0.42	0.13	0.41	0.89	0.13	0.59

Means were separated using Tukey's Honestly Significant Difference (Tukey SD) test at $p = 0.05$. Means with the same letters are not significantly different. Season 1 is September–December 2023, and Season 2 is January–April 2024.

3.4 Discussion

The seasonal variations observed in this study significantly affected the morpho-physiological parameters and yield of pearl millet. Adequate water availability (100% ETc) during the vegetative and reproductive phases enhanced photosynthesis, nutrient uptake, and biomass accumulation, supporting vigorous growth and higher yields (Tables 3.2 and 3.3). However, adverse conditions, such as high temperatures from September to December 2023 and reduced water availability (50% ETc), pose stress on the crop, leading to reduced chlorophyll content, leaf numbers, and stomatal conductance, which subsequently limits photosynthesis and assimilate transport to grains. This is in agreement with the findings of (Londhe et al., 2020), who linked seasonal changes to plant growth and productivity variation in pearl millet.

Variations in water regimes further influenced specific growth characteristics, such as plant height, number of leaves and tillers, leaf temperature, chlorophyll content, and stomatal conductance (Table 3.2). Plants under 100% ETc treatment performed better than those under 75% and 50% ETc treatments across these parameters. This could be attributed to the fact that adequate water facilitates nutrient mobilization, cell elongation, and efficient transpiration, which collectively reduce heat stress and enhance physiological processes (Chavarria & dos Santos, 2012). The findings of this study corroborate those of (Saini et al., 2018; Yadav et al., 2022), who reported increased plant height with enhanced irrigation and soil moisture availability. Furthermore, the results of this study are consistent with those of (Lira et al., 2020), who demonstrated a linear increase in leaf number with increasing water availability. Ausiku et al., (2020) found that lower water availability under rainfed conditions resulted in fewer leaves and reduced yields, which is consistent with the findings of the present study. The reduced number of leaves observed under water stress conditions in this study likely contributed to diminished photosynthetic capacity and, consequently, lower yields. Phoura et al., (2023) reported similar trends for pearl millet tiller production under well-watered conditions. The physiological basis for this phenomenon is that water stress limits the energy available for tiller initiation because water scarcity reduces photosynthetic activity and carbon dioxide uptake, both of which are essential for tiller development (Beveridge et al., 2023). Additionally, under drought stress, pearl millet exhibits plasticity by delaying tiller development to conserve resources (Vadez et al., 2012).

Water-stressed plants experience reduced transpiration, resulting in higher leaf temperatures and increased susceptibility to heat stress (Muller et al., 2021). In this study, as water was reduced (50% ETc), plants showed elevated leaf temperature compared to 100% ETc. Higher leaf temperature at 50% ETc could be attributed to less water evaporating, thereby cooling the leaf surfaces. The findings of this study align with those of (Karthika et al., 2022), who found that soil moisture conservation strategies such as mulching significantly influenced canopy temperature. Elevated leaf temperatures under water stress can result in physiological damage, as demonstrated by (Fahad et al., 2017), who emphasised the critical role of water in sustaining crop productivity under changing environmental conditions. The significant decrease in chlorophyll content under reduced water availability emphasises the impact of drought stress on photosynthetic capacity and, consequently, crop productivity. These findings are consistent with those of (Shukla & Panda, 2023, who observed reduced chlorophyll contents under drought-stress conditions. Drought-induced reductions in chlorophyll content may result from oxidative damage to chlorophyll molecules because water stress increases the accumulation of reactive oxygen species (ROS) (Shanker et al., 2022). Additionally, in this study, the stomatal conductance of pearl millet was reduced at 50% ETc. This indicates that pearl millet closes its stomata to minimise water loss through transpiration under severe water stress. While this adaptation conserves water, it can also limit carbon dioxide uptake, potentially reducing photosynthesis and, consequently, plant growth and yield. These findings are consistent with those of (El-Sabagh et al., 2017) , who reported a higher stomatal conductance under well-watered conditions.

Yield attributes such as stem thickness, panicle size, biomass, grain weight, and 1000-seed weight were also significantly affected by water availability, with well-watered conditions supporting thicker stems, larger panicles, higher dry panicle weight, and better grain development (Table 3.4). From this study, yield and yield attributes were drastically reduced at 50% ETc and were not statistically different at 75% ETc and 100% ETc. These findings highlight that water availability is crucial for sustaining crop productivity, especially under climate variability, as drought stress negatively affects photosynthetic efficiency, nutrient uptake, and yield. A similar trend was reported by a previous study (El-Tigani, 2022). High levels of irrigation resulted in high stem diameter. Furthermore, previous studies have shown that moisture stress reduces the number of productive tillers produced by pearl millet (Kayalvizhi et al., 2021; Salem &

Shoman, 2021). Moisture stress also reduces panicle length (Lira et al., 2020; Bakheit et al., 2021). Photosynthetic activity is also diminished owing to reduced leaf area and stomatal closure, limiting the carbon assimilation and energy production necessary for biomass accumulation (Farooqi et al., 2020). In this study, stomatal conductance was reduced at 50% ETc, which affected the gaseous exchange for biomass accumulation. The results of this study corroborate those of previous studies, which showed that drought or reduced moisture negatively affected biomass accumulation in pearl millet (Choudhury et al., 2022; de Almeida et al., 2022). Limited water availability critically affects the grain weight of pearl millet, primarily by disrupting vital physiological processes essential for grain development (Tharanya et al., 2017). During periods of water stress, reduced turgor pressure and impaired photosynthesis lead to lower carbohydrate synthesis and translocation to the developing grains (Qiao et al., 2024). This resulted in smaller, less dense grains with a diminished weight. Moisture stress during the grain-filling stage is particularly detrimental because it directly curtails starch deposition and other vital nutrients in the grains (Teng et al., 2023). Compared with other cereals, a similar trend in maize was observed by previous studies (Halli et al., 2021; Zou et al., 2021). They found that, at reduced moisture levels, maize yields were still higher, highlighting the adaptability of crops to moderate irrigation in semi-arid environments. (Allamine et al., 2023) also found that deficit irrigation reduced the physiological and phenological parameters of sorghum, consequently affecting yields.

This study emphasises the importance of a sufficient water supply to enhance crop resilience, optimise yield potential, and support sustainable pearl millet production in arid and semi-arid regions. Water availability significantly influences pearl millet growth, necessitating the adoption of efficient irrigation practices such as drip and deficit irrigation to optimise water use without compromising productivity.

3.5 Conclusion

This study highlights that pearl millet growth and yield are highly sensitive to water availability, with water stress inducing physiological changes that prioritise survival over productivity, resulting in reduced morphological and physiological growth and yield. These findings highlight the critical impact of water availability on key morpho-physiological parameters, such as plant height, leaf number, tiller production, chlorophyll content, stomatal conductance, panicle length, biomass, and grain weight. Optimal water conditions (100% ETc) significantly enhance photosynthesis, nutrient uptake, and plant productivity. In contrast, reduced water availability (50% ETc) triggers physiological stress responses, negatively affecting growth and yield by limiting key processes such as stomatal conductance and chlorophyll synthesis. These physiological changes prioritise resource conservation and reduce biomass accumulation and grain production. These results emphasise the importance of effective water management in crop production, particularly in drought-prone regions. Seventy-five percent of ETc is recommended as the most efficient strategy for cultivating pearl millet in semi-arid environments. Developing and implementing optimised irrigation strategies and selecting water-efficient crop varieties are essential to enhance the resilience and productivity of pearl millet under varying environmental conditions. This study contributes to the growing literature on improving crop water-use efficiency and adapting agriculture to water-limited environments. Future work should focus on the long-term effects of water regimes, soil moisture depletion patterns, testing the cultivar’s responses in different environments, and the role of soil microbes in pearl millet growth and development under moisture-limiting conditions. Furthermore, studies comparing pearl millet’s morpho-physiological changes to other cereal crops could broaden the applicability of this work.

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4 ASSESSMENT OF DROUGHT TOLERANCE INDICES AND WATER USE EFFICIENCY IN PEARL MILLET (PENNISETUM GLAUCUM) VARIETIES IN SEMI-ARID NAMIBIA

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Abstract

Globally, water scarcity is a pressing issue that must be addressed to ensure both water and agricultural sustainability. Improving water use efficiency (WUE) in pearl millet through effective agricultural practices is imperative for ensuring food security and sustainability in water-scarce environments, such as Namibia. This study aimed to determine the pearl millet water and irrigation requirements and the effect of irrigation regimes on biomass and grain yield, and consequently on the drought tolerance indices and WUE of pearl millet varieties in Namibia. This study was conducted at the Mannheim Crop Research Station in Tsumeb, Namibia, between 2023 and 2024. A split-block design was used with three irrigation regimes (100%, 75%, and 50% ETc) and two varieties (Kangara and Okashana 2). The total pearl millet water requirement varied from 609.55 mm in 2023 to 478.69 mm in 2024. The results of biomass yield (BY) ranged from 5.54 tons/ha to 1.14 tons/ha in Season 1 and between 3.81 tons/ha and 1.50 tons/ha in Season 2, while the grain yield (GY) ranged from 1.23 tons/ha to 0.38 tons/ha in Season 1 and from 1.02 tons/ha to 0.58 tons/ha in Season 2. Okashana 2 had a significantly higher harvest index (42%, $p = 0.003$) under 50% ETc, indicating drought adaptability. WUE for BY ranged from 0.78 to 1.74 kg.ha/m^3, while WUE for GY ranged from 0.28 to 0.47 kg.ha/m^3. The BY was significantly and positively correlated with grain yield (GY) ($r = 0.77$; $p \leq 0.01$). GY showed a strong positive correlation with BY ($r = 0.88$; $p \leq 0.01$).

The WUE based on GY was positively correlated with both BY ($r = 0.56$; $p \leq 0.01$) and GY ($r = 0.80$; $p \leq 0.01$). There were no statistically significant differences in drought tolerance indices among the cultivars studied. Considering the highly variable rainfall in Namibia, these findings suggest that irrigation water can be reduced by approximately 25% throughout the pearl millet growth stages without affecting the yield, thereby fostering resilience in semi-arid conditions under climate change.

Keywords: deficit irrigation, drought indices, irrigation regimes, grain yield, water use efficiency

4.1 Introduction

Pearl millet (Pennisetum glaucum (L.) R. BR.) is a drought-tolerant cereal crop predominantly cultivated in arid and semi-arid areas under rainfed conditions. It is cultivated globally in India, China, Niger, Nigeria, Burkina Faso, Mali, Ethiopia, and Sudan (Meena et al., 2021), and serves as a primary food source for millions of people, with India being the largest producer (Kumar et al., 2021). Despite its resilience, the global harvested area of pearl millet has declined over the past two decades from approximately 37 million hectares to 29 million hectares (FAOSTAT, 2024). This reduction ranged from 21 million hectares to 19 million hectares in Africa, whereas in Southern Africa it decreased from 440,000 hectares to 238,000 hectares. In Namibia, the area has decreased significantly from approximately 421,000 hectares to 211,000 hectares (FAOSTAT, 2024).

As part of the staple foods in sub-Saharan Africa (SSA), pearl millet is crucial for food security, particularly in regions where erratic rainfall and poor soil fertility limit agricultural productivity. Recently, highly variable rainfall, high air temperatures, and water scarcity have been growing concerns exacerbated by climate change, putting pressure on water resources and adversely affecting pearl millet systems. In SSA, unpredictable rainfall patterns lead to drought and heat stress, which affect the morphological, physiological, and biochemical processes of crops, such as pearl millet (Iqbal et al., 2020). Despite its known drought tolerance, pearl millet is particularly vulnerable to abiotic stressors during critical reproductive stages such as germination, gametogenesis, and early embryo development (Gupta et al., 2015; Choudhury et al., 2022). Water stress during these stages can result in a reduced grain set, lower grain weight, and significant yield losses (Jagadish et al., 2015; Siddique & Helen, 2020). Therefore, supplemental irrigation is crucial in water-limited environments to alleviate the effects of recurring droughts and to ensure sustainable crop yields (Crookston et al., 2020).

Many researchers have focused on the water-use efficiency of crops under changing environmental conditions. Water use efficiency (WUE) is the ratio of crop yield (biomass or grain) to the amount of water used, and is a crucial measure of crop performance under water-scarce conditions (Hatfield & Dold, 2019). With the increasing frequency of droughts and erratic precipitation patterns caused by climate change, improving the WUE is essential for sustainable agricultural practices. Enhancing WUE can boost crop productivity by optimising irrigation schedules, selecting drought-tolerant varieties, and using soil moisture conservation techniques (Rostamza et al., 2011; Hatfield & Dold, 2019). Numerous studies have demonstrated that deficit irrigation can improve the WUE in pearl millet. For example, Salem and Shoman (2021) demonstrated that moderate water stress could enhance WUE while maintaining satisfactory yields. Pilloni et al. (2022) found that higher sowing densities enhance WUE during seasons with high evaporative demand. Additionally, Bani Hani et al. (2022) highlighted the suitability of pearl millet in arid environments, such as Jordan, owing to its natural drought tolerance and high WUE. Determining how efficiently crops can utilise water in various environments is crucial for sustainable water management and food security. Under drought conditions, the harvest index (HI) is often lower, indicating that plants allocate more biomass to roots and survive than to grain production. HI is the proportion of grain yield to the total biological yield (aboveground biomass), indicating the efficiency of the conversion of total biomass into a harvestable product (Ludemann et al., 2023). Zhapayev et al. (2023) found that under drought stress conditions, pearl millet allocates more resources to root growth and survival than to grain production, resulting in a lower harvest index across different genotypes. Drought tolerance indices, such as yield index (YI), yield stability index (YSI), stress tolerance index (STI), stress susceptibility index (SSI), mean productivity (MP), geometric mean productivity (GMP), harmonic mean (HM), and tolerance index (TOL), are essential for evaluating crop varieties under water-stressed conditions. These indices facilitate the selection of cultivars that can withstand drought-stressed conditions and optimise breeding strategies for environments with limited water availability (Rosielle & Hamblin, 1981; Bouslama & Schapaugh Jr., 1984; Fernandez, 1993). Several studies have successfully applied these indices to compare genotypic responses to drought across various agrosystems, thereby informing better crop management practices (Farshadfar & Sutka, 2002; Negarestani et al., 2019; Khandelwal et al., 2024).

Water scarcity and food security are critical challenges in semi-arid regions such as Namibia. Although previous research (Ausiku et al., 2020; Crookston et al., 2020; Pilloni et al., 2022; Bana et al., 2023; Souza et al., 2023) has explored improving WUE in pearl millet across various growing environments using different approaches such as intercropping and adjusting planting densities, few studies have examined the effects of different irrigation levels without additional inputs on WUE and drought tolerance indices in Namibia. Understanding crop responses in different agroecological zones is crucial to devising adaptive strategies tailored to specific locations. Moreover, few studies have integrated drought tolerance indices with water-use efficiency (WUE) under different water regimes at 100% ETc, 75% ETc, and 50% ETc, leaving significant gaps in our understanding of how to enhance WUE and drought resilience in water-limited environments, such as those found in Namibia. This study addressed these gaps by assessing the WUE of two pearl millet cultivars, Kangara and Okashana 2, at 100% ETc, 75% ETc, and 50% ETc under semi-arid conditions in Namibia. Specifically, this study aimed to determine the water requirements of pearl millet and assess the impact of varying irrigation levels on grain and biomass yields, water use efficiency (WUE), and drought tolerance indices.

4.2 Materials and Methods

4.2.1 Study Site Description

The study was conducted over two seasons at the Mannheim Crop Research Station in Tsumeb, Namibia (Figure 4.1; Lat. -19.168611 and Lon. 17.763056). The first trial was conducted from September to December 2023, and the subsequent trial was conducted from January to April 2024. During the first season, the monthly maximum temperatures fluctuated between 38 and 36°C, with average temperatures ranging from 28 to 25°C. The lowest monthly temperature varied from 18°C to 12°C. Rainfall was recorded during November (7.2 mm) and December (33.6 mm). November was the warmest month, whereas September was the coolest month. In the second season, the monthly maximum temperatures ranged from 32°C to 36°C, with average temperatures ranging from 22°C to 25°C and minimum temperatures ranging from 14°C to 18°C. Rainfall during this season fluctuated from 63.3 mm to 18.8 mm. January was the hottest month of this season, and April was the coolest month. The soil at the study site was identified as a sandy clay loam, which represents Arenosols according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2007).

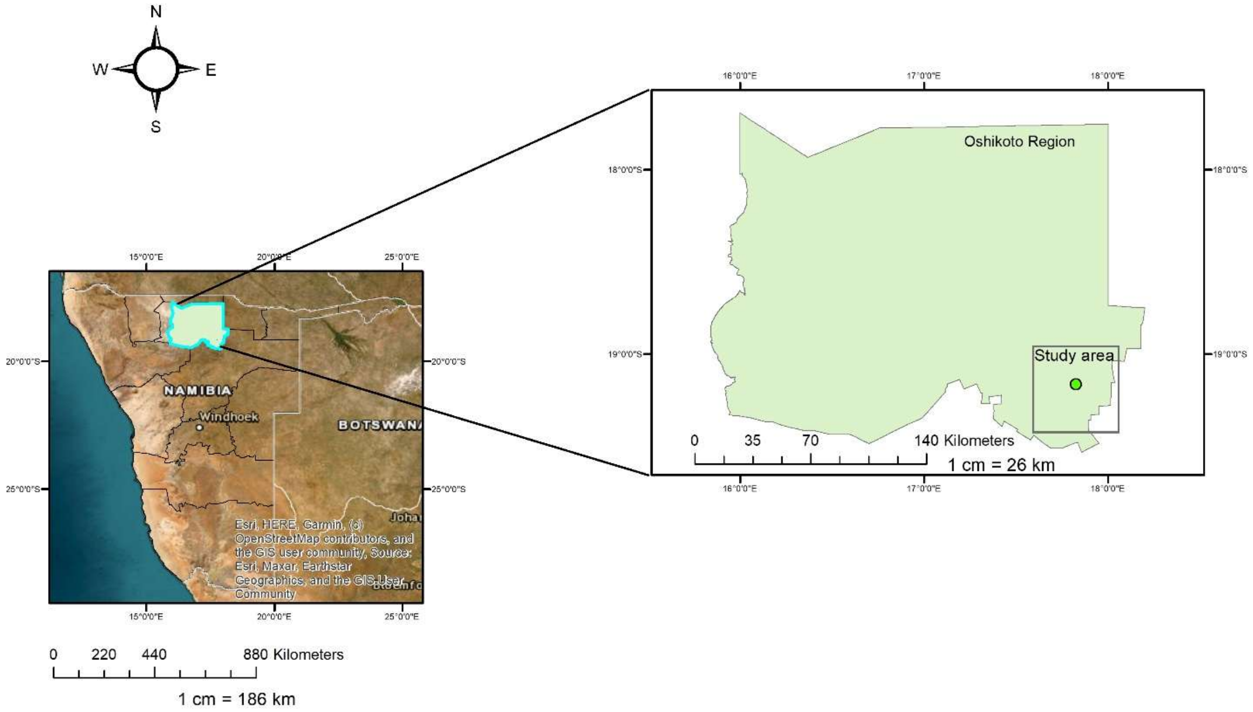

Figure 4-1. Map showing the study area, which was located at the Mannheim Crop Research Station, Tsumeb, in Oshikoto Region, Tsumeb, Namibia.

4.2.2 Experiment Design and Trial Layout

The study employed a split-plot block design, with three main plots for irrigation treatments and two subplots for crop cultivars (Kangara and Okashana 2), each replicated four times. Irrigation levels were calculated using CROPWAT 8.0, which uses the Penman-Monteith method, targeting 100%, 70%, and 50% of crop evapotranspiration (ETc) requirements across various growth stages. The drip irrigation system had 20 mm internal diameter polyethylene laterals with 1 L/h emitters at 0.2 m intervals. Buffer zones of 1 m were established between plots and 2 m between blocks. Post-irrigation checks revealed a complete wetting pattern closure between neighboring emitters on the same lateral line and an overlap of over 85% between rows. Each plot consisted of four rows with approximately 15 plants per row; however, data collection was limited to two central rows. Multiple seeds were initially planted per hole, followed by thinning to achieve a final density of 30 plants, with one plant per hole. The initial trial was conducted from September to December 2023, followed by a subsequent trial from January to April 2024.

4.2.3 Determination of Crop Water Requirement

This study estimated the water requirements for developing an irrigation schedule based on climate, crop specifications, and soil conditions at the experimental site. The FAO Penman-Monteith method was applied to calculate the reference evapotranspiration (ETo) and irrigation requirements using the CROPWAT 8.0 model (Smith et al., 1998). Long-term monthly climate averages for the Oshikoto region (1991–2022) were sourced from the National Aeronautics and Space Administration (NASA) database (https://power.larc.nasa.gov/data-access-viewer/, accessed 25 July 2023). The climate data obtained included mean monthly minimum and maximum temperatures (°C), relative humidity (%), solar radiation (sunshine hours), rainfall (mm), and wind speed (m/s). Crop data were gathered from existing databases and the literature, such as the FAO database (Allen et al., 1998; Smith, 1993). These data were then input into the CROPWAT 8.0 model to calculate the region's potential evapotranspiration (ETo). The actual crop evapotranspiration (ETc) was estimated by multiplying ETo by the crop coefficient (Kc), which was determined based on crop growth stages. To evaluate the crop response to varying water supply levels, 75% and 50% of the ETc values computed from CROPWAT 8.0 were used alongside the control (100% ETc).

4.2.4 Determination of Irrigation Runtime

The ETc per developmental stage was scaled down to a weekly period to determine the irrigation runtime of the experimental plots. The attained ETc (mm/week) was divided by the drip flow rate (mm/h) to determine the number of irrigation hours per week.

4.2.5 Soil Moisture Monitoring

The treatments received the same amount of water for 21 days after sowing. Thereafter, the available soil moisture was determined using Diviner 2000 (Figures A-1 and A-2). Diviner 2000 access tubes were manually installed 10 cm from the second drip line for each plot to measure and monitor moisture. A total of 24 access tubes were installed in each of the 24 plots. Soil moisture readings were obtained daily using a Diviner 2000 meter. The data recorded from the Diviner 2000 probe were calibrated using the default calibration equation supplied by Sentek Pty Ltd. (Sentek Ltd, 2007). This equation provides the relative data. The volumetric water content was recorded incrementally at depths of 10, 20, 30, 40, 50, 60, and 70 cm. This study used a depth of 20 cm to monitor available soil moisture. These readings were taken in the early morning, between 7:00 a.m. and 9:00 a.m., almost daily, throughout the entire crop growth period. All moisture data were downloaded regularly from the Diviner 2000 and stored in an Excel file for calculation. The rainfall recorded during the study period was accounted for using the soil water balance equations (4.1) and (4.2).

$$ET = \Delta GW + IR + P \qquad \text{Equation 4.1}$$

$$IR = ET - P - \Delta GW \qquad \text{Equation 4.2}$$

where ΔGW is the change in soil water content after a rainfall event, and IR + P are irrigation and rainfall, respectively. The assumption was made that there was no substantial drainage and surface runoff between the blocks; therefore, it was not taken into account in this calculation.

4.2.6 Data Collection

Data on agronomic traits were collected following the pearl millet descriptor guidelines described by the International Board for Plant Genetic Resources (IBPGR) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) (IBPGR and ICRISAT, 1993). Five randomly selected plants were collected from each plot at physiological maturity. Panicles and biomass were harvested and air-dried for each treatment. Grain weight (GW) in grams was determined by weighing the grains from each panicle, recorded after threshing, to obtain the yield per treatment. TBM was measured in grams as the sum of the total dry matter of leaves and stems. The yield-based drought tolerance indices included yield index (YI), yield stability index (YSI), mean productivity (MP), geometric mean productivity (GMP), harmonic mean (HM), tolerance index (TOL), stress susceptibility index (SSI), and stress tolerance index (STI) (Table 4.1). Drought indices were computed using the mean yield from 100% ETc as the non-stressed condition and 50% ETc as the stressed condition.

4.2.7 Data Analysis

The collected data were subjected to descriptive statistical analyses using Microsoft Excel (version 16). The effects of the cropping season, water regime, and variety on the grain yield of pearl millet were analysed using a two-way analysis of variance (ANOVA) in R version 4.4.0 (R Core Team, 2021). Drought tolerance indices were calculated using established standard formulas (Table 4.1) and water use efficiency (WUE) (Equation 4.2). Drought indices were computed based on the reference yields under stress and non-stressed conditions: 50% ETc and 100% ETc, respectively. The correlation matrix was computed using Pearson's correlation method to measure the linear relationship between the two variables. This was calculated to determine the level of association between traits or variables. The data were pre-processed to include only numeric columns and any rows with missing and/or omitted values (use = "complete.obs"). The resulting correlation coefficients were squared to obtain R-squared values, which indicated the proportion of variance in one variable that could be predicted from the other.

4.2.7.1 Harvest Index (HI)

The Harvest Index was calculated by dividing the grain yield (GY) by the biomass yield (BY), as shown in Equation 4.1.

$$HI = \frac{GY}{BY} \, x \, 100 \qquad \text{Equation 4.3}$$

4.2.7.2 Water-Use Efficiency (WUE)

The total seasonal water consumption per treatment was recorded, and the crop water-use efficiency (kg/m^3) for each treatment was calculated by dividing the grain yield and biomass (kg) by the total seasonal irrigation water applied (mm). The values were calculated for each season.

$$WUE = \frac{Yield \ (Kg.ha)}{Amount \ of \ water \ (mm)} \qquad \text{Equation 4.4}$$

4.2.7.3 Drought Tolerance Indices (DTI)

Drought tolerance indices assess plant tolerance to drought conditions and identify drought-tolerant genotypes and varieties. Yield-based drought tolerance indices, including the yield index (YI), yield stability index (YSI), mean productivity (MP), geometric mean production (GMP), harmonic mean (HM), stress tolerance (TOL), stress susceptibility index (SSI), and stress tolerance index (STI), were calculated (Table 4.1).

Table 4-1. Drought tolerance/susceptibility indices.

Indices	**Equation**	**Reference**
Yield Index (YI)	$YI = \frac{Y_s}{\acute{Y}_s}$	(Gavuzzi et al., 1997)
Yield Stability Index (YSI)	$YSI = \frac{Y_s}{Y_p}$	(Bouslama & Schapaugh Jr, 1984)
Mean Productivity (MP)	$MP = \frac{(Y_p + Y_s)}{2}$	(Rosielle & Hamblin, 1981)
Geometric Mean Productivity (GMP)	$GMP = (Y_p \, x \, Y_s)^{0.5}$	(Fernandez, 1993)

Harmonic Mean (HM)	$HM = \frac{2(Y_{\mathrm{p}}\, x\, Y_{\mathrm{s}})}{Y_{\mathrm{p}} + Y_{\mathrm{s}}}$	(Farshadfar & Sutka, 2002)
Tolerance Index (TOL)	$TOL = (Y_{\mathrm{p}} - Y_{\mathrm{s}})$	(Rosielle & Hamblin, 1981)
Stress Susceptible Index (SSI)	$SSI = \frac{1 - (Y_{\mathrm{s}} \div Y_{\mathrm{p}})}{SI}$ Where, $SI = 1 - (\frac{\acute{Y}_{\mathrm{s}}}{\acute{Y}_{\mathrm{p}}})$	(Mahalakshmi et al., 1988)
Stress Tolerance Index (STI)	$STI = \frac{(Y_{\mathrm{s}}\, x\, Y_{\mathrm{p}})}{(\acute{Y}_{\mathrm{p}})^2}$	(Fernandez, 1993)

Note: *Yp*, mean genotype yield under non-stressed condition (100% ETc); *Ys*, mean genotype yield under drought-stressed condition (50% ETc); Ý*p* means the mean of all genotypes' yield under non-stressed conditions; Ý*s*, the mean yield of all genotypes under drought-stressed conditions.

4.3 Results

4.3.1 Irrigation Water Requirements

Figure 4.2 (a and b) shows that, modeled at 100% ETc, crop water requirements varied from 36.95 mm/7 days in the initial stage to 67.30 mm/7 days in the late maturity stage (Figure 4.2a). The maximum evapotranspiration rate (ETc mm/stage) of pearl millet occurred during mid-season. The total ETc during the growing season from September to December 2023 was 609.55 mm. In contrast, during the January to April 2024 growing season, pearl millet ETc varied from 29.62 mm/7 days in the initial stage to approximately 52.51 mm/7 days in the mid-season stage (Figure 4.2b). The total ETc during this season was estimated to be 478.69 mm, and the middle stage required more water than the other developmental stages did.

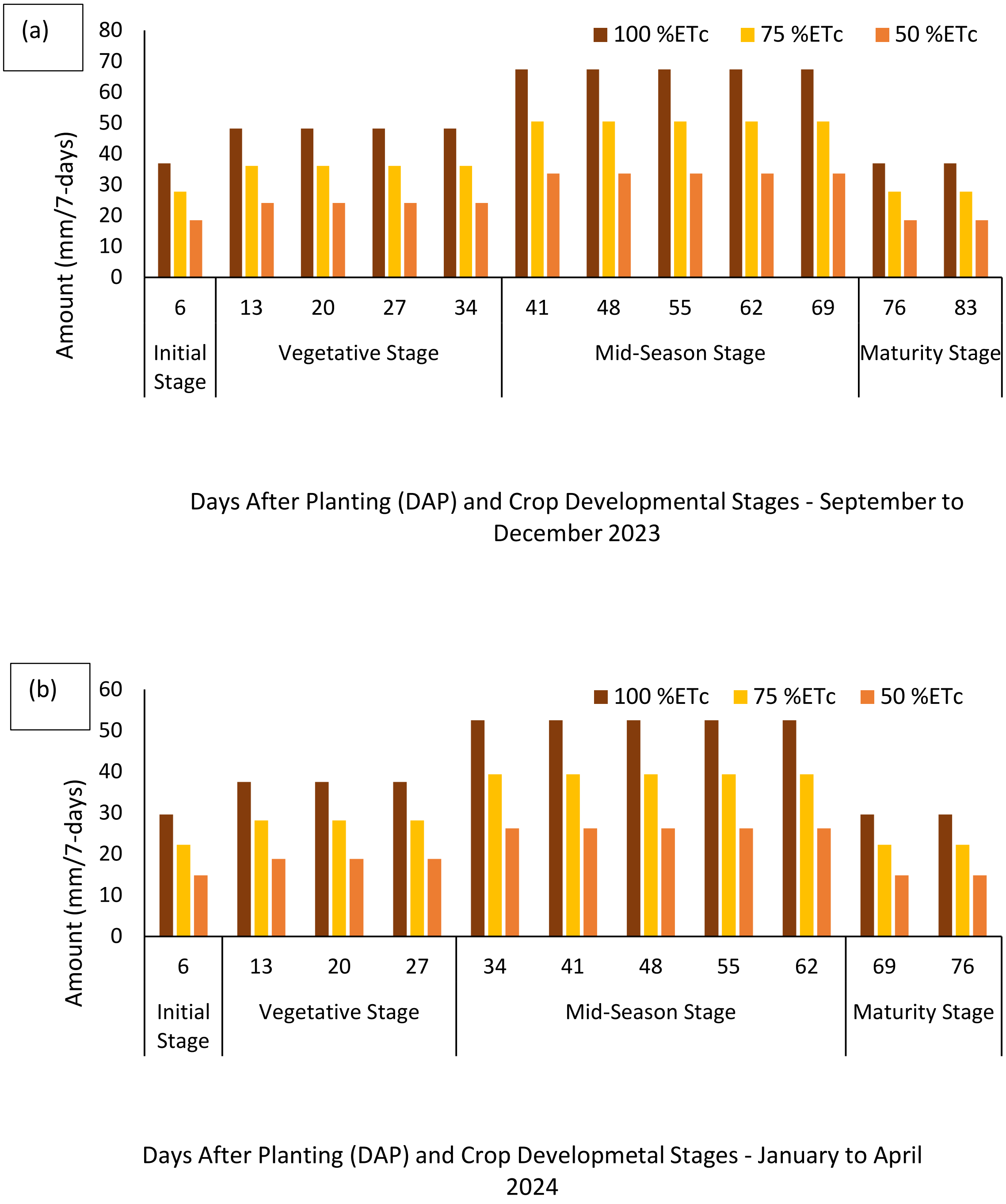

Figure 4-2. Actual evapotranspiration (ETc) of Pearl millet at different developmental stages at the experimental site.

4.3.2 Biomass Yield Response to Water Regime

Figure 4.3 shows the biomass yield of Kangara and Okashana 2 pearl millet varieties at 100%, 75%, and 50% ETc. At 100% ETc, the biomass produced was higher than at 75% and 50% ETc for the September to December 2023 (Season 1) and January to April 2024 (Season 2) growing periods. The biomass produced at 100% ETc was not statistically different from that produced at 75% ETc. Okashana 2 had higher biomass at 100% ETc during both growing periods. At 75% ETc, Kangara produced a higher biomass but did not differ statistically from Okashana 2 in either season. Finally, in Season 1, at 50% ETc, Okashana 2 had a higher biomass than Kangara did. In contrast, in season 2, Kangara had a higher biomass at 50% ETc than Okashana 2. This indicated that the water regime and season significantly affected biomass production.

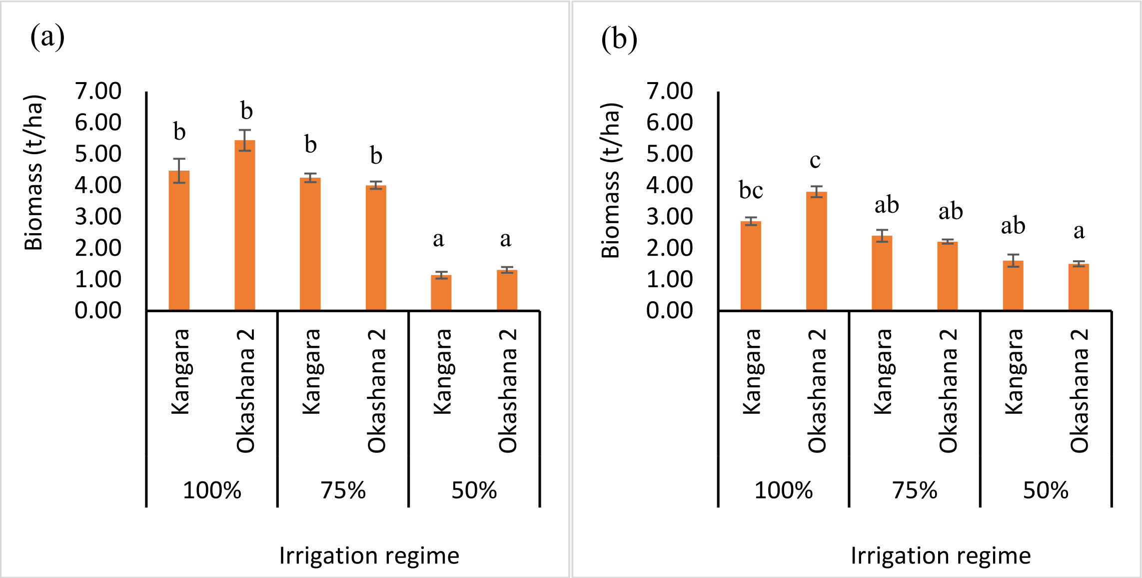

Figure 4-3. Biomass yields of Pearl millet varieties (Kangara and Okashana 2) under different water regimes. (a) September to December 2023 and (b) January to April 2024, growing period. All results are presented as the mean ± SE. Different superscript letters indicate statistical significance at $P < 0.05$, as determined by Tukey's Honest Significant Difference (HSD) test.

4.3.3 Grain Yield Response to Water Regime

Figure 4.4 presents the grain yield response of pearl millet varieties (Kangara and Okashana 2) under different irrigation regimes. From September to December 2023, Kangara at 100% ETc had a higher grain yield, but this difference was not statistically significant compared with Kangara and Okashana 2 at 75% ETc. Both varieties in the same growing period at 75% ETc had a higher yield than Okashana 2 at 100% ETc, whereas both varieties had a lower yield at 50% ETc. From January to April 2024, the yields of Kangara and Okashana 2 at 100% ETc and 75% ETc were not statistically different, but were significantly lower than those at 50% ETc. Higher grain yields were recorded at 100% ETc.

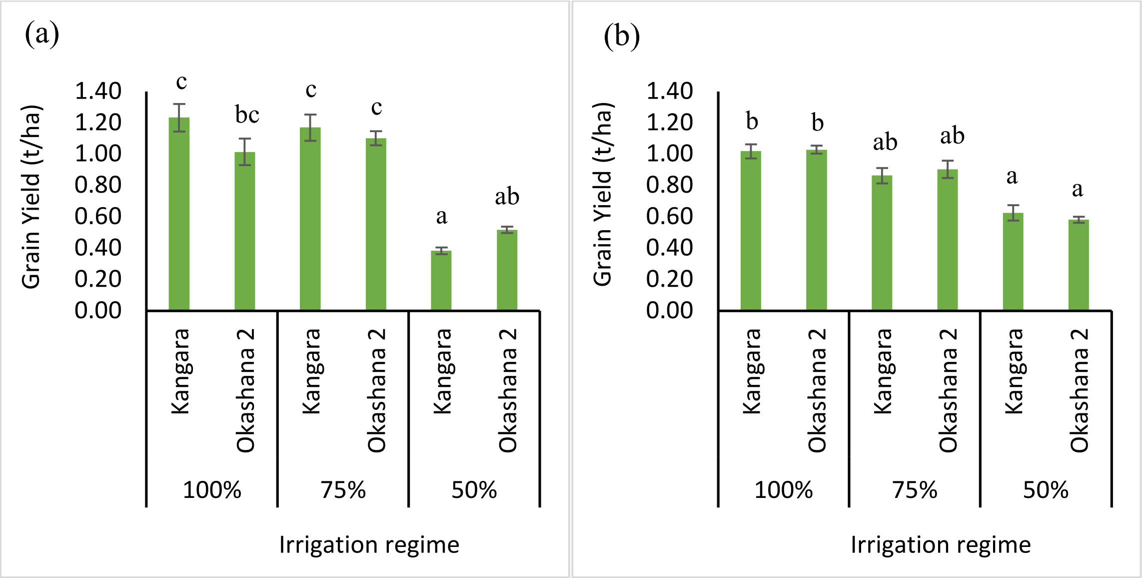

Figure 4-4. Grain yields of Pearl millet varieties (Kangara and Okashana 2) response to different water regimes. (a) September to December 2023 and (b) January to April 2024, growing period. All results are presented as the mean ± SE. Different superscript letters indicate statistical significance at $P < 0.05$, as determined by Tukey's Honest Significant Difference (HSD) test.

4.3.4 Harvest Index (HI)

Figure 4.5 shows the harvest indices of Kangara and Okashana 2 planted under different water regimes. The harvest index for the period from September to December 2023 (Season 1) ranged from 42% to 18%, whereas for the period from January to April 2024 (Season 2), it ranged from 43% to 27%. In season 1, there was no statistically significant difference between treatments and harvest index except for Okashana 2 at 50% ETc and 100% ETc. The highest harvest index was observed in Okashana 2 under 50%

ETc, and the lowest was observed in Okashana 2 at 100% ETc. In Season 2, there was no statistically significant difference between the water regimes, varieties, and harvest index.

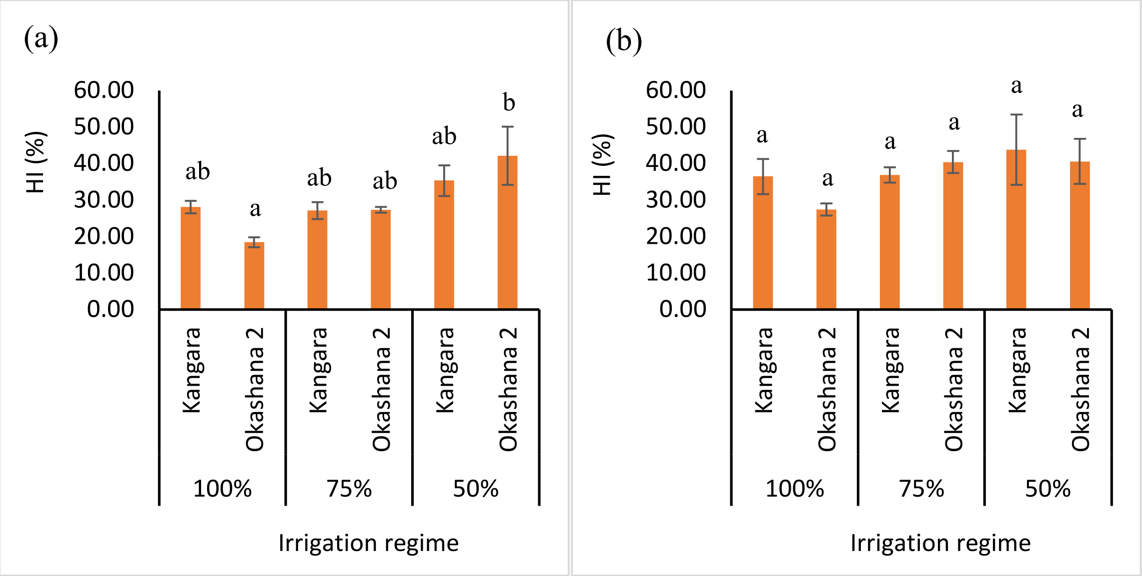

Figure 4-5. Harvest index of Pearl millet varieties (Kangara and Okashana 2) under different water regimes. (a) September to December 2023 and (b) January to April 2024, growing period. All results are presented as the mean ± SE. Different superscript letters indicate statistical significance at $P < 0.05$, as determined by Tukey's Honest Significant Difference (HSD) test.

4.3.5 Biomass Water Use Efficiency

Figure 4.6 shows the biomass water use efficiency (WUE) of the pearl millet varieties under different water regimes. In Season 1, biomass WUE ranged from 1.74 to 0.70 kg/ha/m^3. The WUE of both varieties at 100% ETc and Okashana 2 at 50% ETc did not differ significantly in terms of biomass production. At 75% ETc, Okashana 2 had a slightly higher WUE than Kangara did. In season 2, Okashana 2 had a slightly higher WUE than Kangara in all the treatments. Okashana 2 showed no statistically significant difference from the other treatments, and Kangara at 50% ETc was not statistically different from Okashana 2. Overall, Okashana 2 at 50% ETc exhibited high water-use efficiency (WUE) in terms of biomass production.

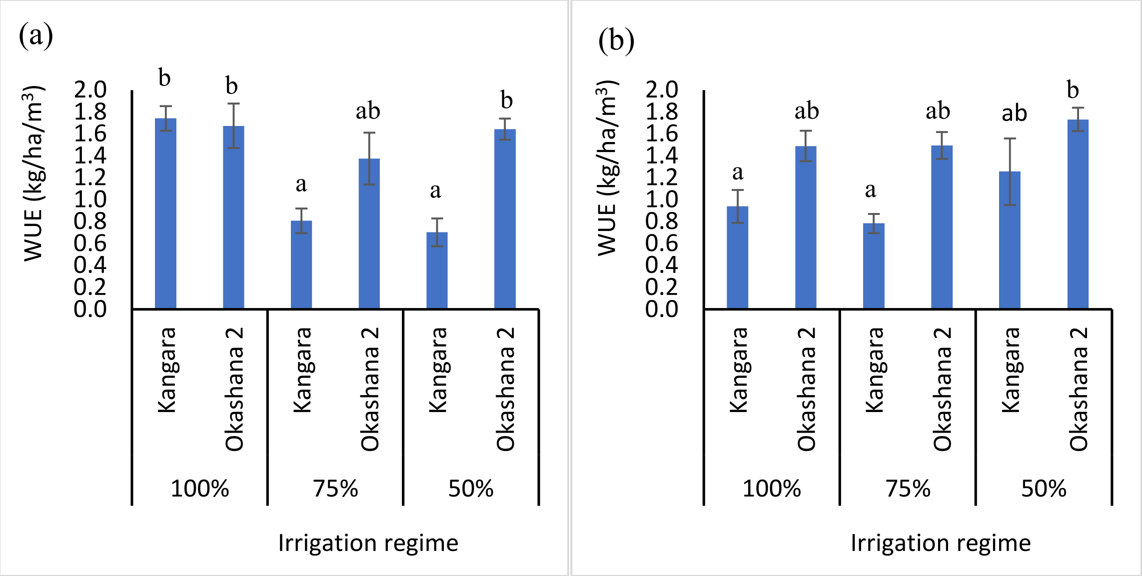

Figure 4-6. Biomass WUE of Pearl millet varieties (Kangara and Okashana 2) under different water regimes. (a) September to December 2023 and (b) January to April 2024, growing period. All results are presented as the mean ± SE. Different superscript letters indicate statistical significance at $P < 0.05$, as determined by Tukey's Honest Significant Difference (HSD) test.

4.3.6 Grain Yield Water Use Efficiency

Figure 4.7 illustrates the water use efficiency (WUE) of two different crop varieties, Kangara and Okashana 2, under various water application treatments over two consecutive growing seasons, 2023 and 2024. For Kangara, WUE is highest at 75% ETc in Season 1 (0.48 kg/ha/m^3), while in Season 2, WUE is highest at 50% ETc (0.49 kg/ha/m^3). In this variety, WUE was generally higher at 75% ETc than at 50% or 100% ETc, with a notable increase in WUE at 50% ETc during the second season. For Okashana 2, WUE was highest at 75% ETc in both Season 1 (0.45 kg/ha/m^3) and Season 2 (0.71 kg/ha/m^3). Lower WUE was observed at 100% ETc in Season 1, but there was an increase in Season 2. Both varieties showed similar WUE at 75% ETc, particularly during season 1. The results of this study indicate that 75% ETc tends to optimise WUE for both Kangara and Okashana 2, with some differences in performance under water stress (50% ETc) and full irrigation (100% ETc).

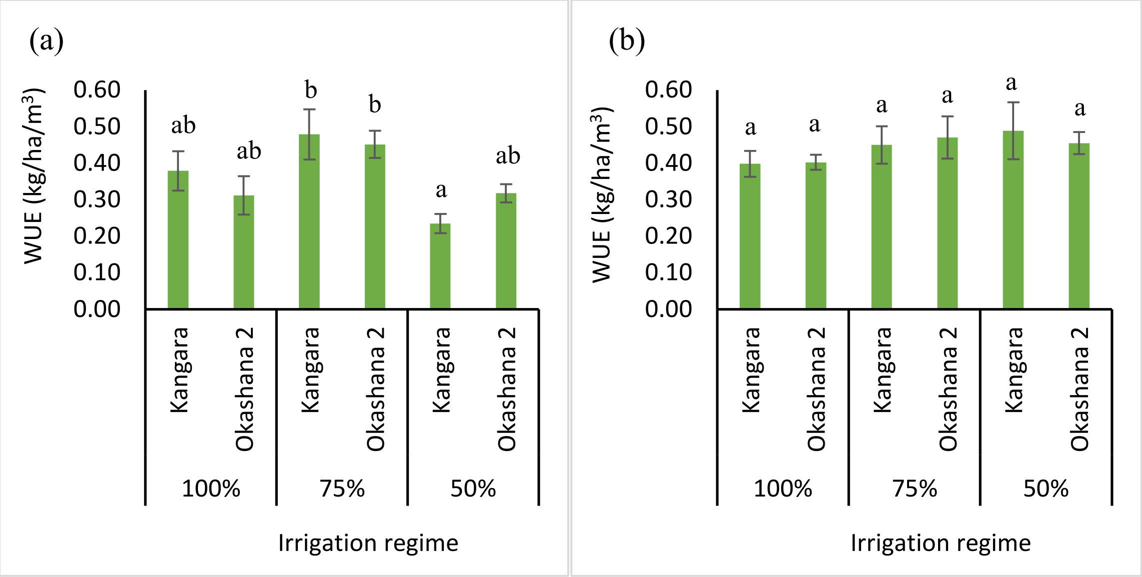

Figure 4-7. Grain WUE of Pearl millet varieties (Kangara and Okashana 2) under different water regimes. (a) September to December 2023 and (b) January to April 2024, growing period. All results are presented as the mean ± SE. Different superscript letters indicate statistical significance at $P < 0.05$, as determined by Tukey's Honest Significant Difference (HSD) test.

4.3.7 Pearson’s correlations among pearl millet yield traits and WUE

The Pearson’s correlation coefficients (*r*) for the pearl millet yield traits and WUE experiments are presented in Table 4.2. In Season 1, BY was significantly and positively correlated with GY in Season 2 ($r = 0.77$; $p \leq 0.01$) and significantly and negatively correlated with HI in Season 2 ($r = -0.66$; $p \leq 0.01$). GY was significantly and positively correlated with BY ($r = 0.88$; $p \leq 0.01$), and HI was negatively correlated with BY ($r = -0.66$; $p \leq 0.01$). WUE (GY) was significantly positively correlated with BY ($r = 0.56$; $p \leq 0.01$), and WUE(GY) was positively and significantly correlated with GY ($r = 0.80$; $p \leq 0.01$).

Table 4-2. Pearson's correlation coefficients show pair-wise for biomass yield, grain yield, harvest index, and WUE of two pearl millet varieties in Season 1 (above diagonal- shaded) and Season 2 (below diagonal).

Trait	BY	GY	HI	WUE (BY)	WUE (GY)
BY	1.000	0.882**	-0.664**	0.340	0.560**
GY	0.772**	1.000	-0.364	0.269	0.800**
HI	-0.663**	-0.151	1.000	-0.138	-0.067
WUE (BY)	0.046	-0.143	-0.223	1.000	0.120
WUE (GY)	0.031	0.372	0.327	0.217	1.000

**. Correlation is significant at the 0.01 level

Note: BY, biomass yield; GY, grain yield; HI, harvest index; WUE(BY), water use efficiency-biomass yield; WUE(GY), water use efficiency-grain yield.

4.3.8 Drought Tolerance Indices (DTI)

Figure 4.8 compares the performances of Kangara and Okashana 2 in terms of drought tolerance indices across the two seasons. (a) The YI, YSI, and STI of Okashana 2 were higher than those of Kangara, while Kangara had a higher SSI than Okashana 2 in season 1. However, the differences in the drought tolerance indices among the varieties were not statistically significant. (b) Kangara had a higher MP, TOL, Yp, and YR than Okashana 2, while Okashana 2 had higher GMP, HM, and Ys; only TOL differed significantly, and only during Season 1. (c) The YI, YSI, and STI of Kangara were higher than those of Okashana 2, whereas Okashana 2 had a higher SSI than Okashana 2 in season 2. However, there were no statistical differences in the drought indices. (d) MP, GMP, HM, Ys, and Yp of Kangara were higher than those of Okashana 2, while the TOL and YR of Okashana 2 were higher than those of Kangara in season 2. However, there were no statistical differences in drought indices. This suggests that the evaluated varieties exhibited similar performance under the studied conditions.

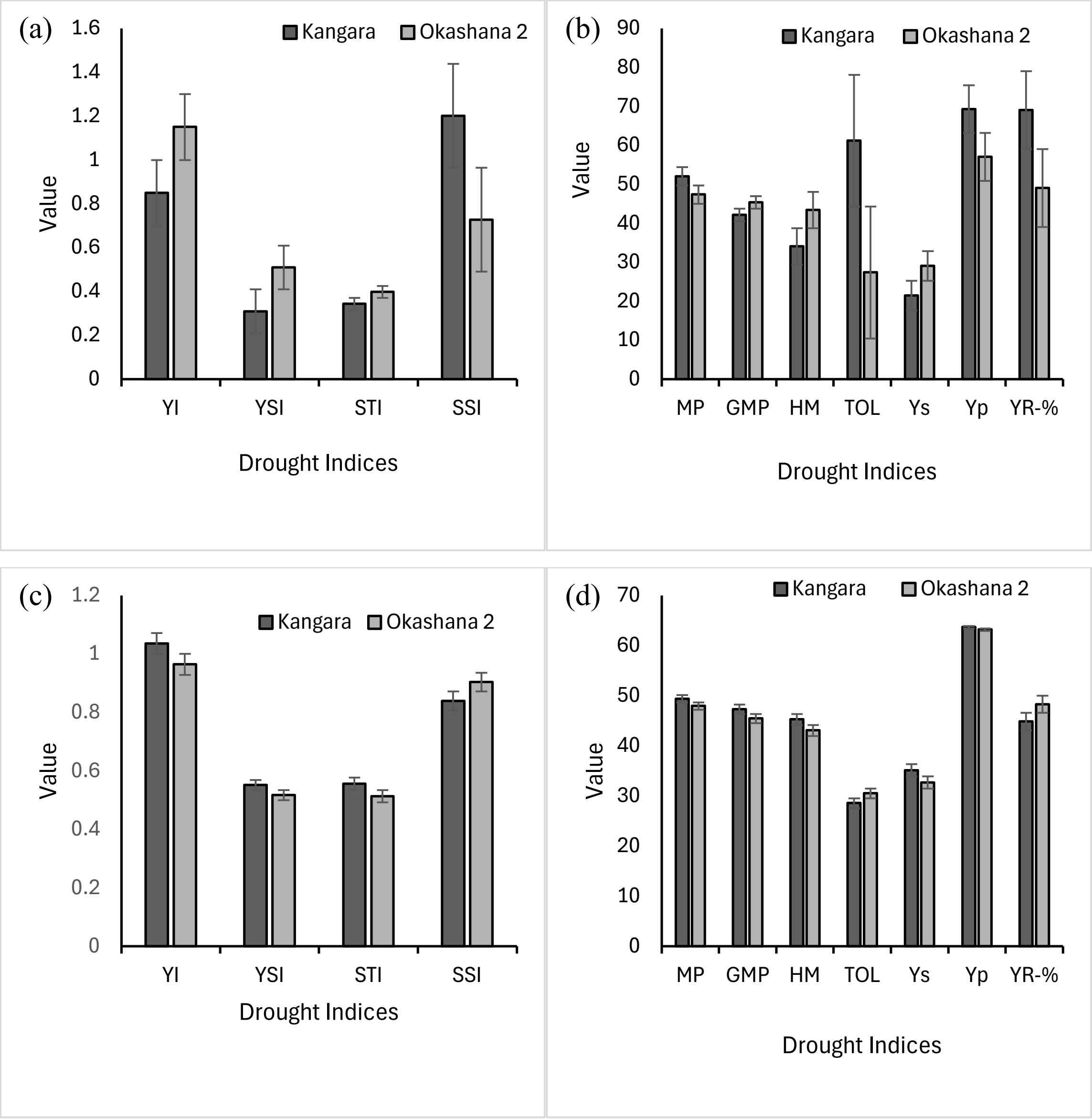

Figure 4-8 (a-d). Drought tolerance indices of Kangara and Okashana 2 under stressed (50% ETc) and non-stressed (100% ETc) conditions. (a) and (b) September to December 2023 (Season 1), and (c) and (d) January to April 2024 (Season 2) growing period. The y-axis is dimensionless as it represents the ratio of yield under stressful and non-stressful conditions. YI; Yield Index, YSI; Yield Stability Index, STI; Stress Tolerance Index, SSI; Stress Susceptibility Index, MP; Mean Productivity, GMP; Geometric Mean Productivity, HM; Harmonic Mean, TOL; Tolerance Index, Ys; Yield under stressed conditions, Yp; Yield under non-stressed conditions, YR; Yield reductions. All results are presented as the mean ± SE. Mean separation was determined by Tukey's Honest Significant Difference (HSD) test at $P < 0.05$.

4.4 Discussion

The results from this study indicate that the September-to-December growing period of pearl millet required more water than the January-to-April planting season. The high crop evapotranspiration (ETc) requirement from September to December 2023 (Season 1) could be attributed to the elevated temperatures recorded during this period compared with the subsequent growing period from January to April 2024 (Season 2). In both growing periods, more water was required during the mid-season stage, which encompasses the flowering and grain filling of pearl millet (Figure 4.2). Flowering and grain filling are often considered important for determining final grain yield. Water stress during these stages can significantly reduce yield potential (Mahalakshmi & Bidinger, 1985; Das et al., 1996; Srivastava et al., 2022). To mitigate the effects of prolonged dry spells, irrigation should be applied during periods of high-water demand or critical growth stages, including tillering, flowering, and grain development (Khairwal et al., 2007; Gangaiah & Yadav, 2024). The findings of this study revealed that the water regime had a significant impact on biomass yield, grain yield, and harvest index. A higher HI indicates that the plant allocates more biomass to the grain, which is desirable for crop productivity (Ludemann et al., 2023). Conversely, a lower HI suggests that more energy is used for vegetative growth than for yield. However, in this study, the evaluated varieties were not statistically different, indicating a similarity in their genetic makeup.

Furthermore, as the quantity of irrigation water decreased, crop biomass and yield decreased, and consequently, the WUE increased. At 50% ETc, both biomass and grain yield decreased significantly, substantiating the importance of water in crop growth and development. In this study, the 75% ETc regime was the most water-efficient for the pearl millet varieties tested under various irrigation regimes. The findings of this study align with those of previous studies on improving the water-use efficiency (WUE) under deficit irrigation. For example, Rostamza et al. (2011) found that moderate water stress increases water use efficiency (WUE) in pearl millet by promoting physiological adaptations, such as stomatal regulation, which reduces water loss and enhances efficiency under water-limited conditions. Similarly, Salem and Shoman (2021) demonstrated that applying 75% crop evapotranspiration (ETc) maintains satisfactory yields while improving water use efficiency (WUE) in arid environments, which is consistent with the results of the current study, which showed optimal WUE at 75% ETc for both cultivars. In the Kashmar region, the highest grain yield and water productivity of pearl millet, at 3395 kg/ha and 0.87 kg/m^3, respectively, were observed under full irrigation (Mokari & Taherian, 2020). When comparing pearl millet with other grain crops, its WUE was lower than that of maize and sorghum (0.51 kg/m^3) (Zengeni et al., 2021). These results demonstrate variability among family crops. Proso millet also demonstrated stable yields and WUE, averaging 0.30 kg/m^2 and 1.83 kg/m^3 under non-irrigated conditions (Ventura et al., 2022). These findings corroborate earlier work and advance the field by highlighting the versatility and potential of moderate deficit irrigation (75% ETc) as a sustainable water management strategy under moisture-limiting conditions. It offers a balance between maintaining the yield and conserving water resources.

In this study, a positive correlation (Table 4.2) was observed between biomass yield (BY) and grain yield (GY) ($r = 0.77$; $p \leq 0.01$), indicating that higher total biomass production tended to result in better grain output. This emphasises the role of overall plant growth in supporting grain development. However, the negative correlation between biomass yield and harvest index (HI) ($r = -0.66$; $p \leq 0.01$) suggests that, as total biomass increases, the amount of biomass allocated to grain decreases. This implies that plants that produce more vegetative biomass may allocate relatively less of their total growth to grain production, thus lowering HI. Together, these findings highlight that while increased biomass supports higher grain yields, it may not always translate into efficient resource allocation for grain production. The findings of this study corroborate those of Zhapayev et al. (2023), who found a strong positive correlation between biomass and grain yield, indicating an efficient assimilate distribution during grain filling. Li et al. (2023) also found that over time, increases in biomass accumulation have contributed more to yield improvements than changes in the harvest index, which has approached its upper limit. Correlation and path analyses revealed that HI, biological yield, and number of productive tillers could serve as effective selection criteria for yield improvement in pearl millet (Rajpoot et al., 2023). The positive correlation between water use efficiency and grain yield (WUE(GY)) with both biomass yield (BY) ($r = 0.56$; $p \leq 0.01$) and grain yield (GY) ($r = 0.80$; $p \leq 0.01$) indicated that improvements in total plant growth and grain production contributed significantly to water use efficiency. As the plant produces more biomass and allocates a substantial portion to grain, it maximises the yield per unit of water used, thereby enhancing WUE(GY). A strong correlation with GY suggests that grain yield is critical in determining WUE(GY), underscoring the importance of reproductive output in water-limited environments. These results corroborate those of Triki et al. (2023), who found a positive correlation between water-use efficiency, as measured by grain yield and biomass yield, in pearl millet varieties.

Drought tolerance indices (DTIs) provide a quantitative measure of the capacity of a genotype to withstand drought. In this study, the DTIs for Kangara and Okashana 2 pearl millet cultivars were calculated, including the yield index (YI), yield stability index (YSI), stress tolerance index (STI), stress susceptibility index (SSI), mean productivity (MP), geometric mean productivity (GMP), harmonic mean (HM), tolerance index (TOL), yield under stress conditions (Ys), and yield under non-stress conditions (Yp). The drought indices of the two varieties were not statistically different from each other, indicating that the two varieties were likely not genetically different. Previous studies have used these indices to evaluate and compare how different genotypes perform (Negarestani et al., 2019; Kumawat et al., 2020; Vaezi et al., 2020). These indices are instrumental in identifying high-yielding genotypes that perform well under both non-stress and drought-stress conditions.

The results of this study indicate that improved water availability contributes substantially to grain yield and maximizes the yield per unit of water used. This study emphasises the significance of understanding the environmental factors and genetic basis of drought tolerance, and leveraging this knowledge to develop pearl millet varieties that can withstand drought stress. Such advancements are vital for ensuring food security in arid and semi-arid regions such as Namibia.

4.5 Conclusion

This study assessed the water use efficiency (WUE) and drought tolerance indices (DTIs) of pearl millet cultivars in a semi-arid region of Namibia. The results demonstrated that water regime had a significant effect on biomass yield, grain yield, and harvest index (HI). Moderate deficit irrigation (75% ETc) has emerged as the most water-efficient regime, maintaining satisfactory yields while also employing an efficient water management strategy. Water use efficiency based on grain yield (WUE(GY)) was positively correlated with both biomass yield ($r = 0.56$) and grain yield ($r = 0.80$), indicating that grain production plays a pivotal role in maximising water productivity. The drought tolerance indices further revealed that both varieties remained stable under the studied climatic conditions. This study emphasises the need to integrate efficient water management strategies, such as aligning the cropping season of the mid-season developmental stage of pearl millet with the expected high rainfall period, deficit irrigation, and genetic improvements, to develop drought-tolerant varieties. These strategies are crucial for sustaining pearl millet production in arid and semi-arid regions and ensuring food security under changing climatic conditions. Future studies should investigate the performance of additional pearl millet cultivars under various water regimes and agroecosystems to identify genotypes with improved drought resilience and higher water-use efficiency. Additionally, long-term studies assessing the combined effects of prolonged drought stress and soil fertility management can provide valuable insights into sustainable water and crop management practices.

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5 EFFECTS OF WATER STRESS ON GRAIN NUTRITIONAL QUALITY OF PEARL MILLET IN SEMI-ARID NAMIBIA

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Abstract

Recurrent dry spells and high temperatures can affect plant growth and productivity. The objective of this study was to determine the effects of water stress, comprising 100%, 75%, and 50% of crop evapotranspiration rate (ETc), on the nutritional quality of Kangara and Okashana 2 pearl millet varieties. The experiment was conducted from September 2023 to April 2024, employing a split-plot design based on a randomized complete block design with four replicates and two sampling periods. The soil texture at the experimental site was classified as sandy clay loam with an overall composition of 54.31% sand, 15.92% silt, and 29.77% clay. The nutritional quality of pearl millet includes moisture, fat, crude fiber (CF), acid detergent fiber (ADF), potassium (K), magnesium (Mg), calcium (Ca), phosphorus (P), zinc (Zn), and iron (Fe), using standardized scientific methods was determined. From September to December 2023, the water regime did not significantly affect the grain moisture content; however, Kangara exhibited higher moisture levels than Okashana 2 ($p < 0.001$). The fat content was significantly influenced by the water regime ($p = 0.02$), with the highest at 100% ETc (5.10%) and the lowest at 75% ETc (3.90%). No significant effects were observed for the crude fiber (CF), acid detergent fiber (ADF), or mineral content. Water stress significantly affected several nutritional traits from January to April 2024. The moisture content differed significantly ($p < 0.001$), with the highest (6.63%) at 75% ETc and the lowest (2.10%) at 50% ETc. Fat content was also significantly affected ($p < 0.001$), with the highest content at 50% ETc (4.99%) and the lowest at 100% ETc (2.11%). Significant differences were observed for ADF ($P = 0.04$), Ca ($P = 0.02$), K ($P < 0.001$), Mg ($P = 0.005$), P ($P < 0.001$), and Fe ($P = 0.003$). The highest Fe (76.61 mg/kg) occurred at 50% ETc, while the lowest (41.83 mg/kg) occurred at 100% ETc. Under drought-stressed (50% ETc) conditions, positive associations and correlations were observed between ADF and CF, Mg, K, P, and moisture, whereas ADF was negatively correlated with moisture. Under non-stressed conditions (100% ETc), positive correlations were observed between CF and ADF, Ca and Mg, and Zn and Fe. In contrast, negative correlations existed between moisture and K and between fat and CF. Principal component biplots showed significant variance explained by Dimension 1 (Dim1) and Dimension 2 (Dim2) for both conditions. Fe and fat clustered together, indicating a positive correlation at 100% ETc, whereas Ca and Zn exhibited a strong positive correlation at 50% ETc. These findings suggest that water regime affects the nutritional composition of pearl millet; however, moderate water regimes of 75% and 50% ETc enhance certain mineral and fibre contents, which indicates its resilience to water stress.

Keywords: *Climate change, Dietary fiber, Drought resilience, Micronutrients, Nutritional quality, Pearl millet, Water stress*

5.1 Introduction

Climate change profoundly affects global food security, with water availability being a key limiting factor for agricultural productivity under field conditions (Ostmeyer et al., 2020). In the coming years, the challenges of water scarcity and reduced irrigation water availability are expected to escalate owing to rising agricultural demands, pollution of natural water sources, and the intensifying effects of climate change. Increasing temperatures and erratic rainfall contribute to prolonged drought conditions, severely reducing crop productivity and yield (Ostmeyer et al., 2020). However, the impact of water stress extends beyond yield, as it can also significantly affect the nutritional quality of crops such as pearl millet. Drought stress has been shown to influence protein content and composition, starch biosynthesis, and micronutrient concentrations, such as iron and zinc, in pearl millet (Satyavathi et al., 2021; Yogi et al., 2023). As the global population increases and climate change worsens, there is an increasing need to develop sustainable agricultural practices that can maintain and enhance the nutritional quality of pearl millet under water-stressed conditions (Dube et al., 2021).

Pearl millet (*Pennisetum glaucum* (L.) R. Br.), a vital cereal crop extensively cultivated in the arid and semi-arid regions of Africa and Asia, is renowned for its resilience to harsh environmental conditions, including elevated temperatures and poor soil fertility. However, recurrent droughts during the growing season significantly threaten productivity, particularly in rain-fed systems. Pearl millet is highly nutritious and provides a rich source of energy and essential nutrients (Pei et al., 2022). It contains carbohydrates, proteins, fats, dietary fiber, ash, and essential micronutrients including iron and zinc. Additionally, these nutrients offer superior digestibility and bioavailability compared with other cereals. Micronutrient deficiencies, mainly iron and zinc deficiencies, pose a significant public health challenge, especially in developing countries where people rely heavily on grains as a primary source of nutrition (Nakandalage & Seneweera, 2018).

Recently, increasing attention has been directed towards combating micronutrient deficiencies, primarily because they have a significant impact on human health and productivity. Pearl millet’s gluten-free properties, its role as a probiotic for maintaining gut health, and its potential benefits in lowering cholesterol make it an essential dietary option in regions with limited food diversity. Furthermore, its rich phytate and polyphenol content provides antioxidant activity, contributing to its nutritional value (Satyavathi et al., 2021). Despite these benefits, the nutritional quality of pearl millet is not static and can be affected by environmental factors such as water stress.

Previous studies have primarily focused on the effects of water stress on yield, crop nutrition, drought, and heat stress physiology (Makarana et al., 2019; Narasimhulu et al., 2023. However, the effects of drought on the nutritional composition of pearl millet have received relatively little attention. Gaining insights into how the nutritional profile of pearl millet responds to water stress is crucial for guiding future agricultural practices and nutritional planning, especially for local cultivars. Drought conditions not only decrease crop yields but also alter the nutritional quality of plants and the bioactive compounds they contain (Choukri et al., 2020. For crops that play a significant role in the diet of millions of people in water-scarce regions, these changes could have critical implications for food security and nutrition.

Despite its importance as a staple food, research on the effects of water stress on the nutritional composition of pearl millet is limited. There is a need for a comprehensive investigation into how water stress affects the nutritional profile of pearl millet grains, particularly with regard to minerals such as iron and zinc, which are essential for human health. Understanding these changes is crucial for developing climate-resilient agricultural systems that can maintain yield and nutritional quality under water-limited conditions. This study aimed to fill this knowledge gap by investigating how water stress affects the nutritional quality of pearl millet, providing important insights for breeding programs and agricultural practices to enhance resilience and nutritional value in challenging environments.

5.2 Materials and Methods

5.2.1 Study site

Field trials were conducted at the Mannheim Research Station in the Oshikoto region, located in north-central Namibia, at an elevation of 1234 m above sea level (MASL).

5.2.2 Determination of soil composition

The soil samples were collected from each treatment group. Four samples were collected from each treatment at depths of 0–30 cm and mixed to obtain a composite sample. A composite sample was used for both the chemical and physical analyses. Soil sampling was performed using a steel cylinder core sampler with a volume of 100 cm^3. Soil samples were dried at a temperature not exceeding 35 °C and then sieved through a 2 mm sieve for physicochemical analysis.

Physicochemical analyses were conducted to determine soil texture and chemical composition. Soil texture classification was based on the proportions of sand, silt, and clay particles, following the USDA classification system. Soil composition was assessed by measuring pH, electrical conductivity (EC), sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), organic matter (OM), organic carbon (OC), and carbonate at Analytical Laboratory Services (PTY) LTD, Windhoek, Namibia, and the Soil

Laboratory for the Ministry of Agriculture, Water and Land Reform, Windhoek, Namibia. EC was determined in the supernatant of the 1:2.5 soil-to-water suspension before measuring the pH, and pH was measured in a 1:2.5 soil-to-water ratio suspension on a mass-to-volume basis. Available phosphorus was determined using the Olsen method, and exchangeable cations (K, Mg, Na, and Ca) were measured using atomic absorption spectrophotometry. OM was determined by measuring the weight loss of the dried samples when they were heated in a muffle furnace at 360 °C for four hours. OC was determined using the Walkley-Black method (sulfuric acid-potassium dichromate oxidation). The carbonate estimate was determined by applying 10% hydrochloric acid to dry soil and observing the effervescence.

5.2.3 Nutritional composition of pearl millet

Grain samples of Okashana 2 and Kangara cultivated under three irrigation regimes (100%, 75%, and 50% ETc) were collected for laboratory analysis after the two growing periods of 2023 and 2024, respectively. Grains from five randomly selected plants in each treatment group were selected for nutritional analysis. The seeds were milled prior to analysis of their nutritional composition using standard procedures.

5.2.3.1 Moisture Content Determination

Moisture content was determined according to the Association of Official Analytical Chemists (AOAC, 2000) using the official method No. 925.10 by the oven drying method (Model: DHG-9140A; Zenith et al., China).

5.2.3.2 Crude Fat Determination

The crude fat content was determined using the Soxhlet method, as described in the Association of Official Chemists International (1995) and the official method 4.5.01 (920.39).

5.2.3.3 Crude Fibre and Acid Detergent Fibre Determination

Crude fibre and acid detergent fibre were analysed according to the Association of Official Analytical Chemists International (AOAC) 1995 Method 4.6.01 (962.09).

5.2.3.4 Minerals (Mg, K, P, Ca, Fe, and Zn)

Mineral concentrations were determined according to the methods described by AOAC (1990), using atomic absorption flame spectroscopy. After destroying the organic matter through dry ashing, the residue was dissolved in a mixture of hydrochloric and nitric acids, and the elements were analysed from the same solution using an atomic absorption spectrophotometer.

5.2.4 Statistical Analysis

The data obtained were analysed using one-way and two-way analysis of variance (ANOVA) in R version 4.4.0 (R Core Team, 2021) to test the effect of water regime (100% ETc, 75% ETc, and 50% ETc) and variety on the nutritional composition of pearl millet and their interaction. Pearson's correlation test was conducted to assess the significance of the degree of association between moisture content, crude fat, crude fiber, acid detergent fiber, and mineral elements. Significant differences between treatments were determined using Tukey's honest HSD test at a 95% confidence level.

5.3 Results

5.3.1 Soil texture and pH

The soil texture and pH values are summarized in Table 5.1. The soil texture at the experimental site was heterogeneous, with an overall composition of 54.31% sand, 15.92% silt, and 29.77% clay. The sand composition differed significantly across the treatments, with the highest sand composition of 55.93% observed under 50% ETc and the lowest of 53.23% under 100% ETc. The silt composition did not differ significantly. The clay compositions were highly statistically different. The highest clay composition was 31.35% under 100% ETc, whereas the lowest was 28.13% under 50% ETc. The mean soil pH across the different water regimes was not statistically different. The mean pH was 8.59. The lowest pH was 8.53 under 50% ETc, whereas the highest was 8.67 under 100% ETc.

Table 5-1. Mean values for soil texture and pH results for the 50%, 75% and 100% ETc irrigation regimes treatments during the 2023/2024 season.

Water Regime (ETc)	Sand (%)	Silt (%)	Clay (%)	Texture	pH
50%	55.93^{b}	15.93	28.13^{a}	Sandy clay loam	8.53
75%	53.78^{a}	16.40	29.83^{b}	Sandy clay loam	8.57
100%	53.23^{a}	15.43	31.35^{c}	Sandy clay loam	8.67
Grand Mean	54.31	15.92	29.77	Sandy clay loam	8.59
p-values	0.005	0.21	<0.001		0.37
s.e.d	0.63	0.50	0.51		0.10

Note: P-values are probability values corresponding to a variance ratio; s.e.d: standard errors of mean differences. Means are differentiated using Tukey's Honestly Significant Difference (Tukey's HSD) test at *p* = 0.05. Superscript letters denote significant differences between means.

5.3.2 Chemical properties of soil

The chemical properties of the soil are listed in Table 5.2. There were no statistically significant differences in soil chemical properties between the study plots. However, there was only a statistically significant difference in K concentration (P = 0.003). These results highlight the homogeneity of soils under the study conditions.

Table 5-2. Mean values and significant tests for soil chemical properties for the 50%, 75%, and 100% ETc irrigation regimes treatments during the 2023/2024 season.

Water Regime (ETc)	ECw (uS/cm)	OM (%)	OC (%)	P (mg/kg)	K (ppm)	Ca (mg/kg)	Mg (mg/kg)	Na (mg/kg)	Carbonate (estimate)
50%	450.50	1.02	0.59	3.30	317.75^{b}	3703.75	75.00	23.75	5 to 10
75%	499.00	1.06	0.61	0.78	274.50^{ab}	3700.75	75.75	57.75	5 to 10
100%	413.75	1.02	0.59	0.00	226.75^{a}	3701.00	75.75	51.50	5 to 10
Grand Mean	454	1.04	0.60	1.36	273	3702	75.50	44.3	5 to 10
p-values	0.73	0.87	0.87	0.33	0.003	0.99	0.62	0.13	

s.e.d	107	0.09	0.05	2.17	18.93	25.2	0.87	15.79

Note: P-values are probability values corresponding to a variance ratio; s.e.d: standard errors of differences of means. Means are differentiated using Tukey's Honestly Significant Difference (Tukey's HSD) test at *p* = 0.05. Superscript letters denote significant differences between means.

5.3.3 Mineral content of Okashana 2 and Kangara varieties during the September to December 2023 growing period

The mineral compositions of Okashana 2 and Kangara during the September to December 2023 growing period are presented in Table 5.3. The water regime had no statistically significant effect on grain moisture content; however, the variety showed a statistically significant difference in grain moisture content ($p < 0.001$). The moisture content ranged from 8.91% to 10.07%. Kangara demonstrated a higher moisture content than Okashana 2. Water regime had a statistically significant effect on fat content ($p = 0.02$). The highest fat content was 5.10% at 100% ETc, followed by 4.65% at 50% ETc, and 3.90% at 75% ETc. Water regime and variety did not have a statistically significant effect on crude fiber (CF), acid detergent fiber (ADF), calcium (Ca), potassium (K), magnesium (Mg), phosphorus (P), zinc (Zn), or iron (Fe). No interaction effect of water regime and variety was observed on the assessed parameters. This finding indicates that the studied minerals remained stable across water regimes during the growing period.

Table 5-3. Mineral content of Okashana 2 and Kangara varieties during the September to December 2023 growing period.

A. Water Regime (ETc)	NUTRITIONAL COMPOSITION OF PEARL MILLET									
	Moist (%)	Fat (%)	CF (%)	ADF (%)	Ca (%)	K (%)	Mg (%)	P (%)	Zn (mg/kg)	Fe (mg/kg)
100%	9.22	5.10^{b}	2.01	4.54	0.01	0.48	0.09	0.31	51.73	57.84
75%	10.07	3.90^{a}	2.45	4.85	0.01	0.50	0.10	0.33	54.40	68.57
50%	8.91	4.65^{ab}	2.20	4.62	0.01	0.43	0.10	0.37	54.81	73.15

Grand Mean	9.40	4.55	2.22	4.67	0.01	0.47	0.10	0.34	53.65	66.52
SE	1.11	0.66	0.56	0.62	0.002	0.09	0.01	0.04	9.17	14.39
LSD (5%)	1.39	0.83	0.71	0.8	0.002	0.11	0.01	0.05	11.54	18.11
Sig	0.21	0.02	0.43	0.67	0.24	0.44	0.29	0.07	0.82	0.21
B. Varieties										
Kangara	10.94	4.50	2.40	4.68	0.01	0.44	0.10	0.34	53.77	63.24
Okashana 2	7.86	4.60	2.04	4.65	0.01	0.50	0.10	0.34	53.52	69.80
LSD (5%)	1.14	0.67	0.58	0.64	0.002	0.09	0.01	0.04	9.42	14.78
Sig	<0.001	0.75	0.20	0.92	0.27	0.15	0.70	0.99	0.96	0.35
C. Interaction										
A x B	0.003	0.09	0.81	0.44	0.98	0.65	0.008	0.10	0.20	0.82

Note: Values represent the mean of triplicate samples analysed (n = 3). LSD, least significant difference; SE: Standard error. Means are differentiated using Tukey's Honestly Significant Difference (Tukey's HSD) test at *p* = 0.05. Superscript letters denote significant differences between means.

5.3.4 Mineral content of Okashana 2 and Kangara varieties during the January to April 2024 growing period.

The mineral compositions of Okashana 2 and Kangara during the January to April 2024 growing period are presented in Table 5.4. The water regime had a statistically significant effect ($p<0.001$) on moisture content. The moisture contents at 75% and 100% ETc were not statistically significantly different from each other, but were statistically different from the moisture content at 50% ETc. The highest moisture content (6.63%) was observed at 75% ETc, whereas the lowest (2.10%) was observed at 50% ETc. Water regime had a statistically significant effect on fat content ($p<0.001$). The fat content at 50% ETc and 75% ETc was not significantly different, but it differed from the fat content at 100% ETc. The highest fat content was 4.99% at 50% ETc, and the lowest was 2.11% at 100% ETc. The water regime had no statistically significant effect ($p = 0.40$) on crude fiber (CF). The water regime had a statistically significant effect ($p = 0.04$) on ADF. ADF at 100% ETc was significantly different from that at 50% ETc, but was not significantly different from that at 75% ETc. The highest ADF content (8.05%) was observed at 50% ETc, whereas the lowest ADF content (5.88%) was observed at 100% ETc. The water regime had a statistically significant effect on calcium (Ca) content (p = 0.02). Ca content at 100% ETc and 75% ETc (0.007%) was not significantly different from each other, but was different at 50% ETc (0.01%). The water regime had a statistically significant effect (p<0.001) on potassium (K). The highest K content was 0.59% at 100% ETc, and the lowest was 0.45% at 50% ETc. The water regime had a statistically significant effect (p = 0.005) on magnesium (Mg). The highest Mg content was 0.10% at 50% ETc, and the lowest was 0.08% at 75% and 100% ETc. The water regime had a statistically significant effect (p<0.001) on phosphorus (P). The highest P was 0.34% at 75% ETc, and the lowest was 0.25% at 50% ETc. The water regime had no statistically significant effect on zinc (Zn). The highest Zn content was 50.86 mg/kg at 75% ETc, and the lowest was 43.30 mg/kg at 100% ETc. The water regime had a statistically significant effect on iron (Fe) content (p = 0.003). The highest Fe content was 76.61 mg/kg at 50% ETc and the lowest was 41.83 mg/kg at 100% ETc. These results indicated that the water regime had a significant impact on several parameters during the growing period. Notably, reduced moisture content affected the moisture content, K, and P. This suggests that the studied pearl millet is stable in maintaining its nutritional composition even under reduced moisture conditions.

Table 5-4. Mineral content of Okashana 2 and Kangara varieties during the January to April 2024 growing period.

A. Water Regime (ETc)	NUTRITIONAL COMPOSITION OF PEARL MILLET									
	Moist (%)	Fat (%)	CF (%)	ADF (%)	Ca (%)	K (%)	Mg (%)	P (%)	Zn (mg/kg)	Fe (mg/kg)
100%	6.57^{b}	2.11^{a}	2.82	5.88^{a}	0.007^{a}	0.59^{b}	0.08^{a}	0.32^{b}	43.30	41.83^{a}
75%	6.63^{b}	4.32^{b}	3.47	6.61^{ab}	0.007^{a}	0.57^{b}	0.08^{a}	0.34^{b}	50.86	52.47^{a}
50%	2.10^{a}	4.99^{b}	3.58	8.05^{b}	0.01^{b}	0.45^{a}	0.10^{b}	0.25^{a}	43.96	76.61^{b}
Grand Mean	5.10	3.81	3.29	6.85	0.01	0.53	0.09	0.30	46.04	56.97
SE	1.10	0.72	1.01	1.29	0.002	0.04	0.009	0.03	6.44	13.64
LSD (5%)	1.38	0.91	1.23	1.63	0.003	0.05	0.01	0.04	8.10	17.16

Sig	<0.001	<0.001	0.40	0.04	0.02	<0.001	0.05	<0.001	0.12	0.003
B. Varieties										
Kangara	4.91	3.83	3.20	6.86	0.01	0.55	0.09	0.30	44.78	50.02
Okashana 2	5.29	3.79	3.38	6.84	0.01	0.52	0.09	0.31	47.30	63.92
LSD (5%)	1.13	0.74	1.03	1.33	0.002	0.04	0.009	0.04	6.62	14.01
Sig	0.48	0.91	0.72	0.98	0.82	0.11	0.28	0.81	0.42	0.05
C. Interaction										
A x B (Sig)	0.48	0.65	0.81	0.72	0.85	0.38	0.25	0.69	0.50	0.24

Note: Values represent the means of triplicate samples analysed (n = 3). LSD, least significant difference; SE: Standard error. Means are differentiated using Tukey's Honestly Significant Difference (Tukey's HSD) test at *p* = 0.05. Superscript letters denote significant differences between means.

5.3.5 Level of associations among nutritional components of pearl millet under drought-stressed (50% ETc) and non-stressed (100% ETc) conditions

The levels of association between the assessed nutritional components under drought-stressed (50% ETc) and non-drought-stressed (100% ETc) conditions are presented in Table 5.5. Under 50% ETc, significant positive associations were observed between ADF and CF (r=0.91, p<0.001), Mg and K (r=0.62, p<0.05), P and moisture (r = 0.91, p < 0.001), and Zn and moisture (r=0.75, p=0.01). This suggests that ADF has a direct impact on CF content, and moisture content has a direct effect on P. ADF was negatively and significantly correlated with moisture content (r = -0.80, p < 0.001), and P was negatively and significantly correlated with ADF (r = -0.63, p = 0.05). Under 100% ETc, positive and significant correlations were observed between CF and ADF (r=0.88, p<0.001), Ca and Mg (r=0.73, p<0.001), Mg and Zn (r=0.61, p=0.05), and Zn and Fe (r=0.64, p=0.05). This suggests that the variables directly influence each other's content. A significant negative association was observed between moisture and K (r=-0.70, p=0.05), fat and CF (r=-0.76, p=0.01), fat and ADF (r=-0.83, p<0.001), and K and Zn (r=-0.59, p=0.05). This suggests that these variables are independent of one another.

Table 5-5. Pearson correlation coefficients (r) showing the magnitude of associations of the nutritional content of pearl millet varieties under drought-stressed conditions (50%ETc), upper diagonal and non-drought-stressed conditions (100% ETc), lower diagonal conditions.

	Moist	Fat	CF	ADF	Ca	K	Mg	P	Zn	Fe
Moist		-0.29	-0.51	-0.80**	0.29	-0.23	-0.16	0.91***	0.75**	-0.06
Fat	0.22		-0.07	0.05	-0.53	0.04	0.50	-0.51	-0.57	0.01
CF	-0.05	-0.76**		0.91***	-0.11	0.00	0.06	-0.36	-0.07	0.27
ADF	-0.20	-0.83***	0.88***		-0.15	0.14	0.07	-0.63*	-0.35	0.26
Ca	0.38	0.53	-0.29	-0.28		-0.33	-0.21	0.0	0.31	0.50
K	-0.70*	-0.50	0.35	0.33	-0.26		0.62*	-0.42	-0.33	0.44
Mg	0.05	0.41	-0.12	-0.13	0.73***	-0.07		-0.51	-0.37	0.30
P	-0.13	-0.22	0.06	0.18	-0.52	0.01	-0.45		0.55	-0.34
Zn	0.33	0.39	-0.02	0.05	0.38	-0.59*	0.61*	-0.38		0.24
Fe	0.27	0.53	-0.53	-0.38	0.32	-0.53	0.46	-0.23	0.64*	

Note: Moist: Moisture, CF: crude fiber, ADF: acid detergent fiber, Ca: calcium, K: potassium, Mg: magnesium, P: phosphorus, Zn: zinc, Fe: iron. *p=0.05, **p=0.01, ***p<0.001 significance.

5.3.6 Principal Component Analysis (PCA)

5.3.6.1 Non-stressful conditions (100% ETc)

The relationship between the nutritional components of pearl millet under non-stressful conditions (100% ETc) is illustrated in Figure 5.1, using principal component biplots. The variables along the Dim1 axis explained 41.5% of the total variance, indicating that these variables have a substantial influence on the data proportion. Conversely, 21.6% of the variance was explained by variables on the Dim2 axis. Acute angles between variables suggest a positive correlation, perpendicular variables indicate minimal or no correlation, and variables in opposite dimensions indicate a negative correlation. Fe and fat were clustered together, indicating a positive correlation; however, there was an inverse association between

K, ADF, CF, and fat and Fe, highlighting a potential trade-off wherein higher potassium accumulation may limit fat and iron levels. Zn, Mg, and Ca were grouped together, suggesting similar variability and contributions to the composition of pearl millet.

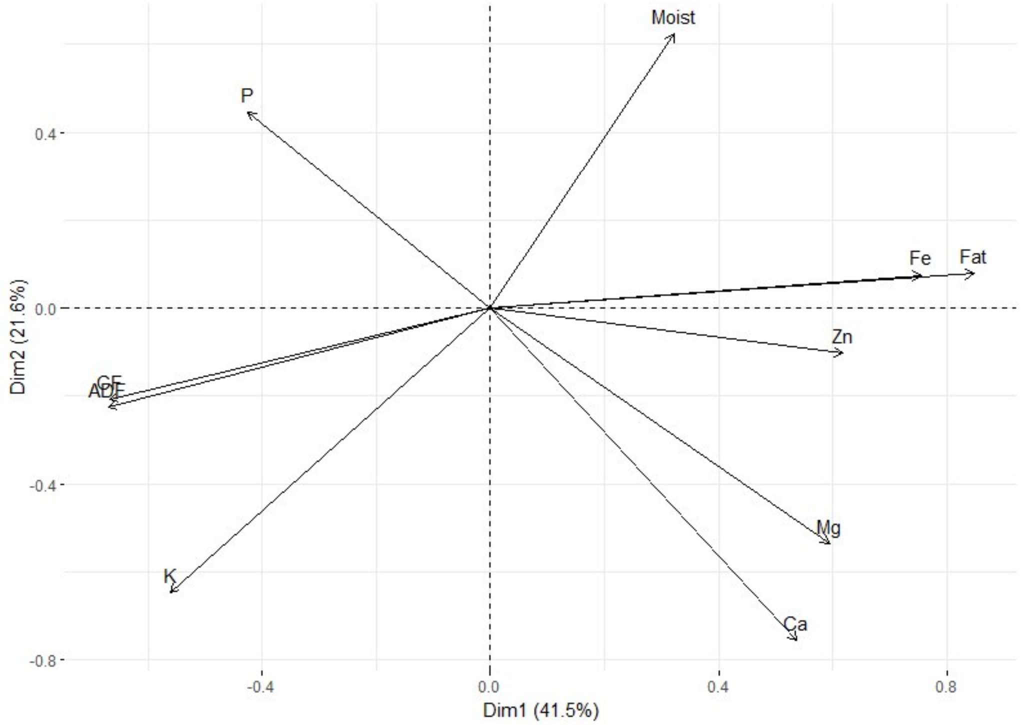

Figure 5-1. Principal component analysis biplot of nutritional contents under 100% ETc. Moist: Moisture, CF: crude fibre, ADF: acid detergent fibre, Ca: calcium, K: potassium, Mg: magnesium, P: phosphorus, Zn: zinc, Fe: iron.

5.3.6.2 Stressful conditions (50% ETc)

The relationship between the studied nutritional components of pearl millet under stressful conditions (50% ETc) is illustrated in Figure 5.2, using principal component biplots. The variables along the Dim1 axis explained 37.9% of the total variance, indicating that these variables had a significant influence on the proportion of data. Conversely, 21.1% of the variance was explained by variables on the Dim2 axis. Acute angles between variables suggest a positive correlation, perpendicular variables indicate minimal or no correlation, and variables in the opposite dimensions indicate a negative correlation. Under the 50% ETc treatment, Ca and Zn exhibited strong positive correlations. The substantial influence of moisture on Dim1 suggests that water availability plays a critical role in nutrient availability and may be vital for managing pearl millet under water-limited conditions. The relationship between fat, Ca, and Zn suggests that cultivars high in Ca and Zn may exhibit lower fat contents.

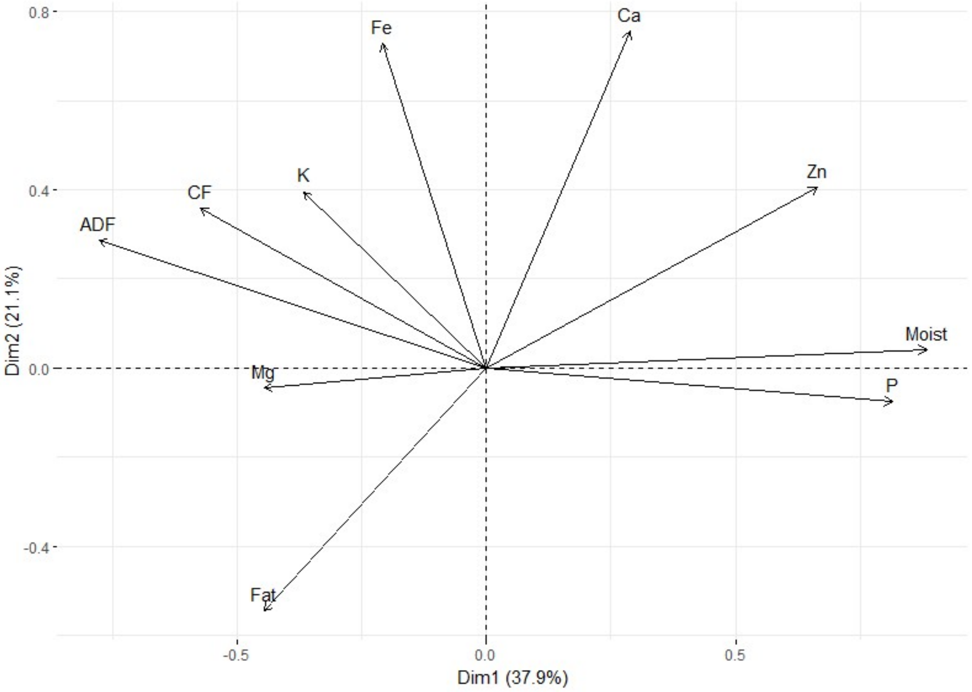

Figure 5-2. Principal component analysis biplot of nutritional contents under 50% ETc. Moist: Moisture, CF: crude fibre, ADF: acid detergent fibre, Ca: calcium, K: potassium, Mg: magnesium, P: phosphorus, Zn: zinc, Fe: iron.

5.4 Discussion

The escalating influence of climate change on temperature and precipitation patterns has significant implications for crop production and, consequently, the nutritional composition of agricultural yields. The results of this study highlight the effects of different water regimes (100%, 75%, and 50% ETc) and varieties (Kangara and Okashana 2) on the nutritional composition of pearl millet. Water availability is integral to nutrient and mineral mobilisation throughout a crop's life cycle. The soil nutrient content significantly affects the nutritional composition of millets, with higher levels of soil nitrogen and phosphorus resulting in increased essential amino acid and α-tocopherol contents (Wang et al., 2024). The soil texture at the experimental site was heterogeneous, consisting of sandy clay loam with an overall composition of 54.31% sand, 15.92% silt, and 29.77% clay (Table 5.1). The lack of statistically significant differences in soil chemical composition indicated that the plots were laid in a homogeneous area, potentially resulting in minimal interference from the treatments studied.

The findings of this study indicate that the water stress experienced during both growing seasons resulted in a decrease in grain moisture content. This could be attributed to the reduced availability of water for translocation to the grains at 50% ETc. Kangara exhibited a higher grain moisture content than Okashana 2 during the growing period from September to December 2023. This suggests that Kangara was more water-retentive or less efficient in terms of water use than Okashana 2 during this period. In contrast, from January to April 2024, Okashana 2 had higher grain moisture content, although the difference was not statistically significant. This highlights the seasonal variability contributing to the differences in the observations. The grain moisture content ranged from 2.10% to 10.07%. These values are lower than those reported by Kulthe et al. (2016), who found that pearl millet contained 11.21-12.43 % moisture in the genotypes studied. Jandu and Kawatra (2019) found that the moisture content of the pearl millet varieties evaluated varied between 7.41% and 8.61%. These results demonstrate the influence of heterogeneous genotypes and potential confounding environmental factors on the grain moisture content in pearl millet. Furthermore, the results of this study corroborate those of Alam et al. (2021), who found that drought stress during maize grain filling can result in decreased kernel water content, shorter kernel-filling duration, and lower final kernel weight. Water availability positively affects grain moisture content because plants with an adequate water supply maintain higher turgor pressure, which facilitates nutrient and water transport to developing grains, consequently affecting grain yield and quality (Seleiman et al., 2021). Conversely, drought conditions hinder the osmotic potential of plants, leading to low nutrient absorption and thereby affecting crop development (Ashrafi et al., 2022).

The study also found significant differences in fat content among the water regimes, with 75% ETc showing the lowest fat concentration compared to 50% and 100% ETc from September to December 2023. This trend could be attributed to the adaptive nature of pearl millet at 50% ETc, which triggers stress-induced metabolic pathways. However, at 75% ETc, the conditions might not have been optimal for some metabolic pathways, nor too stressful for some stress-induced metabolic pathways to be triggered. A similar pattern was observed from January to April 2024, when the fat content was higher at 50% ETc. Seasonal variations and water regimes influence the crude fat content by affecting plant metabolic processes and resource allocation during grain development. Lipids also play crucial roles in stress signalling and adaptation (Liang et al., 2023). In this study, the fat content varied between 2.11% and 5.10%. These results were slightly lower than those reported by Choudhary et al. (2016), who found that the fat content of pearl millet ranged from 4.0% to 8.0%. This variation may be due to differences in genotypic and environmental conditions. Adequate water availability supports lipid biosynthesis by ensuring optimal enzyme activity and energy flow, which leads to increased fat accumulation. Generally, primary metabolites, including lipids, decrease in response to increased water stress (Laftouhi et al., 2024). Shegro et al. (2012) found that water stress alters lipid metabolism in sorghum and reduces fat content in the grain. However, in this study, no clear relationship was established between water stress and fat content in Kangara and Okashana 2.

The results showed no statistically significant difference between the water regime and CF in either growing period; however, from January to April 2024, a statistically significant difference ($p = 0.04$) was observed between the water regime and ADF. This suggests that water stress has little to no effect on these traits in pearl millet. This resilience may be related to the crop's inherent drought tolerance mechanisms, which prioritise the maintenance of essential functions even under water-limited conditions (Manga et al., 2011). Other studies have similarly found that crops such as barley and sorghum exhibit minimal changes in fiber content under drought stress, as the plants conserve resources for structural integrity (Farooq et al., 2012). As water plays a crucial role in plant mineral mobilisation, drought stress reduces the uptake of essential minerals, such as Mg, K, P, Ca, Fe, and Zn from the soil, potentially resulting in decreased concentrations of these minerals in the grain. Pearl millet generally shows a minimal effect of the water regime on mineral composition. The lack of significant differences in micronutrient concentrations (Ca, K, Mg, P, Zn, and Fe) across the water regimes from September to December 2023 indicates that pearl millet maintains its micronutrient profile, even under water-stressed conditions. From January to April 2024, K and phosphorus levels were higher in higher water regimes (75% and 100% ETc) and lower at 50% ETc. Ca and Fe levels were higher at 50% ETc and lower at 100% ETc, whereas Zn availability was lower at 100% ETc. This finding aligns with reports on other cereals such as sorghum and wheat, which also show relative stability in micronutrient content under drought conditions (Bouis & Welch, 2010). Higher moisture levels may dilute iron uptake or distribution within the plant or grain, possibly because of physiological changes in nutrient transport or assimilation caused by excessive water availability. In contrast, Zou et al. (2020) found that drought can affect the uptake and distribution of nutrients, particularly iron and zinc, within plants. However, the consistent micronutrient levels observed in this study suggest that pearl millet, as a drought-resilient crop, can maintain its nutritional quality even under suboptimal water availability, making it a valuable source for combating micronutrient malnutrition in the context of climate change.

Correlation analysis between different traits is crucial for selection or crop improvement programs that aim to achieve sustainable crop production under highly variable climatic conditions. In the present study, the association between mineral composition traits was determined under stressed (50% ETc) and non-stressed (100% ETc) conditions. From the results, under 50% ETc, a strong positive correlation was observed between ADF and CF (*r*=0.91), P and moisture (*r*=0.91), and Zn and moisture (*r*=0.75), indicating that some interactions occurred between them, whereas under 100% ETc, a positive correlation between CF and ADF (*r*=0.88), Ca and Mg (*r*=0.73), Zn and Fe (*r*=0.64), and Mg and Zn (*r*=0.61). The order and magnitude of associations between these traits under different water scenarios suggest that similar physiological mechanisms and biochemical and soil factors control their mobilisation, uptake, and transportation to pearl millet grains without affecting their accumulation in the grains. As shown in Table 5.2, at 50% ETc, soil P content was higher, which may highlight the role of soil P in the accumulation of P in grains and in mitigating the adverse effects of water stress on grain moisture content. This demonstrates the resilience of pearl millet varieties in extracting phosphorus from the soil despite limited water availability. Phosphorus is vital for plants to maintain water balance and to tolerate drought stress (Khan et al., 2023). ADF and CF were highly correlated under both stressed and non-stressed conditions, indicating the stability of these two components under various environmental conditions. ADF is a fiber composed of cellulose and lignin (Van Soest & Robertson, 1979). This measure is linked to the digestibility and energy content of forage and is used to determine the total digestible nutrients or net energy in hay, haylage, and corn silage. Generally, forages with lower ADF levels tend to have a higher energy content (Wright & Lackey, 2008). In this study, ADF ranged between 4.54% and 4.85% from September to December 2023, and between 5.88% and 8.05% from January to April 2024 during the growing period. Although there was no statistically significant difference between the water regime and ADF from September to December 2023, the lowest ADF was recorded at 100% ETc, indicating that, with high water availability, the energy level in pearl millet grains decreases. From January to April 2024, the ADF was lower under 100% ETc.

In terms of seasonality, the ADF from September to December 2023 was lower than in the concurrent season, indicating that higher energy levels in terms of ADF can be achieved during this period. These results are consistent with those of Seydosoglu et al. (2023), who found ADF ratios ranging from 3.44% to 11.43% in the studied pearl millet genotypes. In this study, crude fiber (CF) ranged from 2.01% to 3.58%. Previous studies have reported CF levels ranging from 1.67% in the HHB-67 improved variety (Jandu & Kawatra, 2019) to 2.07-2.63% in other cultivars (Kulthe et al., 2016). The correlation results from this study showed that Zn and Fe were positively correlated. These results corroborate those of Govindaraj et al. (2022) and Kamble et al. (2022), who reported a positive association between Fe and Zn in pearl millet. A strong positive correlation between Fe and Zn contents has been consistently observed across studies ($r = 0.58$-0.81), suggesting the possibility of simultaneous improvement in both nutrients (Govindaraj et al., 2022; Mahendrakar et al., 2019). Furthermore, an association between the Ca and Mg levels was established in this study. Kavita et al. (2023) also found a positive correlation between Ca and Mg levels. The correlation between these two macronutrients (Ca and Mg) can be attributed to their uptake, translocation pathways, and physiological functions during plant growth and development. In this study, Mg and Zn levels were positively correlated. Govindaraj et al. (2022) found a correlation between Mg and Zn in some parental lines of pearl millet varieties.

The principal component analysis biplot illustrates the trait associations of pearl millet under water-stressed (50% ETc) and non-water-stressed (100% ETc) conditions. The longer vector lengths observed under 100% ETc than under 50% ETc indicated wide variations among the water regimes and nutritional traits. The short vectors showed minimal differences among traits observed under water-stressed conditions. The correlation coefficients in Table 5.5 substantiate the PCA biplot results and show similar directions between nutritional trait associations. A positive correlation is observed between ADF and CF, Ca and Mg, Mg and Zn, and Zn and Fe in the 100% ETc biplot, consistent with the correlations in the correlation matrix. Under water-stressed conditions, the PCA biplot depicted a positive correlation between ADF and CF, P with moisture, and Zn with moisture. The results of this study suggest that the associated traits remain stable under changing water conditions and can be genetically bred independently of other traits without implications. Breeding programs can utilize these associations to enhance the resilience and nutritional quality of pearl millet varieties across diverse environmental conditions.

5.5 Conclusion

This study investigated the effects of water stress (100%, 75%, and 50% crop evapotranspiration rate) on the nutritional quality of Kangara and Okashana 2 pearl millet varieties. The results showed the influence of growing season on nutritional composition, with minimal significant differences in some nutritional traits, such as ADF, Ca, Mg, and Fe. There were no varietal differences between the cultivars evaluated (Kangara and Okashana 2). A significant positive association was found between nutritional traits, including Ca, Mg, Zn, and Fe. These results suggest that the studied pearl millet varieties remain relatively nutritionally stable under water-limited conditions, with implications for breeding programs aimed at improving nutritional quality and drought resilience. Future studies should explore and evaluate the mechanisms underlying nutritional traits in different environments. Other hybrid varieties should be investigated for potential optimisation of nutritional quality under water-limited conditions and should also be evaluated.

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6 SIMULATION OF CLIMATE CHANGE EFFECTS ON PEARL MILLET YIELD AND WATER PRODUCTIVITY UNDER SEMI-ARID CONDITIONS IN NAMIBIA USING THE AQUACROP MODEL

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ABSTRACT

Variations in temperature and precipitation resulting from climate change pose substantial risks to agricultural yields. Although these changes cannot be prevented, adaptation and mitigation strategies can help to sustain food production. This study examined the effect of climate change on pearl millet using two planting dates (December 15 and January 15) under both historical and future emission scenarios (SSP2-4.5 and SSP3-7.0) using the AquaCrop model under rainfed conditions in Namibia. Experimental data from 2023 to 2024 were used for model calibration and validation, while climate projections from Global Climate Models under SSP2 and SSP3 4.5 and 7.0 were applied for future scenarios. The results indicate reduced precipitation and increased temperatures from 2020 to 2059 compared to 1995 to 2014, accompanied by an increase in reference evapotranspiration (ETo). Water productivity (WP) is projected to decline by 22% (2020-2039) and 11% (2040-2059) during the respective periods. It is expected to decrease by 35% and 41%, respectively, in January. Dry yields for December planting are expected to decline from 0.90 to 0.81 tons/ha (2020-2039) under SSP2-4.5 and SSP3-7.0, while January yields drop from 1.83 to 1.21 tons/ha under the same scenarios. Between 2040 and 2059, the December planting yield is expected to vary between 0.83 and 0.81 ton/ha under SSP2-4.5 and SSP3-7.0, respectively. Meanwhile, during the same period, the January yield is expected to vary between 1.14 and 1.2 tons/ha under SSP2-4.5 and SSP3-7.0, respectively. The ratio of biomass produced under the December 15 planting date varied from 21% in the historical period to 18% in future scenarios, while under the January 15 planting date, biomass produced varied from 26% in the historical period to 21% and 22% in future scenarios. These results underscore the crucial role of optimising planting dates in mitigating climate-related risks. A planting date of January 15 is recommended to sustain future grain yield and biomass. Furthermore, proper planning for more variable rainfall and potential water stress after 2040 is crucial for sustaining yields under both climate scenarios. This study provides critical insights for the development of climate-adaptive agricultural strategies that enhance crop and water productivity, thereby supporting sustainable agricultural production.

Keywords: *AquaCrop Model, Namibia, Pearl millet, Shared Socioeconomic Pathways, Water productivity*

6.1 Introduction

Globally, climate change is increasingly recognised as a significant global challenge that affects agriculture and food security (Masson-Delmotte et al., 2021). Among the crops resilient to climate change, pearl millet (Pennisetum glaucum (L.) R. Br.) is a vital staple in regions facing water scarcity. Globally, pearl millet accounts for approximately 75% of the total millet production. Approximately 97% of pearl millet production is in Africa and Asia, with India being the largest producer among the nations, followed by China, Nigeria, and Niger (Deevi et al., 2024; FAOSTAT, 2024). The Statistics Division (ESS) of the Food and Agriculture Organization of the United Nations (FAO) indicated that the global area dedicated to production has experienced variations in recent years, reflecting changes in yield and environmental conditions during different periods. The same pattern was observed in Africa between 2004 and 2022, with yields varying from 5046 to 8937 (100 g/ha). In southern Africa, the estimated yield value between 2004 and 2022 ranged from 1059 to 4333 (100 g/ha) (FAOSTAT, 2024). In Namibia, yields ranged from 809 kg/ha to 4,296 kg/ha (100 g/ha) during the same period. These trends can be ascribed to environmental variability experienced in different years. According to projections from the International Food Policy Research Institute's IMPACT model, global demand for millet is expected to increase from 48.5 million tons to 66.5 million tons between 2030 and 2050 (Deevi et al., 2024). This underscores the need for and importance of integrating sustainable millet production into projected climatic conditions to meet projected demand. Understanding the potential effects of climate change on the water productivity of pearl millet is crucial for devising adaptive strategies to sustain agricultural productivity in the face of evolving environmental conditions. Water productivity assessments contribute to the development of practical strategies for water management and fostering agricultural resilience in semi-arid environments (Ghimire et al., 2025), where water scarcity hinders agricultural sustainability.

Although pearl millet is known for its resilience in arid and semi-arid regions under rain-dependent conditions, recent and recurring highly variable rainfall and high temperatures have affected its productivity. It is a staple food crop in Namibia and is cultivated mainly in rainfed systems. However, the adverse consequences of climate change, including altered rainfall patterns, high temperatures, and severe weather events, are increasingly threatening the sustainability of pearl millet production worldwide (Singh et al., 2017; Rama Rao et al., 2019). Climate change presents significant challenges to global agricultural systems by influencing crop growth, development, and overall yields. Alterations in temperature and rainfall patterns caused by climate change have a significant impact on physiological processes that regulate the growth and productivity of pearl millet. Increasing temperatures can accelerate or decelerate plant development, shorten the reproductive phase, and increase the frequency of heat stress events during vital growth stages, thereby adversely affecting grain formation and yield (Epa, 2017; Mangani et al., 2023). Moreover, changes in precipitation patterns, such as variations in the timing, intensity, and spatial distribution of rainfall, can lead to either water shortages or surpluses, thereby intensifying stressful conditions and reducing crop yield (Swarna et al., 2024). Increasing carbon dioxide concentrations have been shown to enhance plant growth through the rapid expansion of leaf area development, which can increase transpiration capabilities (National Research Council, Life Studies, Commission on Geosciences, Committee on Climate Uncertainty, 1991). Furthermore, Epa (2017) highlighted that laboratory experiments indicated that higher CO_2 levels could boost plant development and yield. However, additional confounding factors, such as fluctuating temperatures, ozone exposure, and limitations in water and nutrients, may offset potential yield increases. Exposure to high temperatures has been shown to decrease the number of spikes and florets per pearl millet plant (Djanaguiraman et al., 2018), which affects potential yield. The complex interactions between environmental factors, plant physiological responses, and agronomic management practices shape the influence of climate change on pearl millet yield. Water availability, soil fertility, pests and diseases, and genotype-specific adaptations play important roles in determining the resistance of pearl millet crops to climatic variability and extremes. Additionally, the differential responses of pearl millet cultivars to varying climatic conditions underscore the importance of genetic diversity and breeding efforts in developing climate-resilient cultivars that can maintain yields under changing environmental conditions (Choudhary et al., 2023).

Given these complex interactions and the high cost of experimental equipment, further studies are necessary to understand the potential effects of projected climatic conditions on pearl millet, necessitating the use of simulation models. Understanding these different processes of plant physiology requires more time, in terms of repeated crop measurements and other resources, to ensure the accuracy of research. Simulation models are often employed because of the complexities and limitations of the approaches used to determine the absolute consequences of environmental changes on crop yields. Different crop models and climate change scenarios have been proposed and widely used to determine the effects of projected climate change on plants. Several models have been employed to predict various indicators for different crops (Ullah et al., 2019; Sow et al., 2024; Vieira Junior et al., 2024). For example, Ullah et al. (2019) utilised the CSM-CERES-Millet model to assess the impact of climate change on pearl millet, revealing yield reductions under RCPs 4.5 and 8.5 in Pakistan. Assessing and implementing appropriate management practices tailored to specific agroecological environments under changing environmental conditions is essential for maximising yield potential and strengthening the resilience of agricultural systems.

Recent studies have focused on calibrating and validating AquaCrop models for various crops under diverse environmental conditions. The model has demonstrated strong capabilities in replicating the productivity of crops, biomass, and water consumption for forage cactus, millet, and sorghum in Brazil’s semi-arid regions (Pinheiro et al., 2024); perennial ryegrass in Colombia (Terán-Chaves et al., 2022); and canola under moisture irrigation in South Africa (Dirwai et al., 2021). These studies reported high coefficients of determination ($R^2 > 0.80$) and good accuracy in predicting the crop parameters. These findings demonstrate the potential of crop models in agricultural planning and decision-making for improved water use and yield estimation.

Shared Socioeconomic Pathways (SSPs) are scenarios developed by global researchers to explore different future pathways of societal development and their implications for climate change and other environmental issues (Riahi et al., 2017). The SSPs outlined distinct narratives, each describing a diverse trajectory of socioeconomic development, population growth, technological progress, and environmental management. These scenarios range from sustainable development (SSP1) to a world of regional rivalry and inequality (SSP3) to a fossil-fuelled development pathway (SSP5). The SSP framework is used in conjunction with climate models to assess how various societal decisions may influence climate change, along with adaptation and mitigation strategies (O'Neill et al., 2017). These scenarios serve as valuable tools, allowing us to project the potential climate impacts on agriculture.

By subjecting pearl millet to SSP scenario tests, we simulated a range of probable future climates to address fundamental questions regarding the impact of climate change on evapotranspiration rates, physiology, yield, and overall water productivity of pearl millet in Namibia. Moreover, by integrating experimental data and scenario-based modeling, this study provides insights into sustainable crop production and water management under future climatic conditions. This study aimed to (1) investigate how projected climate conditions influence the expansion of pearl millet canopies, closure of stomata, and rates of evapotranspiration, and (2) examine how the timing of planting affects water productivity, dry yield, and biomass production through simulations conducted using the AquaCrop model.

6.2 Materials and Methods

6.2.1 Description of the Model

The Land and Water Division of the Food and Agriculture Organization (FAO) developed the AquaCrop model to evaluate the effects of environmental conditions and field management practices on crop production (Steduto et al., 2009). It simulates plant–soil interactions by evaluating parameters such as crop development, aerial biomass, transpiration, and grain yield in relation to water productivity (WP)

(Raes et al., 2009; Salman et al., 2025). The model consists of four steps executed in series at each daily time step, which are outlined by Raes et al. (2018). First, green crop canopy cover (CC), followed by transpiration. The simulated aboveground biomass (B) (Equation 6.1) integrates all the photosynthetic products that the crop assimilates during the season to simulate crop yield using a Harvest Index (HI). The actual Harvest Index (HI) was calculated by modifying the reference Harvest Index (HIo) during the simulation using a factor that accounts for stress impacts (Steduto et al., 2009) after computing the biomass (B). Crop yield (Y) was calculated using Equation (6.2):

$B = WP \times \Sigma Tr$ ____ Equation 6.1

Where B represents the total aerial biomass yield (kg m-2), WP denotes water productivity (kg (m-2 · mm)), and Tr refers to the day-to-day crop transpiration rate (mm/day-1).

$Y = HI \times B$____ Equation 6.2

where Y represents the crop yield, HI stands for the Harvest Index, and B denotes the biomass (kg m-2).

6.2.2 Model Parametrisation

The AquaCrop model (version 7.1) requires meteorological, crop, management, and soil data. To achieve equilibrium between simplicity, precision, robustness, and ease of use, a minimal set of crop parameters is required (Salman et al., 2025). The data were as follows:

6.2.2.1 Meteorological Data

The AquaCrop model requires daily, 10-day, or monthly records of maximum and minimum air temperatures, relative humidity, wind velocity, precipitation, and hours of sunshine or solar radiation. The daily ETo was determined from these elements using ETo calculation, which is an integrated module derived from the FAO Penman-Monteith method (Allen et al., 1998). Namibia's monthly historical climate data for 1995-2014 were obtained from the Climate Change Knowledge Portal. Additionally, the ensemble mean of the projected climatic conditions was obtained from the same portal (https://climateknowledgeportal.worldbank.org/country/namibia/climate-data-projections, accessed 05

August 2024). The ensemble mean represents data that have been modeled using global climate models from the Coupled Model Intercomparison Projects (CMIPs), which are managed by the World Climate Research Program. The predicted climate data applied in this study were for two SSP-RCP scenarios (SSP2-4.5 and SSP3-7.0). The data were presented at a spatial resolution of 0.25° × 0.25°, equivalent to 25 km × 25 km (Climate Change Knowledge Portal, 2024). SSP2-4.5 represents a moderate emission pathway in which socioeconomic factors continue along historical trends without major shifts. Meanwhile, SSP3-7.0 represents a world with high greenhouse gas emissions, regional competition, and a resource-intensive economy (Meinshausen et al., 2020; Shiogama et al., 2023). Hence, SSP2-4.5 and SSP3-7.0 for 2020 – 2039 and 2040–2059 were selected for future climate change impact assessments to model the projected scenarios. Climate files (.CLI) were generated using meteorological data, including ETo (.ETo), and daily minimum and maximum temperatures (.TMP) and files for relative humidity and rainfall data (.PLU).

6.2.2.2 Crop Data

The AquaCrop database contains crop files that are fully calibrated and classified into two categories: conservative and non-conservative crop parameters. Conservative crop parameters remain relatively stable over time and are not significantly affected by management practices, geographical locations, or climate. Unless proven otherwise, these parameters were assumed to remain unchanged across different cultivars. Conservative parameters included stress thresholds of canopy cover (CC) per seedling, typical root expansion, pattern of water withdrawal, and normalised biomass water productivity (WP*). These parameters were not altered during the modeling process because they were not measured during the experimental studies. The FAO has determined and validated other parameters specific to crops, but not tied to specific locations, for major crops such as pearl millet in various locations. Therefore, these were used as default values in the model. In contrast, non-conservative or cultivar-specific parameters require adjustments when selecting a cultivar or when environmental conditions differ from those assumed during calibration. These parameters included growth cycle length and plant density. Data for these non-conservative inputs were obtained from field data collected during two growing seasons (September to December 2023 and January to April 2024). The simulation periods were linked to the growth cycle.

6.2.2.3 Management Data

Management data are essential for modeling cultivation practices and field events, particularly those related to field and irrigation management (Zhang et al., 2022). AquaCrop can be used to conduct simulations for various irrigation methods, including rain-fed and irrigated systems. It is essential to specify the irrigation method because it influences the simulation of soil moisture dynamics. In this study, irrigation management was calibrated according to the irrigation schedule using a drip irrigation system to administer 100%, 75%, and 50% of crop evapotranspiration (ETc), which was calculated during field trials conducted from September to December 2023 and January to April 2024. These data were then used to generate an irrigation file (.IRR) in AquaCrop. To develop a schedule, two critical variables must be determined for each irrigation event: the application time and amount. Soil fertility was deemed sufficient and not a limiting factor for the crop canopy, water efficiency, and biomass yield. Additional field management practices included the following: (i) absence of weeds, (ii) no use of mulch, and (iii) zero runoff.

6.2.2.4 Soil Characteristics Data

In AquaCrop, the soil profile consists of layers with distinct soil horizons, each possessing unique physical properties along with groundwater information (Food and Agriculture Organization of the United Nations, 2017). Soil type in the study area was identified using the United States Department of Agriculture (USDA) soil textural taxonomy (Taxonomy, 2014). The default soil horizon characteristics for the soil texture identified in the study area remained unchanged in the AquaCrop database. The groundwater depth in the study area was assumed not to influence crop growth through soil capillary pressure; therefore, it was not taken into consideration. Soil information was used to generate a soil file from AquaCrop (.SOL).

6.2.3 Model Application

6.2.3.1 Model calibration, validation, and evaluation

Field data collected during the 2023 and 2024 cropping seasons were used to calibrate the model and validate its performance. A comparison was made between the model predictions and observed data, followed by an analysis of the validation statistics. The R^2, which represents how well the observed and simulated values align, was used to evaluate the model outputs. The R^2 value represents the variance in the observed data as explained by the model. It ranges from 0 to 1, with higher values indicating a better fit between the observed and simulated data. Generally, an R^2 greater than 0.5 is considered to represent good collinearity between observed and simulated values (Moriasi et al., 2007). The root-mean-square error (RMSE) and mean absolute error (MAE) were used to evaluate the model. RMSE was used to test the differences between the forecasted and observed values. Simultaneously, the MAE determines the mean of the absolute differences between the predicted and actual values, serving as an indicator of prediction accuracy that does not account for the direction of the errors (Hodson, 2022).

6.3 Results

6.3.1 AquaCrop Model Calibration

6.3.1.1 Grain Yield Season 1 (September to December 2023)

Figure 6.1 compares the simulated and actual yields for the first cropping season (September-December 2023). The simulated yields ranged from 0.70 to 2.93 tons/ha, while the measured yields ranged from 0.76 to 2.88 tons/ha. The model-simulated pearl millet yielded well, with average simulation statistics for yield of $R^2 = 0.97$, RMSE = 0.10 (tons/ha), and MAE = 0.08 (tons/ha).

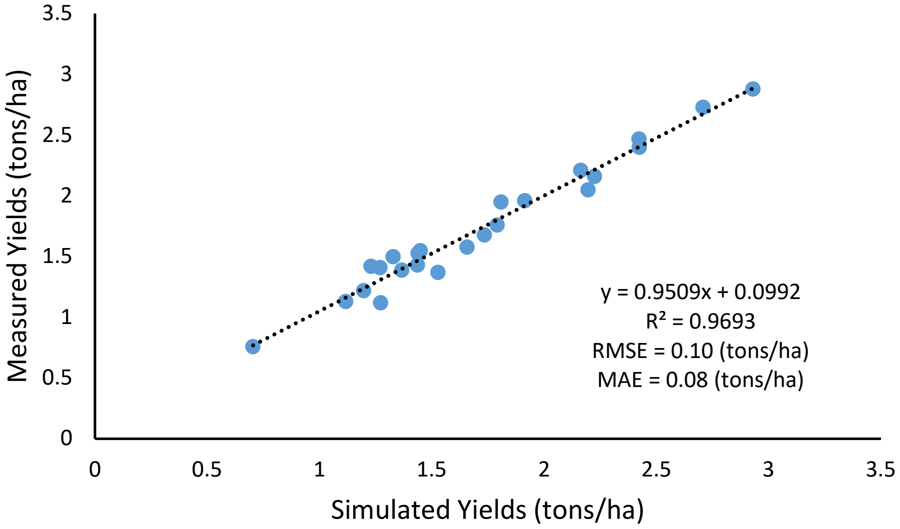

Figure 6-1. The actual and simulated yields of pearl millet under different irrigation regimes during the AquaCrop calibration (September to December 2023). RMSE: root mean squared, MAE: mean absolute error.

6.3.2 AquaCrop Model Validation

6.3.2.1 Grain Yield Season 2 (January to April 2024)

Figure 6.2 shows the simulated and actual yield scenarios. The simulated yields ranged from 0.71 to 2.97 tons/ha, while the measured yields ranged from 0.96 to 3.00 tons/ha. Model performance was indicated by an R^2 of 0.95, an RMSE of 0.12 (tons/ha), and an MAE of 0.10 (tons/ha).

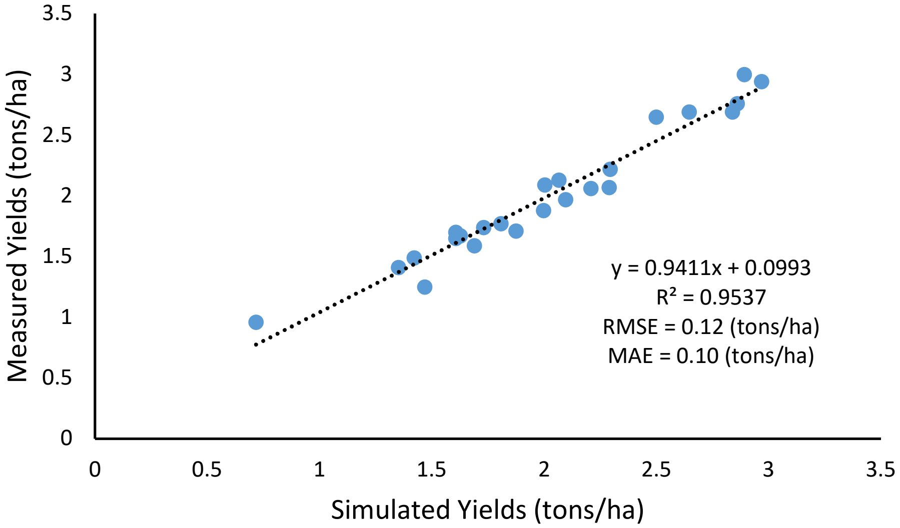

Figure 6-2. Relation between the actual and simulated yields of pearl millet under different irrigation regimes during the AquaCrop validation (January–April 2024). RMSE: root mean squared, MAE: mean absolute error.

6.3.3 Climate Scenario Simulations

6.3.4 Historical and Projected Meteorological Data

Historical and projected meteorological data are shown in Figure 6.3. The SSP2-4.5 and SSP3-4.5 scenarios for the 2020-2039 project lower rainfall than the historical period, while the maximum average temperature during the same period also shows an increase compared to the historical temperature. Compared with the historical period (1995-2014), rainfall will decrease by 13.22, 12.05. 21.66 and 14.74mm for SSP2-4.5 (2020-2039), SSP3-7.0 (2020-2039), SSP2-4.5 (2040-2059), and SSP3-7.0 (2040-2059), respectively. The maximum monthly temperature is expected to increase by 0.97 °C, 0.96 °C, 1.74 °C, and 1.86°C for SSP2-4.5 (2020-2039), SSP3-7.0 (2020-2039), SSP2-4.5 (2040-2059), and SSP3-7.0 (2040-2059), respectively, compared to the historical period. The minimum monthly average temperature is expected to increase by 0.83 °C, 0.88 °C, 1.56 °C, and 1.74°C for SSP2-4.5 (2020-2039), SSP3-7.0 (2020-2039), SSP2-4.5 (2040-2059), and SSP3-7.0 (2040-2059), respectively, compared to the historical period.

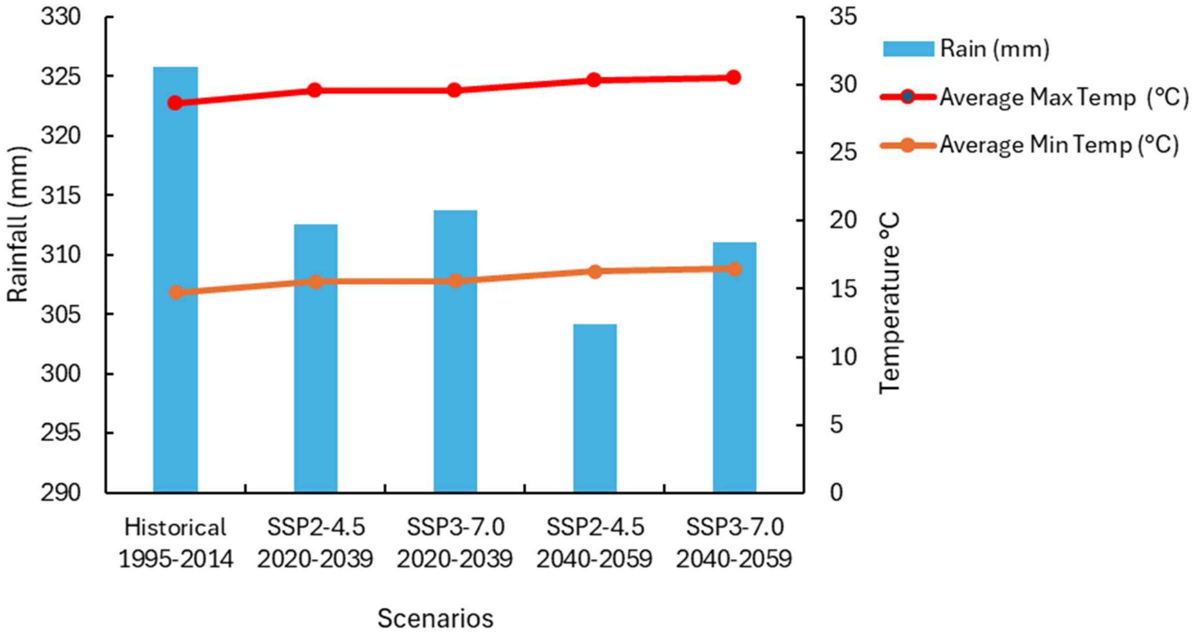

Figure 6-3. Average monthly rainfall, average monthly maximum and minimum temperature for the historical and projected climate scenarios for Namibia.

6.3.5 Rain and Evapotranspiration during the crop-growing cycle

Figure 6.4 shows the rain, evapotranspiration, evaporation, and transpiration during the pearl millet growth period for two planting dates (December 15 and January 15). (a) shows the planting date on December 15th. The reference evapotranspiration (ETo) estimated during the historical period (1995-2014) was 531.8 mm per growing period, while the highest ETo estimated for the same planting date was 554 mm under the SSP2-4.5 2040-2059 scenario. The highest rainfall is projected to be 212.8 mm under the historical period of 1995-2014, while the lowest is estimated to be 199.5 mm under the SSP2-4.5 2040-2059 scenario. (b) the historical period of 1995-2014, during the 15th of January planting date, the ETo was lower at 449.3 mm and estimated to be the highest (513.9 mm) during the SSP2-4.5 2040-2059. The highest rainfall was estimated to be 188.6 mm during the historical period of 1995-2014, and the lowest rainfall was projected to be 178.1 mm during SSP2-4.5 for the period 2040-2059. The two planting dates assessed had a similar pattern of parameters evaluated; however, the 15th of December planting date showed the highest ETo (554 mm, SSP2-4.5 2040-2059).

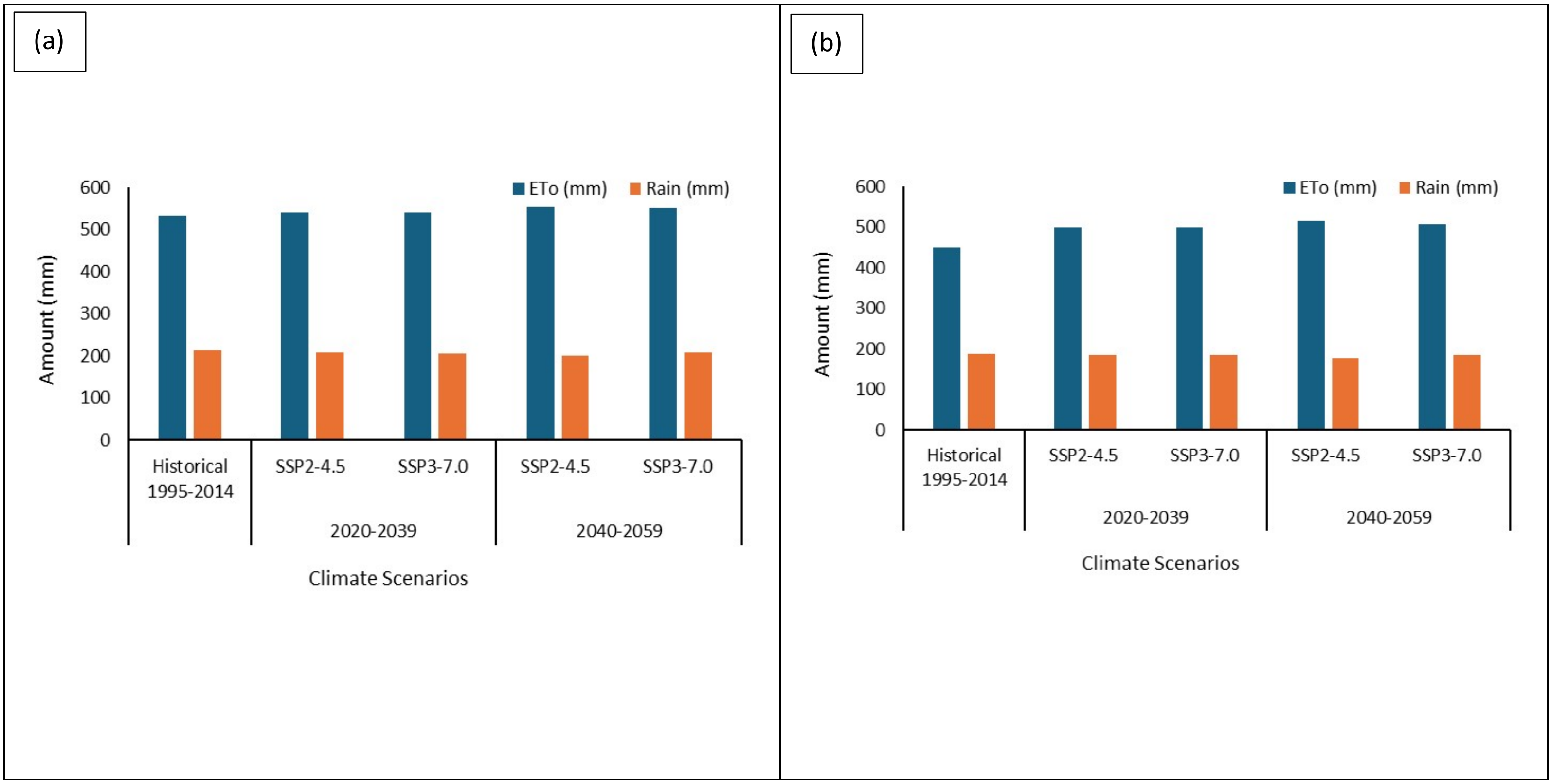

Figure 6-4. Reference evapotranspiration and Rainfall during the pearl millet growing period for two planting dates under the historical and future climate scenarios: (a) 15 December and (b) 15 January.

6.3.6 Canopy expansion and Canopy closure

Canopy expansion and closure owing to moisture stress are shown in Figure 6.5. In both scenarios, the historical (1995-2014) canopy expansion was less limited by water stress than that in the other climate change scenarios. (a) According to the 15th of December planting date, the historical period from 1995 to 2014 indicated that canopy expansion was less limited by water stress compared to other scenarios. Between 2020 and 2039, under both the SSP2-4.5 and SSP3-7.0 scenarios, approximately 63% of canopy expansion was limited by water stress. SSP2-4.5 and SSP3-7.0 (2040-2059) exhibit more limited canopy expansion due to water stress (64%). Regarding stomatal closure, the graph shows an increase from the historical (50%) to future scenarios (55%). (b) Under the January 15 planting date, only 60% of the canopy expansion was limited by water stress during the historical period, whereas in future scenarios, the canopy expansion will be limited by approximately 62%. Approximately 52% of stomatal closure during the crop cycle occurred during the historical period. Approximately 55% of the stomatal closure was modelled in future scenarios. These show that the projected climatic conditions are likely to affect canopy expansion and stomatal closure.

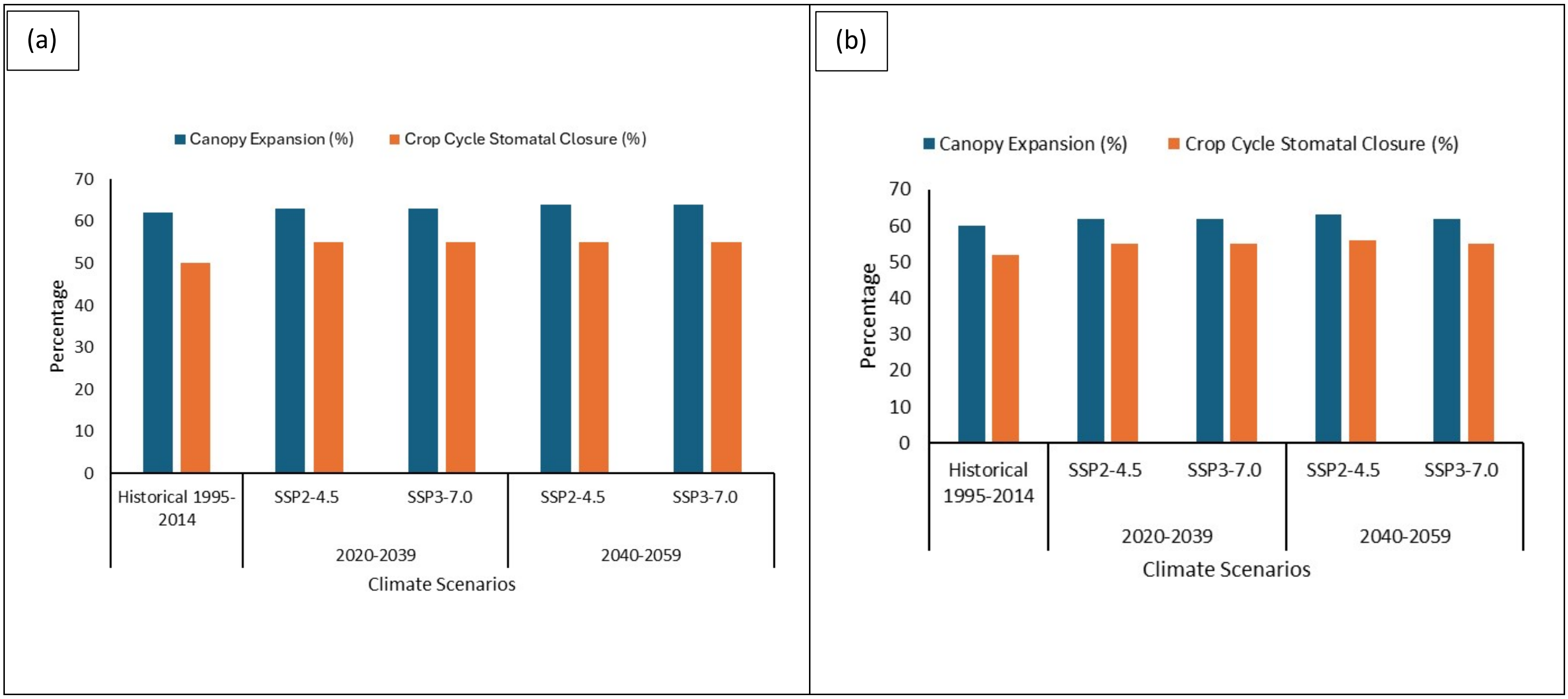

Figure 6-5. Canopy expansion and stomatal closure of the pearl millet growing period for two planting dates under the historical and future climate scenarios: (a) 15 December and (b) 15 January.

6.3.7 ET Water Productivity

Figure 6.6 shows the water productivity of pearl millet on two planting dates, the 15th of December and the 15th of January. (a) During the historical period (1995-2014), water productivity was higher than future climate scenarios (0.31 kg/m^3), followed by SSP2-4.5 2020-2059 (0.29 kg/m3), SSP3-7.0 2040-2059 (0.28 kg/m^3), SSP3-7.0 2020-2039 (0.27 kg/m^3) and lastly SSP2-4.5 2020-2039 (0.27 kg/m^3). (b) The historical period (1995-2014) exhibits the highest water productivity of 0.73 kg/m^3 compared to future scenarios, followed by SSP2-4.5 (2020-2039), SSP3-7.0 (2020-2039), and SSP3-7.0 (2040-2059), all with 0.45 kg/m^3, and lastly SSP2-4.5 (2040-2059) with 0.43 kg/m^3. The highest water productivity was simulated to be in the 15th of January planting date.

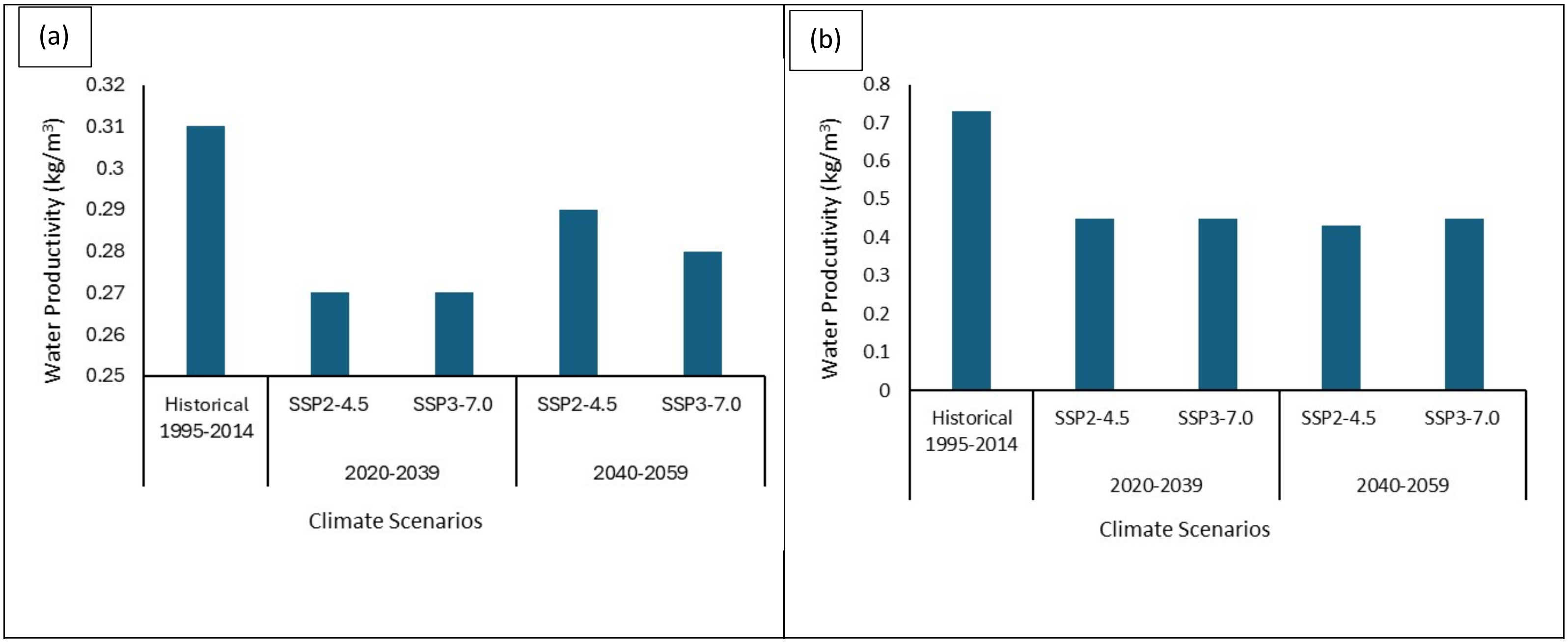

Figure 6-6. Water productivity of pearl millet growing period for two planting dates under the historical and future climate scenarios: (a) 15 December and (b) 15 January.

6.3.8 Dry yield

Figure 6.7 shows the modelled historical and future climate yield projections for the pearl millet. (a) The historical period shows that yield was higher (0.90 tons/ha) than in future climate scenarios under the 15th of December planting date. This is followed by SSP2-4.5 2040-2059 (0.83 tons/ha), SSP3-7.0 2040-2059, and both SSP2-4.5 and SSP3-7.0 under 2020-2039 show a similar yield of 0.81 tons/ha. (b) For the 15th of January planting date, the historical period modelled the highest yield of 1.83 tons/ha, followed by

SSP2-4.5 (2020-2039), SSP3-7.0 (2020-2039), and SSSP3-7.0 (2040-2059), with yields of 1.21 tons/ha and 1.14 tons/ha, respectively.

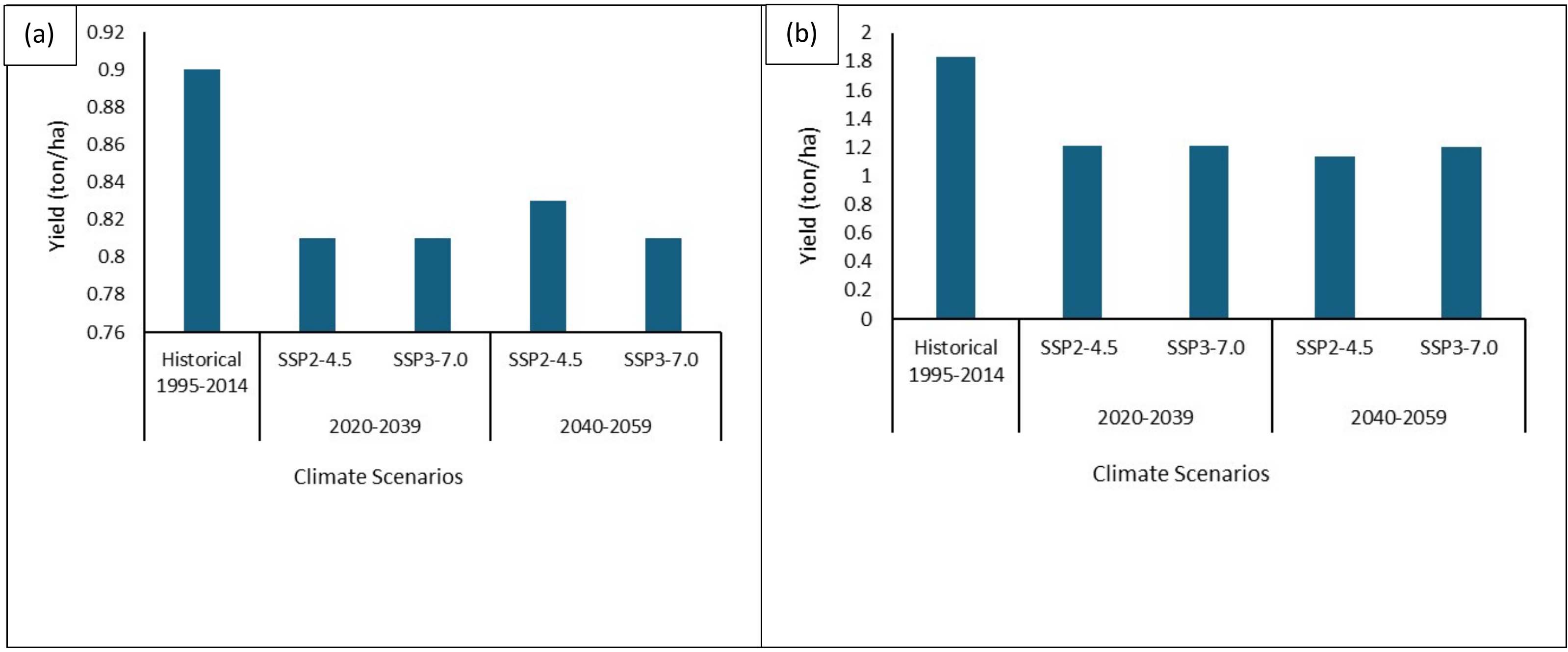

Figure 6-7. Yield of pearl millet growing period for two planting dates under the historical and future climate scenarios: (a) 15 December and (b) 15 January.

6.3.9 Ratio of biomass produced

Figure 6.8 shows the projected changes in biomass ratio across different climate scenarios. (a) shows the highest biomass production ratio of approximately 21% during the historical period (1995-2014), whereas the future scenarios showed a significant decrease from the historical scenario. All the future scenarios showed a similar biomass production ratio of 18%. (b) The historical period showed the highest biomass production ratio, at 26%, followed by the 2020-2039 scenario for SSP2-4.5 and SSP3-7.0, at 21%. For 2040 and 2059, under both SSP2-4.5 and SSP3-7.0, the projected biomass production was 20%. This indicates that, for the January 15 planting date, more biomass will be produced than for the December 15 planting date, making January 15 a more suitable planting date in the future.

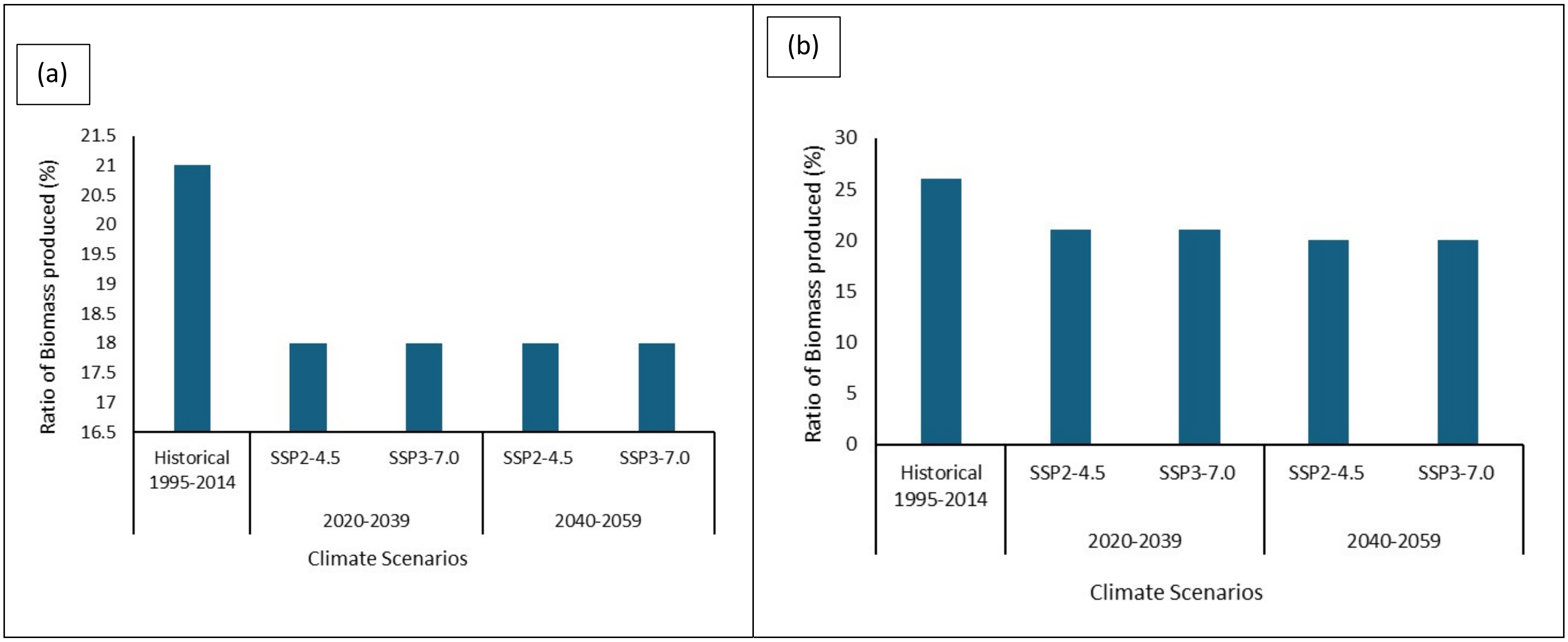

Figure 6-8. Ratio of biomass produced during the pearl millet growing period for two planting dates under the historical and future climate scenarios: (a) 15 December and (b) 15 January.

6.4 Discussion

This study investigated the potential impact of climate change on the water productivity of pearl millet in Namibia's semi-arid regions, utilising the FAO AquaCrop model. The varying responses of pearl millet to moisture stress and high temperatures affect its water productivity and overall performance. The association between plant development and water use has been studied for centuries, evolving from philosophical to modern scientific research (Brendel, 2021). Environmental factors such as solar radiation, vapor pressure deficit, and soil water content influence transpiration rates and crop yields (Li et al., 2021; Schreiner-McGraw & Baffaut, 2023).

The results of this study demonstrate that the AquaCrop model is effective in assessing the water productivity of pearl millet. The results showed that the model-simulated pearl millet yielded well, with an average coefficient of determination (R^2) of 0.97. Additionally, the validation results showed that the simulated yields remained relatively constant, ranging from 0.71 to 2.97 tons per hectare. These results corroborate those reported by Berhane and Kefale (2018) and Sathyamoorthy et al. (2023). The AquaCrop model was successfully calibrated and validated to simulate the green vegetative cover, aboveground dry matter, and grain yield of pearl millet across various sowing windows, nitrogen levels, and climate change scenarios. Early sowing at 125% of the recommended nitrogen level resulted in the highest observed and simulated grain and straw yields (Sathyamoorthy et al., 2023). In comparison, late sowing at 75% of the recommended nitrogen level yielded the lowest yield. The AquaCrop model demonstrated good predictive ability for pearl millet growth and productivity across various sowing dates and nitrogen levels (Sathyamoorthy et al., 2023). According to Bello and Walker (2016), the AquaCrop model effectively simulated canopy development, biomass accumulation, total evapotranspiration, and harvested grain quantity for the two pearl millet accessions under rainfed and irrigated conditions. However, its accuracy in representing the dynamic content of soil moisture for pearl millet was moderate and required improvement.

Climate models projected higher temperatures and lower rainfall for 2020-2059 than for the historical period (1995-2014). The SSP2-4.5 and SSP3-4.5 pathways showed a slight decline in the projected rainfall after 2040 – 2059 and a slight increase in the maximum average temperature compared to the 2020-2039 scenarios. This may indicate challenges in pearl millet production if distribution becomes erratic. If rain occurs in shorter, more intense periods or is unevenly distributed, it could lead to water stress or crop damage, thereby affecting yield. The SSP2-4.5 scenario generally projects a stable to slightly declining rainfall trend post-2040, whereas SSP3-7.0 shows a similar trend of slightly declining rainfall. However, under a higher emissions scenario, other stress factors such as higher temperatures may exacerbate evapotranspiration losses, thus affecting pearl millet production.

Previous studies have consistently demonstrated a strong relationship between evapotranspiration (ET) and biomass accumulation in both crops and trees. For wheat and maize, a geospatial modeling approach has demonstrated high correlations between evapotranspiration (ET), gross primary production, and yield (Wang et al., 2023). Li et al. (2021) reported a logistic relationship between annual transpiration and aboveground biomass of poplar trees. Similarly, Schreiner-McGraw and Baffaut (2023) demonstrated a significant correlation among maize transpiration, biomass, and yield. On the other hand, Collins et al.

(2021) investigated the potential of reducing the transpiration rate under high atmospheric demand to enhance wheat yields, finding yield increases of up to 2.6% across Australia. These findings underscore the significance of understanding plant water use to enhance crop productivity and develop effective water management strategies.

The results showed that water stress limited canopy expansion and stomatal closure in both planting date scenarios. However, this limitation was more pronounced on the December 15th planting date. These results are in agreement with those of previous studies. According to Sankararao et al. (2022), a UAV-based HSI sensor operating within the 400–1000 nm spectrum was utilised to detect water stress in a pearl millet crop, revealing decreased canopy growth and stomatal closure when the plants experienced water deficiency. Additionally, de Almeida et al. (2022) found that moisture stress affects the expansion of the pearl millet canopy and stomatal closure, consequently affecting the yield and water productivity. Stomatal conductance, photosynthesis, and transpiration are reduced in pearl millet under soil moisture stress coupled with temperature variations, thereby affecting biomass production (Khanthavong et al., 2022). Despite these effects, pearl millet employs short-term physiological adjustments, such as osmotic regulation and stomatal conductance, along with long-term developmental plasticity in root growth and tillering to mitigate drought stress (Shrestha et al., 2023).

The effects of climate change on pearl millet production in sub-Saharan Africa are highly variable, with vapor pressure deficit, frequency of wet days, and temperature being the primary factors influencing yield (Emediegwu et al., 2022). According to the results, future scenarios indicate that water productivity and biomass production will be lower than in the historical period. This can be attributed to the projected high temperatures, which result in a soil moisture deficit. These results corroborate those of previous studies, which have shown that under limited water conditions, water productivity increases as irrigation levels decrease, with the highest productivity observed at 40% water replacement (de Almeida et al., 2022). Furthermore, combining soil mulching (7.2 tons/ha) with irrigation, which meets 75% of the water requirement, can optimise pearl millet productivity in hyper-arid areas (Salem & Shoman, 2021). De Almeida et al. (2022) found that the lowest irrigation amount decreased the biomass yield but increased the water productivity. Drought stress reduces pearl millet biomass and induces oxidative stress at the seedling stage despite its tolerance to arid conditions (Choudhury et al., 2022).

The projected high temperatures could lead to more rapid soil moisture loss, increasing the risk of water stress during the growing season and negatively affecting pearl millet productivity. Adaptation strategies, such as adjusting planting times to align with shifts in rainfall and temperature patterns, can optimise crop growth and minimise heat stress, thereby sustaining crop productivity. Planning for more variable rainfall and potential water stress after 2040 is crucial to sustain yields under both climate scenarios.

6.5 Conclusion

This study provides an understanding of the potential implications of climate change on pearl millet water productivity, as simulated using the FAO AquaCrop model under semi-arid conditions in Namibia. These findings suggest that AquaCrop can be successfully used to project and plan crop productivity under future climatic conditions. The results indicate that a decline in rainfall, projected increases in temperature, and evapotranspiration rates are expected. These environmental changes are expected to result in reduced canopy expansion, high rates of stomatal closure, reduced water productivity, lower yields, and reduced biomass, which could affect food availability in the future. Therefore, climate adaptation and mitigation strategies, such as adjusting pearl millet planting dates and irrigation water management in Namibia, will be instrumental in ensuring food security in the future. Future studies should focus on evaluating additional planting dates and assessing AquaCrop across different regions to develop tailored solutions for each specific region.

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7 SYNTHESIS

7.1 Synthesis

This study aimed to assess the water use efficiency and productivity of pearl millet under the semi-arid conditions of Namibia. The study was guided by four objectives: (1) to determine the effects of irrigation regimes on the agro-physiological and morphological responses of Kangara and Okashana 2 pearl millet cultivars, (2) to evaluate drought tolerance indices and water use efficiency under varying water regimes, (3) to investigate the influence of irrigation regimes on the nutritional quality of the two cultivars, and (4) to assess the potential effects of climate change on pearl millet water productivity using Shared Socioeconomic Pathways (SSPs).

The results of this study show that across the two cropping seasons, irrigation regimes had a significant influence on both physiological and yield responses of pearl millet. Under 100% ETc, both Kangara and Okashana 2 maintained higher plant height, leaf number, number of tillers, chlorophyll content, and stomatal conductance, which translated into increased biomass and grain yield. However, the 75% ETc regime maintained acceptable productivity, suggesting that moderate deficit irrigation is an optimal strategy for water-scarce conditions. While at 50% ETc, plant height, leaf number, number of tillers, chlorophyll content, and stomatal conductance were significantly reduced. This pattern of reduced plant height at 50% ETc might be attributed to reduced turgor pressure in cells, which directly limits cell expansion, resulting into shorter stems. These results corroborate those of previous researchers who found that low irrigation regimes significantly reduced plant growth, biomass production, and chemical composition, and higher water availability generally improves these factors (Halilou et al., 2020; Lira et al., 2020).

Higher WUE in this study was recorded at 75% ETc, which suggests that this irrigation regime might be an optimum strategy for sustainable pearl millet production under the studied conditions. This may also indicate that pearl millet still maintains its photosynthetic capacity, thereby enhancing WUE. Kangara and Okashana 2 did not differ significantly in terms of drought tolerance indices assessed, which might be associated with the similar genetic makeup and cross-pollination that might have occurred during flowering. These findings corroborate those of Bhattarai et al. (2020), who found that pearl millet had high water use efficiency at 75% of evapotranspiration (ETc) compared to forage sorghum and corn under limited irrigation. Furthermore, Salem et al. (2021) showed that pearl millet water use efficiency was high at 75% of the water requirement when combined with 7.2 tons/ha soil mulch. This shows that under proper agronomic practices, pearl millet WUE can be enhanced to conserve limited water resources available in water-scarce environments.

Although growth and yield declined with reduced water regimes, the nutritional composition remained relatively stable, with certain nutrients, such as Fe and Zinc, even enhanced. The increase in Fe content and Zinc levels at 50% ETc reflects a degree of nutritional resilience that could sustain food quality under climate change. This could be attributed to a smaller grain size at 50% ETc than at 100% ETc, which may reflect that nutrients are concentrated in smaller grains than in bigger ones. Nutritional resilience under stress confirms earlier studies showing that pearl millet maintains or even improves micronutrient content under drought, strengthening its role as a climate-resilient staple for food security in arid regions. For instance, Rai et al. (2017) found that both Fe and Zn concentrations increased under terminal drought conditions than under irrigated conditions.

AquaCrop simulations under SSP scenarios projected reduced rainfall, rising temperatures, and higher evaporative demand. Water productivity is expected to decline by 22–35%, with dry yields decreasing substantially between 2020 and 2039. Planting date of 15 January emerged as the most resilient option, mitigating yield losses under projected future climates as opposed to the 15 December planting date. Results of this study are in agreement with a study conducted in West Africa, which also showed that water productivity and yields of pearl millet are projected to decline by 10-20% in the future due to increased temperature and moderate decreases in precipitation (Salack et al.,2015).

This study, by integrating field trials, physiological responses, water use efficiency (WUE), and nutritional quality in response to varying moisture levels and climate modeling, demonstrated that pearl millet exhibits both vulnerability and resilience under semi-arid conditions. This synthesis shows that moderate deficit irrigation (75% ETc) balances productivity and resilience, while pearl millet's nutritional stability under drought reinforces its role as a climate-smart crop for food security in semi-arid Namibia.

In Namibia, where rain-fed pearl millet systems remain vulnerable to climatic variability, the findings highlight the need for site-specific data to devise sustainable water management strategies in crop production and shifting planting dates as an adaptive strategy to climate variability and change. This study, therefore, recommends late planting of pearl millet to attain sustainable yields. Policy makers and extension services should also promote awareness of seasonal planting dates adjustments as a practical adaptation strategy to enhance crop productivity and resilience under changing climate conditions. Ultimately, this study contributes to the discourse on pearl millet water use efficiency and productivity. Furthermore, the study adds to the scientific and practical understanding of how water use efficiency, drought resilience, and climate-smart practices can be leveraged to optimise pearl millet productivity and support food security in water-scarce environments like Namibia.

7.2 Implications for Water Management and Pearl Millet Production in Namibia

Assessing pearl millet water-use efficiency and productivity in Namibia is crucial for agricultural water planning and management to ensure sustainable crop production in the face of climate change and increasing water scarcity. Agriculture is the primary consumer of freshwater globally, accounting for 80–90% of all human withdrawals from rivers, lakes, and aquifers (Morison et al., 2008); therefore, efficient water management in this sector is essential for national development, food security, and economic sustainability. This study offers critical insights into pearl millet production under semi-arid conditions by examining the effects of different irrigation regimes on two cultivars, Okashana 2 and Kangara. Given Namibia’s highly variable and erratic rainfall, effective irrigation practices are crucial for bridging rainfall deficit periods, enhancing crop yields. Although full irrigation can maximise yields, deficit irrigation strategies offer a viable alternative by improving water-use efficiency without significantly reducing productivity. Precision agriculture tools, such as soil moisture sensors and weather-based irrigation scheduling, further enhance irrigation efficiency by aligning water application with key crop growth stages. Integrating drought resilience into pearl millet breeding programmes, particularly with drought-tolerant varieties like Okashana 2, and incorporating weather forecasting into agricultural planning are essential strategies for improving adaptive capacity. Strengthening collaboration among researchers, policymakers, and farmers, alongside policies that support the adoption of climate-smart farming practices, is critical for enhancing resilience among smallholder farmers. In Sub-Saharan Africa, where rainfall is highly variable and water resources are increasingly threatened by climate change and population growth (Koutroulis et al., 2019), implementing efficient water demand management is essential for the sustainability of the scarce water resource.

7.3 Conclusion

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is one of the vital staple crops in Namibia and is particularly well-suited to the country's semi-arid climate. However, declining yields, driven by increasing water scarcity and climate change, pose serious threats to food and nutritional security. Given the increasing threat of climate change and its adverse effects on crop productivity and food security in Namibia, the findings of this study offer critical insights for sustainable pearl millet production. Water availability affects plant growth and yield. The 50% ETc regime reduced plant height, leaf number, tillering, chlorophyll content, stomatal conductance, panicle development, biomass, grain yield, and 1000-seed weight. In contrast, the 75% ETc regime maintained acceptable yields, demonstrating that moderate deficit irrigation could be a viable water-saving strategy without significantly compromising productivity. Yield data further showed the sensitivity of pearl millet to water stress, with biomass yields ranging from 1.14 to 5.54 tons/ha and grain yields from 0.38 to 1.23 tons/ha across the two seasons. Water use efficiency values showed that productivity per unit of water declined with increasing stress, reinforcing the need for optimised irrigation management. Furthermore, the nutritional composition of pearl millet demonstrated a degree of resilience under water stress. Although some components, such as fat content and moisture, varied significantly, key mineral nutrients, including iron and phosphorus, were maintained or enhanced under lower water regimes. This suggests that, although yields might be affected, the nutritional quality of the crop can be preserved, supporting the role of pearl millet in addressing food and nutritional security in arid and semi-arid environments. Model simulations using AquaCrop under future climate scenarios indicate rising temperatures, decreased precipitation variability, and reduced water productivity. These projections suggest a potential 22–35% decline in water productivity, with yield reductions particularly pronounced during early planting dates. Notably, planting on January 15 yielded better results than planting on December 15, suggesting that a strategic shift in the planting date can mitigate climate-related yield losses. This study therefore recommends deficit irrigation (75% ETc) and optimised planting schedules as effective adaptation strategies for maintaining pearl millet production under water-scarce and changing climatic conditions.

7.4 Future Work

Future research should build on the findings of this study by exploring a broader range of pearl millet cultivars beyond Okashana 2 and Kangara to determine the adaptability and water use efficiency (WUE) of other varieties under similar semi-arid conditions. Furthermore, seasonal replication studies across different environments would help to capture the variability in environmental conditions and their effects on crop performance, offering a more comprehensive understanding of drought tolerance. Soil nutrient availability, mediated by microorganisms, should also be studied to fully capture the mechanisms underlying pearl millet growth and survival under various environmental conditions, including drought. Additionally, future research should focus on incorporating advanced modeling techniques that account for more detailed projections of climate change impacts under diverse socioeconomic scenarios. Finally, studies on the socioeconomic such as cost-benefit analysis on conveying irrigation water for pearl millet production, as well as the scalability of such practices for smallholder farmers, would provide important insights for policy development and sustainable agricultural planning in water-scarce regions such as Namibia.

7.5 References

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Appendices

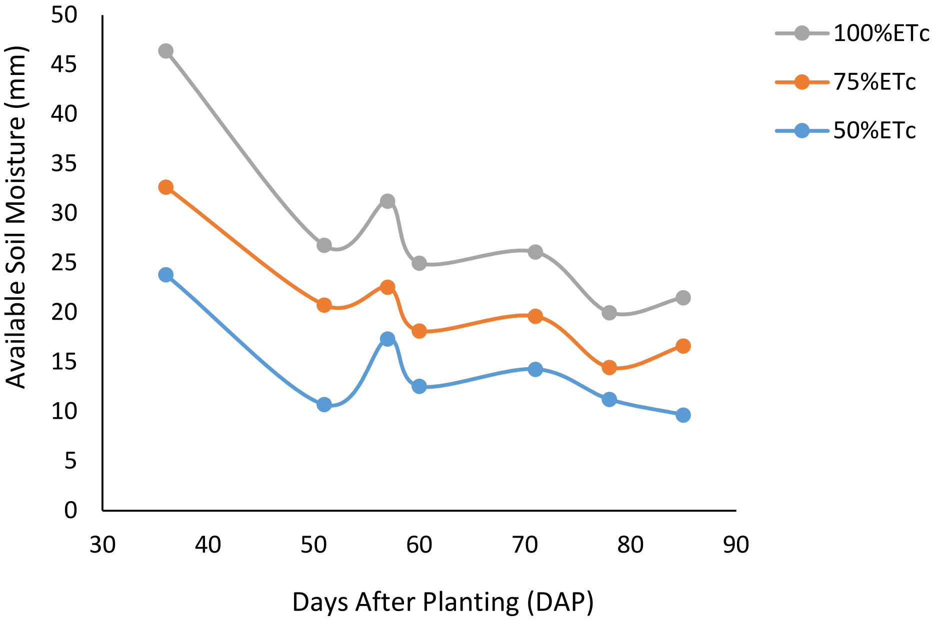

Figure A-1. Soil moisture content in the experimental plots during the September to December 2023 cropping period.

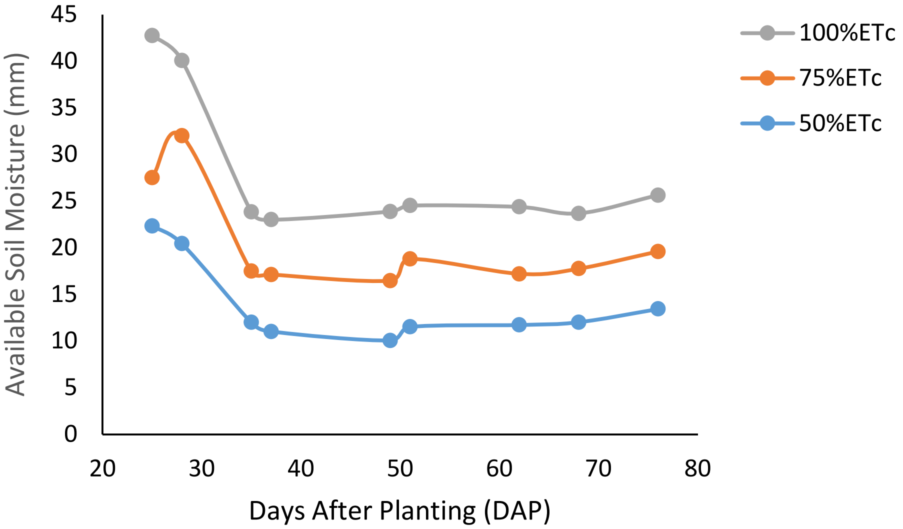

Figure A-2. Soil moisture content in the experimental plots during the January to April 2024 cropping period.

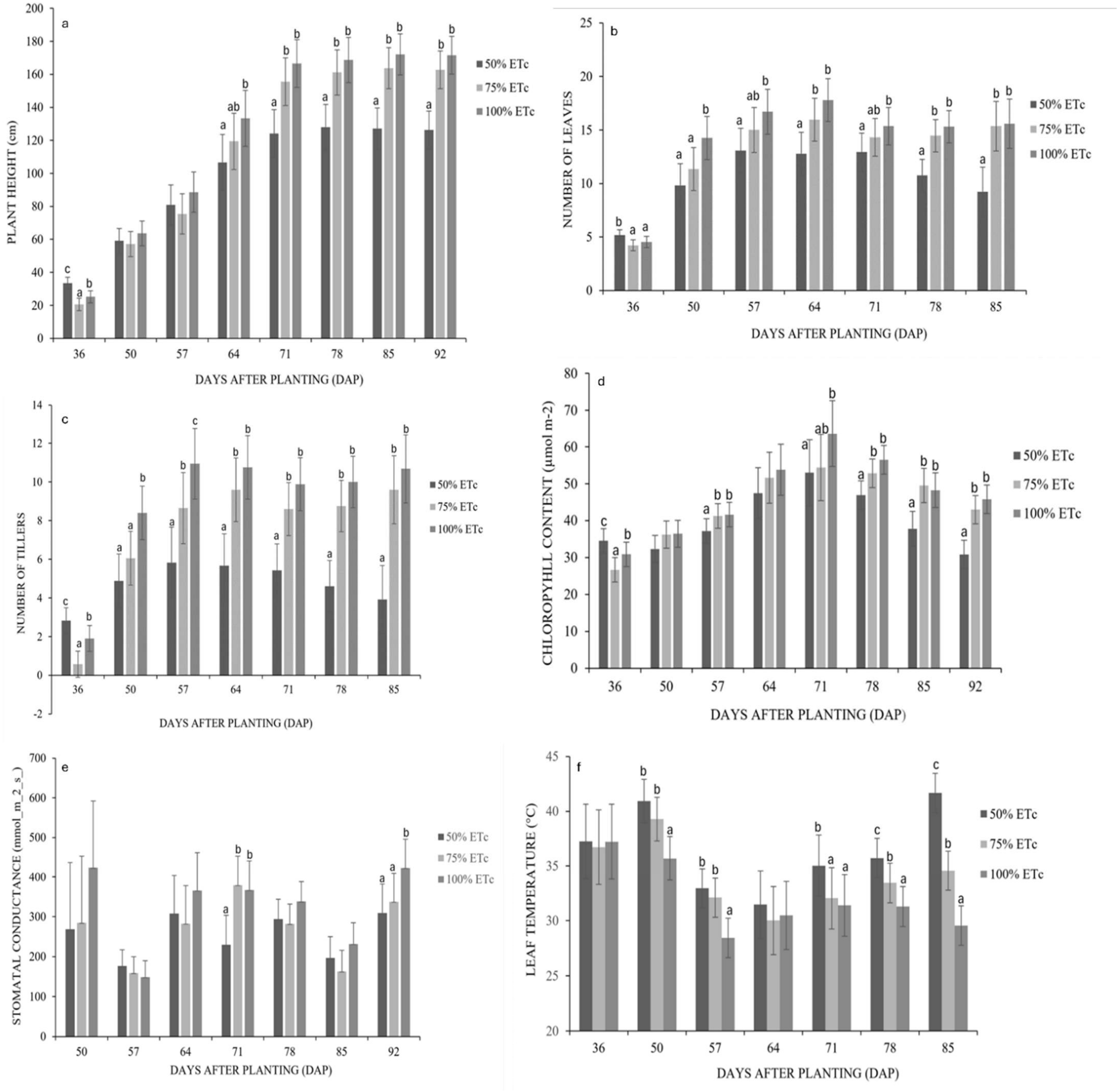

Figure A-3. Physiological and morphological responses of pearl millet developmental stages under different water regimes during the 2023 season (a-f). Means were separated using the Least Significant Difference (LSD) test at P = .05. Means followed by the same letter are not significantly different. Bars without letters indicate no significant difference. Duncan's Multiple Range test was used.

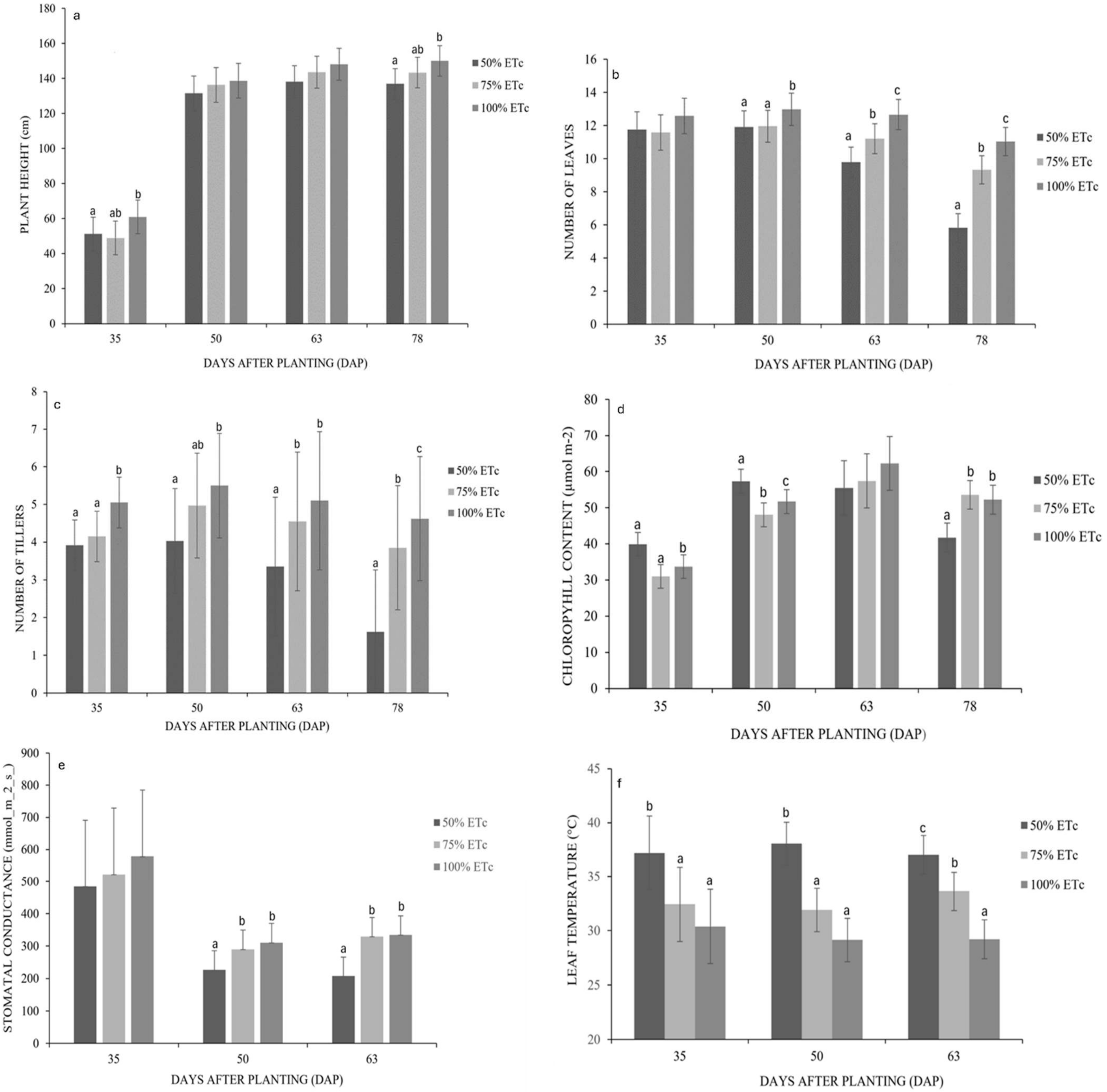

Figure A-4. Physiological and morphological responses of pearl millet at different developmental stages under various water regimes during the 2024 season (a-f). Means are separated by the Least Significant Difference (LSD) Test at P = .05. Means followed by the same letters are not significantly different. Bars without letters are not significantly different. Duncan's Multiple Range test was used.