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Co-Cultivation and Matching of Early- and Late-Maturing Pearl Millet Varieties to Sowing Windows Can Enhance Climate-Change Adaptation in Semi-Arid Sub-Saharan Agroecosystems

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Citation: Awala, S.K.; Hove, K.; Valombola, J.S.; Nafuka, H.N.; Simasiku, E.K.; Chataika, B.; Horn, L.N.; Angombe, S.; Akundabweni, L.S.M.; Mwandemele, O.D. Co-Cultivation and Matching of Early- and Late-Maturing Pearl Millet Varieties to Sowing Windows Can Enhance Climate-Change Adaptation in Semi-Arid Sub-Saharan Agroecosystems. *Climate* **2023**, *11*, 227. https://doi.org/10.3390/cli11110227

Academic Editor: Nir Y. Krakauer

Received: 24 July 2023
Revised: 2 September 2023
Accepted: 5 September 2023
Published: 10 November 2023

Abstract: In semi-arid regions, climate change has affected crop growing season length and sowing time, potentially causing low yield of the rainfed staple crop pearl millet (*Pennisetum glaucum* L.) and food insecurity among smallholder farmers. In this study, we used 1994–2023 rainfall data from Namibia's semi-arid North-Central Region (NCR), receiving November–April summer rainfall, to analyze rainfall patterns and trends and their implications on the growing season to propose climate adaptation options for the region. The results revealed high annual and monthly rainfall variabilities, with nonsignificant negative trends for November–February rainfalls, implying a shortening growing season. Furthermore, we determined the effects of sowing date on grain yields of the early-maturing Okashana-2 and local landrace Kantana pearl millet varieties and the optimal sowing window for the region, using data from a two-year split-plot field experiment conducted at the University of Namibia—Ogongo Campus, NCR, during the rainy season. Cubic polynomial regression models were applied to grain-yield data sets to predict grain production for any sowing date between January and March. Both varieties produced the highest grain yields under January sowings, with Kantana exhibiting a higher yield potential than Okashana-2. Kantana, sown by 14 January, had a yield advantage of up to 36% over Okashana-2, but its yield gradually reduced with delays in sowing. Okashana-2 exhibited higher yield stability across January sowings, surpassing Kantana's yields by up to 9.4% following the 14 January sowing. We determined the pearl millet optimal sowing window for the NCR to be from 1–7 and 1–21 January for Kantana and Okashana-2, respectively. These results suggest that co-cultivation of early and late pearl millet varieties and growing early-maturing varieties under delayed seasons could stabilize grain production in northern Namibia and enhance farmers' climate adaptation. Policymakers for semi-arid agricultural regions could utilize this information to adjust local seed systems and extension strategies.

Keywords: drought; food security; short growing season; rainfed agriculture; subsistence farming

1. Introduction

Dryland crop production depends on prevailing rainfall conditions, influenced by global and regional climatic systems. Pearl millet (*Pennisetum glaucum* L.) is the staple food for resource-poor smallholder farmers in arid and semi-arid regions of sub-Saharan Africa (SSA) and South Asia [1,2]. The crop is grown under marginal soil and rainfed conditions without supplemental fertilizer and irrigation inputs [3]. However, its productivity level in SSA is much lower than in other regions [4]; thus, SSA continues to suffer from poverty and food insecurity [5,6]. Recent demographic projections suggest that to feed the growing population, global agricultural production needs to increase by 60% to 100% by 2050; thus, in SSA, such production levels require investment in agriculture [7]. On the other hand, recent climate-change impact trends suggest that major cereal crop production in SSA could decrease by some 20% by mid-century [8–10]. Therefore, scientific research on pearl millet is needed to ensure sustainable production and bolster the food security levels in arid and semi-arid SSA regions amid climate change.

Climate change affects crop growth, development, yield, and quality [11,12], reducing food and nutritional security. The phenomenon is associated with, among others, rising temperatures [13–20], extreme precipitation events [21–27] and reduced growing seasons [28–31], disrupting agroecosystems [32]. Increased temperature is triggered by the atmospheric concentration of greenhouse gases (GHGs), such as carbon dioxide (CO_2) and methane (CH_4), leading to global warming, which reduces the net carbon gain through increased plant respiration rates, thus decreasing crop growth and productivity [33]. High temperatures decreased the yield of sweet corn [34] and maize [35,36], but insignificantly increased millet yield [37]. Simulation studies show that rising temperatures would reduce yields in wheat and maize [38], rice [33], and maize, soya beans, dry beans, and sunflower [39,40]. Petersen [41] also projected that warming temperatures will decrease maize and soybean yields, but will not influence rice. Extreme rainfall events mainly affect crop performance in two ways, via drought and through flood. Both drought and flood are detrimental to most crops [6,42]: they deprive plants of water or oxygen, decreasing leaf photosynthesis, transpiration, stomatal conductance, and water potential, thus suppressing growth and productivity [43–46]. However, in semi-arid regions, droughts are more common than floods [47]. A study conducted in Tanzania by Mongi et al. [20] showed declining rainfall trends with variable spatiotemporal distributions and increased duration and frequencies of intra-seasonal dry spells. However, other studies have projected positive correlations of maize yields with rainfall [27,36,48]. Due to rising temperatures, the length of growing seasons under future climate scenarios is expected to decline [49,50], accelerating crop maturity, thus reducing plant biomass accumulation and total productivity [51]. In Tanzania, Kihupi et al. [52] observed decreasing trends in the growing season length and number of wet days as rainfall onset is increasingly delaying. In Angola and the southern Congo basin, reductions in austral spring growing season days were associated with reduced precipitation and increased evapotranspiration [49]. However, Mupangwa et al. [53] analyzed the growing season length in southern Zimbabwe and found no significant changes.

Semi-arid and arid regions worldwide are most vulnerable to the effects of climate change [26,54–59]. Namibia, a semi-arid SSA country where pearl millet is the staple food, has been affected by food insecurity since independence in 1990 [60–62]. The country is characterized by low and erratic rainfall, intense heat, and a high evapotranspiration rate [63]. Its average annual rainfall is 250 mm, but most of this rainfall is received in northern areas, which constitute Namibia's major crop-growing zone [42,64]. The North-Central Region (NCR), the country's most densely populated area, is projected to have 85,860 new people by 2031 [65]. Most inhabitants in the NCR are resource-poor subsistence farmers whose livelihoods mainly depend on agriculture [42,66]. The majority of the farming households cultivate crops, and pearl millet is the dominant crop in the local agroecosystem, primarily cultivated for its grain production for food [67,68]. A recent simulation study has revealed that, besides addressing the food security problem, millet can reduce the impact of agriculture on global warming since it releases less greenhouse gases than other cereals [69].

In the NCR, pearl millet is cultivated under rainfed conditions during the rainy summer months, from November to April [42]. Rains may arrive as earlier as October, but farmers generally wait for more consistent sowing rains in January and February [70]. Ordinarily, the farmers use unimproved, long-duration and late-maturing local landrace varieties, which are susceptible to end-of-season drought [67,71,72]. However, some farmers have recently adopted improved varieties, which are known to be early-maturing, high-yielding, and drought-tolerant, and have more stable yields than the traditional ones. Although the farmers seem to have identified earliness as the most desirable character over grain yield, they wisely continue to grow their landrace varieties together with the improved ones [66,67,70], possibly for cultural or climate-change adaptation reasons. The farmers who prefer traditional varieties over improved ones cited that they have better taste and longer grain storability [72]. Disaggregated data concerning the areas sown by the respective varieties are lacking; however, Mendelsohn and Firm [66] reported that 17%, 41%, and 42% of the farmers sow improved, traditional, and mixed varieties, respectively. They also reported that only 4% and 42% of all households apply chemical fertilizer and small amounts of manure, respectively. However, such proportions are subject to change over the years and between years, depending on rainfall conditions, seed and fertilizer accessibility, and the level of agricultural mechanization.

Rainfall patterns in the NCR are changing due to the impact of global climate change. Recently, the arrival of the first rains has been delayed substantially; also, rainfall can cease abruptly before the typical ending of the growing season, shortening the growing season and affecting crop performance. Rainfall in the region is characterized by irregular events of variable amounts and intensities, resulting in inter-annual droughts, floods, or intra-season dry spells, consequently causing low crop yields or even complete crop failures [42,62]. In other countries, farmers have perceived decreasing rainfall amounts, rising temperatures, and shortening of growing seasons' length over the years, causing prolonged droughts, uneven rainfall distributions, and unpredictable onset and ending of rains, thus reducing agricultural productivity, food security, and income [20,73,74]. Therefore, grain production by traditional pearl millet varieties in the NCR may be affected by new climate change-induced growth conditions [42]. Analysis of data from the FAOSTAT [4] database revealed that the average pearl millet yield in Namibia for the 2012–2021 period was as low as 0.23 t/ha, three times lower than the SSA average yield of 0.76 t/ha and nearly six times lower than the South Asia average yield of 1.33 t/ha. Nevertheless, the pearl millet yields in the country have been changing variably since the release of the first improved variety, Okashana-1, in 1990. For example, Matanyaire [67] noted a large yield gap between on-farm and on-station yields, with on-farm yields of 0.15–0.20 t/ha compared with on-station yields of 3.63–3.87 t/ha during the 1992/93 season. However, current FAOSTAT [4] database data show an on-farm grain yield range of 0.09–0.36 t/ha for the 2011/2012–2020/2021 period. Moreover, much higher on-farm pearl millet yields, ranging from 0.71–0.94 t/ha, were found by Hirooka et al. [75] in their yield survey study conducted in 2016 in the Omusati Region, NCR. Rohrbach et al. [70] stated that the actual grain yield obtained by farmers depends mainly on the timing and amount of localized rainfall, time of sowing, and level of crop management; thus, farmers tend to practice multiple sowings to reduce production risk. Besides the yield data, the average size of the area sown with pearl millet per household in northern Namibia has been reported: Matanyaire [67] reported 2.96 ha for the 1992/93 season, Mendelsohn and Firm [66] reported 1.7–3.6 ha, while a recent study by Hirooka et al. [75] reported individual households harvesting a slightly smaller area of 2.01–2.29 ha.

Various studies have shown that the growing season length and crop varieties of different maturity groups react differently to sowing dates. Studies by Nwajei et al. [76] and Nwajei [77] demonstrated that pearl millet varieties respond differently to sowing dates: the early-sown crop has higher nutrient uptake, growth, and grain yield than the late-sown one. So far, agronomic studies elucidating the yield potential of traditional pearl millet varieties relative to their improved counterparts across the growing season have yet to be established for the NCR. As such, during the growing season, local farmers tend to sow any pearl millet variety based on their wishes, seed availability, or soil moisture conditions, regardless of the onset of the growing season, which can be early, normal, or late. Farmers and scientists across the globe have proposed various climate-change adaptation strategies, including adopting adaptive cropping systems [6,78,79], investment in low-cost irrigation [10], effective fertilization [3,80,81], using adaptive crop varieties [69] and applying tied ridges with fertilizer microdosing [82]. Adaptation strategies also entail growing drought-tolerant, early-maturing crop varieties, increasing wetland cultivation, harvesting water for small-scale irrigation, keeping livestock [73,74], and adjusting sowing dates and cultivars [83]. Minoli et al. [83] predicted that timely adaptation of growing periods would increase crop yields by approximately 12%, reducing climate change's negative impacts and enhancing the positive CO_2 fertilization effect. Although some studies in semi-arid regions highlight that sowing directly after the first rains poses a higher risk of water stress during crop growth [84,85], other researchers [86,87] observed higher crop yields under early planting. In Nigeria, the traditional pearl millet variety Gero Badeggi [88] produced 9.33 t/ha of grain under early sowing [76]. It is hence crucial to establish the optimal sowing window of pearl millet for the NCR to optimize production resources and increase grain production among local farming communities in the face of climate change.

Therefore, the objectives of this study were to (i) analyze rainfall patterns and trends and their implications on the growing season, (ii) evaluate the grain yield dynamics of Namibia's popular pearl millet varieties under different sowing dates, and (iii) determine the optimal sowing window for the semi-arid NCR to propose climate-smart adaptation options for smallholder farming households in northern Namibia.

2. Materials and Methods

2.1. Study Location and Environmental Conditions

The pearl millet sowing-date field experiment was carried out for two summer rainy seasons, 2017–2018 and 2019–2020, at the University of Namibia—Ogongo Campus Farm (17°40′ S, 15°18′ E, 1109 m ASL), North-Central Region (NCR), Namibia. With an area of 84,582 km^2, accounting for 10% of the country's land area [68], the NCR comprises four administrative regions, Ohangwena, Omusati, Oshana, and Oshikoto [75,89], characterized by a semi-arid climate (also see Figure 1). Soils in the NCR are classified into three major groups: cambic arenosols, eutric cambisols, and haplic calcisols [64], with sand being the dominant soil fraction [90,91]. Most areas fall within the Cuvelai Drainage Basin, originating in southern Angola, where rainfall is higher than in Namibia (Figure 1). The NCR is characterized by a semi-arid climate, with an average temperature of >22 °C [92] and receiving an average annual summer rainfall ranging from 450 to 500 mm during November–April [42]. The remaining months represent the dry season.

To expound on the historical and current rainfall behaviors and their impact on agriculture in the NCR, we analyzed the May 1994–April 2023 rainfall data for annual and monthly rainfall patterns and trends in the subsequent subsection, using data from the Omahenene Research Station, a government station located nearby the experimental site. Additionally, we summarized rainfall and other weather data for the experimental years 2018 and 2020 obtained from the study site.

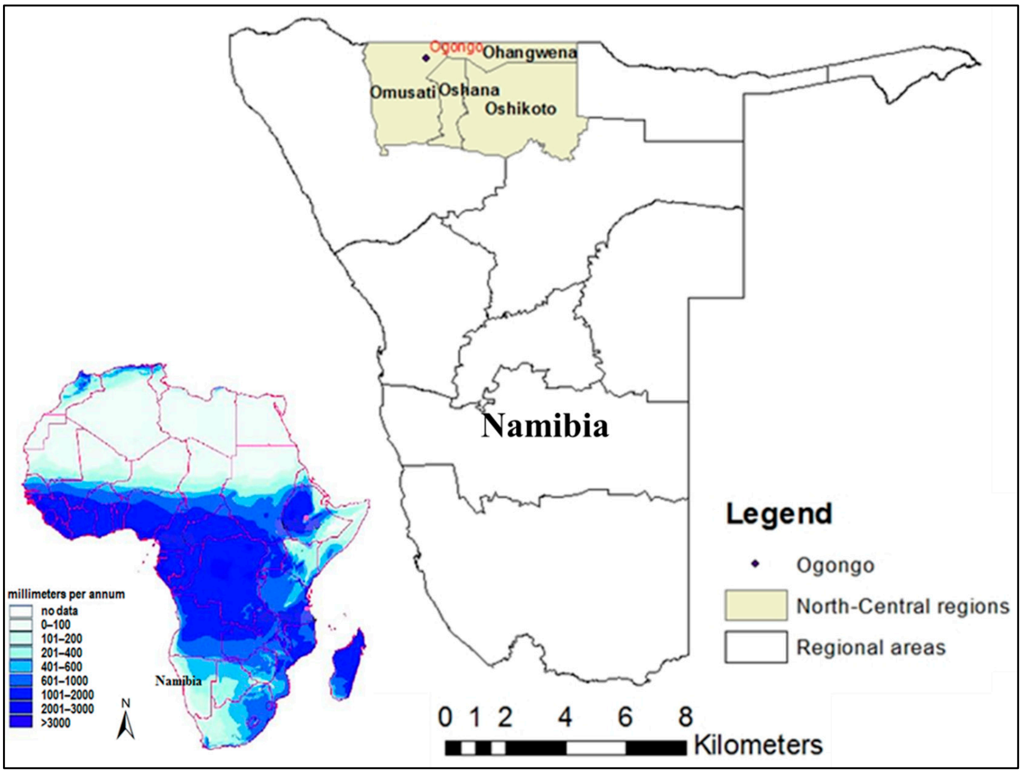

Figure 1. A map showing the location of the University of Namibia—Ogongo Campus, North-Central Region (NCR), Namibia, situated in a semi-arid sub-Saharan region. Source: Adapted from FAO/Agrhymet Network and ESRI.

2.2. Rainfall Analysis

2.2.1. Standard Deviation and Mean

Rainfall data for the past 30 years, May 1994–April 2023, from the Omahenene Research Station were analyzed for several parameters, including the average annual rainfall and average monthly rainfall and associated standard deviation (SD). The absolute dispersion of the data denotes the SD, while the data's average denotes the data's mean [93]. For a continuous random variable Y, with moments existing up to order 4, let μ = (Y) be the mean of Y, denoted by Equation (1) as:

$$\mu_i = E(y-\mu)^i, i = 2,3,4 \tag{1}$$

2.2.2. Mann–Kendall (MK) Test

The rainfall data were analyzed for time-series annual and monthly trends. Mann [94] stated that given n consecutive observation of a time series $z_t,\ t = 1,\ldots,n$, the Kendall rank correlation (τ) of z_t with $t = 1,\ldots,n$ can be used to test for monotonic trends. The MK test evaluates the null hypothesis of no trend against the alternative hypothesis of an increasing or decreasing trend. In this study, we performed the MK trend test by computing the statistic (S) given by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(y_i - y_j) \ldots j > 1 \tag{2}$$

where y_j denotes the sequential data values, n denotes the size of the time-series sample, and:

$$sign(y_i - y_j) = \begin{cases} -1, y_i - y_j < 0 \\ 0, y_i - y_j = 0 \\ 1, y_i - y_j > 0 \end{cases} \tag{3}$$

Since in our study $n > 8$, we obtained estimates of σ^2 and μ for S, as suggested in Mann [94] and Kendall and Stuart [95]:

$$E(S) = 0 \tag{4}$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{g=1}^{n} q_i(g-1)(2g+5)g}{18} \tag{5}$$

where q_i is the number of ties of length g. Then:

$$S \sim N(0,1) \tag{6}$$

The significance of standardized S in (6) was estimated from the Gaussian cumulative distribution function using the following equation:

$$Z = \begin{cases} \frac{S-1}{\sqrt{var(S)}}, S > 0 \\ 0, S = 0 \\ \frac{S+1}{\sqrt{var(S)}}, S < 0 \end{cases} \tag{7}$$

A positive Z value $(Z > 0)$ denotes an increasing trend, whereas a negative Z $(Z < 0)$ indicates a decreasing trend. In testing for the significance of increasing or decreasing monotonic trends at α level of significance, the decision rule here is to reject the null hypothesis (H_o) if: $|Z| > Z_{1-\alpha/2}$, with $Z_{1-\alpha/2}$ obtained from the cumulative normal distribution tables. In the present study, we used an α value of 5%.

2.2.3. Sen's Slope Estimate

The magnitude of the nonparametric trend in the time series is determined using Sen's estimator [96], used in hydrometeorological time-series studies [97–99]. This method was therefore used in this study to estimate the magnitudes of the slope of annual and monthly trends based on the following equation:

$$sen - slope = Median\left(\frac{y_a - y_b}{a - b}\right), \forall b < a \tag{8}$$

with y_a and y_b being rainfall amounts measured at time a and b, respectively.

2.3. Agronomic Evaluation

2.3.1. Experimental Treatments, Design, and Management

The study used two open-pollinated pearl millet varieties, Okashana-2 (SDMV 92032) and Kantana, commonly cultivated in northern Namibia's subsistence agriculture. Developed by ICRISAT for drought-prone, low-rainfall regions, Okashana-2 is an improved, early-maturing, and high-yielding variety (taking 40–55 days to flower) released for commercial cultivation in 1998 [71,100]. Okashana-2 replaced the first ever improved variety, Okashana-1 (SDMV 93032), released in Namibia in 1990, but it was later discontinued due to its weaker stem and softer grains; therefore, Okashana-2 possesses improved plant and grain traits than its predecessor [70]. On the other hand, Kantana is a tall, late-maturing local landrace, with 60–73 days to flowering [101,102]. The pearl millet seeds were acquired from a local seed retailer.

The field experiment was based on a split-plot design with five sowing dates—the 1 January, 15 January, 1 February, 15 February, and 1 March—for the main plots and the two pearl millet varieties Kantana and Okashana-2 as the subplots, arranged in four replications. The experiment was conducted in loamy sand. Each year, the experimental area was ripped to 30–50 cm soil depth to facilitate water infiltration and disk-harrowed to incorporate weed materials into the soil. The total experimental area was 741 m^2 with individual plots (experimental units) measuring 12 m^2, separated by a 1 m-wide alleyway. Each plot received a pre-planting basal fertilizer at 30–45–30 N, P, and K kg/ha, respectively.

Pearl millet was sown following the sowing date treatments. The seeds were initially oversown on each hill, keeping 75 cm spacing between rows and 40 cm spacing between hills. Individual plots comprised four rows, each with 10 plants for a population of 40 plants.

The seedlings were thinned 2–3 weeks following field emergence to leave one plant per hill. Weed control was performed manually immediately after thinning and continued irregularly during the crop growth cycle to keep a weed-free experiment. No top-dressing or pesticides were applied in the experiment. However, in the second year of the study, the experiment was given supplemental irrigation by applying approximately 10.0 mm twice in January to save the seedlings from a long dry spell. Bird scaring was done from the grain setting stage until harvest to minimize grain losses due to birds.

Grain yield data were collected using plants in the two center rows, leaving out all outermost plants to serve as borders. At crop maturity, a sampling area of 2.4 m^2, ideally comprising eight plants, was established in each plot and then harvested for yield sampling. All panicles in each sampling area were harvested and air-dried for 3–4 weeks. The panicles were threshed and winnowed manually to obtain clean grains. The clean grains were weighed before testing their moisture contents using a grain moisture tester (PM-830-2, Kett, Japan) to adjust the grain weights to 14% moisture content. The grain yield per hectare was finally determined.

2.3.2. Data Analysis

One of the objectives of this study was to analyze the grain yield data for two pearl millet varieties, Kantana and Okashana-2, and to explore the relationship between their sowing dates and grain yields using polynomial regression. Data were analyzed using Python programming language and the methodology described below. An initial ANOVA model was run in variation partitioning across years, with years as a random effect. The year effect was not significant ($p = 0.224$); however, there were variations for the fixed effects of sowing date ($p = 0.037$), variety ($p = 0.005$), and their interaction ($p = 0.001$). For each variety, the grain yield data of the individual years were pooled, arranged according to the different sowing dates categorized into five time points—1 January, 15 January, 1 February, 15 February, and 1 March—and reprocessed using the NumPy and Pandas libraries in Python. The sowing dates and corresponding grain yields were organized into two separate arrays, one for each variety. Polynomial regression was chosen to model the relationship between the sowing dates and grain yields for each variety. The polynomial features and linear regression classes from the sci-kit-learn libraries were utilized. Different polynomial degrees were tested, and a degree of 3 was selected as the optimal fit for both varieties based on the mean squared error. Bootstrapping with 1000 iterations was performed to estimate the uncertainty in the regression models. Confidence intervals were computed for the predicted grain yields at each sowing date. The results were visualized using Matplotlib to create two subplots, each representing the grain yield data, the polynomial regression curve, and the associated confidence intervals for Kantana and Okashana-2 pearl millet varieties. Each variety's regression equations and correlation coefficients were calculated for each regression curve.

The correlation coefficient was calculated to evaluate the strength of the relationship between sowing dates and grain yields for each variety. The mathematical formulation of polynomial regression involves fitting a polynomial function to the data by estimating the polynomial coefficients. The general form of a polynomial regression model is:

$$y = \beta_0 + \beta_1 \times x + \beta_2 \times x^2 + \ldots + \beta_n \times x^n + \varepsilon \quad (9)$$

where:

y is the dependent variable (in this case, the grain yield).
x is the independent variable (in this case, the sowing date).
$\beta_0, \beta_1, \beta_2, \ldots, \beta_n$ are the coefficients of the polynomial, which represent the intercept and the slopes of the polynomial terms.

$x^2, x^3, \ldots, x^n$ are the higher-order polynomial terms.
ε is the error term, representing the deviation of the actual data points from the fitted polynomial curve.

In the specific case of the polynomial regression performed in the code, the third-degree polynomial (degree = 3) is used, so the mathematical formulation of polynomial regression models for each variety is presented below.

For Kantana:

$$y\_K = \beta_0\_K + \beta_1\_K \times x + \beta_2\_K \times x^2 + \beta_3\_K \times x^3 + \varepsilon\_K \quad (10)$$

For Okashana-2:

$$y\_Ok = \beta_0\_Ok + \beta_1\_Ok \times x + \beta_2\_Oka \times x^2 + \beta_3\_Oka \times x^3 + \varepsilon\_Oka \quad (11)$$

The goal of the polynomial regression is to estimate the coefficients β_0, β_1, β_2, and β_3 that best fit the data points, thus providing a polynomial curve that represents the relationship between the sowing date (x) and the grain yield (y) for each pearl millet variety. The correlation coefficient can be used to assess the goodness of fit of the polynomial regression model and quantify the strength of the relationship between the variables.

Based on the polynomial regression results, both Kantana and Okashana-2 pearl millet varieties produced the maximum grain yields in January. Therefore, the crop yield data for 1–28 January, which conformed to the normal distribution and equal variance assumptions, were used to predict the optimum sowing windows. Individual varieties' grain yield values were grouped within the four weeks of January, considered as sowing windows, i.e., week 1 (1–7 days), week 2 (8–14), week 3 (15–21), and week 4 (22–28). Yield comparison within a variety across the weeks of January was performed using box plots.

3. Results

3.1. Weather Conditions

3.1.1. Descriptive Statistics for Annual and Monthly Rainfall

The descriptive statistics for annual and monthly rainfall for May 1994–April 2023 are presented in Table 1. The long-term annual average rainfall was 475.3 mm, associated with a high standard deviation (SD) of 185.4 mm, implying high inter-annual rainfall variability. The long-term monthly rainfall distribution patterns depicted two distinct seasons: the dry winter season, from May to October, with literally no rainfall, and the summer rainy season, from November to April, accounting for 97.5% of the total annual rainfall (also see [42]). March had the highest average rainfall of 112.6 mm, followed by February, January, and December with 107.3, 103.4, and 71.6 mm, respectively. In contrast, April and November had the lowest average rainfall values of 29.7 mm and 38.5 mm. Rainfall variability within months was also high, being the highest for February (86.8 mm), followed by March (72.4 mm), January (66.4 mm), and December (65.3 mm). The descriptive statistics revealed that during the past 30 years, the NCR was characterized by highly variable annual and rainy season month rainfalls.

Table 1. Statistical characteristics of annual and monthly rainfall at Omahenene Research Station, North-Central Namibia during 1994–2023.

Statistic	Annual	Month											
		May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Mean (mm)	475.1	1.5	0.0	0.0	0.0	0.2	10.3	38.5	71.6	103.4	107.3	112.6	29.7
SD	185.4	5.7	0.0	0.0	0.0	1.1	18.5	31.6	65.3	66.4	86.8	72.4	35.6

The time-series annual rainfall variability patterns for 1994–2023 are shown in Figure 2. Inter-annual rainfall variability was relatively high. The highest rainfall during the last three decades was 907.8 mm recorded in 2011, followed by 822.8 mm in 2009 and 786.1 mm in 2008. These high-rainfall years were characterized by incidents of floods that struck the region. On the other hand, incidents of inter-annual droughts are common in the NCR; for example, annual rainfall was mostly below average (475.1 mm) during the periods 1994–1999 and 2018–2023. The lowest rainfall of 134.3 mm was recorded in 2019, followed by 157.0 mm received in 2023 and 218.0 mm observed in 2013 and noticeably falling in the last decade. All these years were associated with severe droughts. Other years with very low rainfalls were 2021 and 2022. The results demonstrated that droughts and floods occurred in the NCR during 1994–2023.

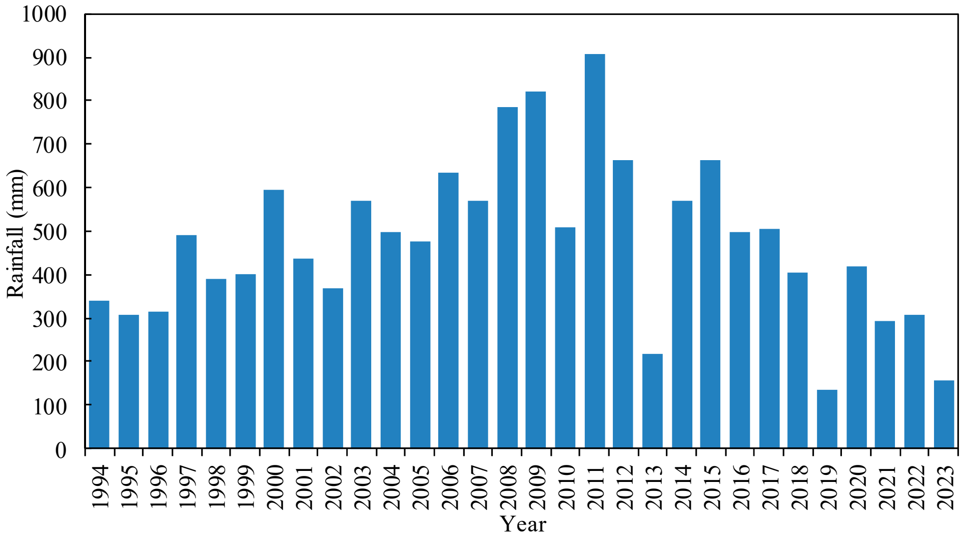

Figure 2. Annual rainfall patterns at Omahenene Research Station, North-Central Namibia, during 1994–2023.

3.1.2. Annual and Monthly Rainfall Trends

Table 2 shows the Mann–Kendall statistic (Z_{MK}) and Sen's slope estimator for total annual and average monthly rainfall at the Omahenene Research Station, North-Central Namibia, from 1994 to 2023. Based on the MK-trend test and Sen's slope estimator test results, annual rainfall showed a nonsignificant, marginal negative or decreasing trend. From May to October, the dry-season months lacked trends due to the lack of rainfall, except October, which showed a nonsignificant negative rainfall trend. The November–April rainy season months showed no significant ($p > 0.05$) heterogeneous rainfall trends, with decreasing trends, manifested in negative Z and Sen's slope values, for November, December, January, and February, and increasing trends, denoted by positive Z and Sen's slope values, for March and April. The negative rainfall trends associated with October–February implied a reduction in rainfall in these months, while the increasing trends for March and April denoted an increase in rainfall in these two months. These results indicated that the long-term annual rainfall had a nonsignificant negative trend; also, for monthly rainfall, the first four rainy months (November–February) had nonsignificant negative trends, while March and April had positive trends.

Table 2. Mann–Kendall statistic (Z_{MK}) and Sen's slope estimator for total annual and average monthly rainfall at Omahenene Research Station, North-Central Namibia, 1994–2023.

Statistic	Annual	Dry Season						Rainy Season					
		May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Z_{MK}	−0.002	–	–	–	–	0.116	−0.094	−0.011	−0.097	−0.062	−0.140	0.083	0.102
p-value	1.000 ns	–	–	–	–	0.488 ns	0.498 ns	0.943 ns	0.464 ns	0.643 ns	0.284 ns	0.532 ns	0.442 ns
Sen's slope (mm/year)	−0.036	–	–	–	–	0.000	0.000	−0.033	−0.800	−0.833	−1.727	0.763	0.194

–, values could not be calculated as rainfall was zero. ns, not significant.

3.1.3. Solar Radiation, Temperature, and Rainfall during the Experiment

The patterns of the 2017–2018 and 2019–2020 growing seasons' pooled solar radiation, temperature, and rainfall data are illustrated in Figure 3. The monthly average solar radiation was 22.0 MJ/m^2/day; however, solar radiation decreased by six units from 25.0 MJ/m^2/day in November to 19.5 MJ/m^2/day in May. The average temperature during the experiment was 25.0 °C, but the temperature decreased by seven units across the rainy season, from 28.0 °C in November to 21.0 °C in May. The average total rainfall between November and May in the growing season was 460 mm. The average total rainfall gradually increased from 24 mm (5.2%) in November to 90 mm (19.6%) in December to reach a peak of 146 mm (31.7%) in January. After the peak, rainfall declined sharply through 84 mm (18.3%) in February and 63 mm (13.9%) in March, abruptly ceasing with 53 mm (11.5%) in April. No rainfall was received in May during the experiment. Further information on solar radiation and temperature during the experiment is presented in Figure 3a, while that for rainfall is illustrated in Figure 3b.

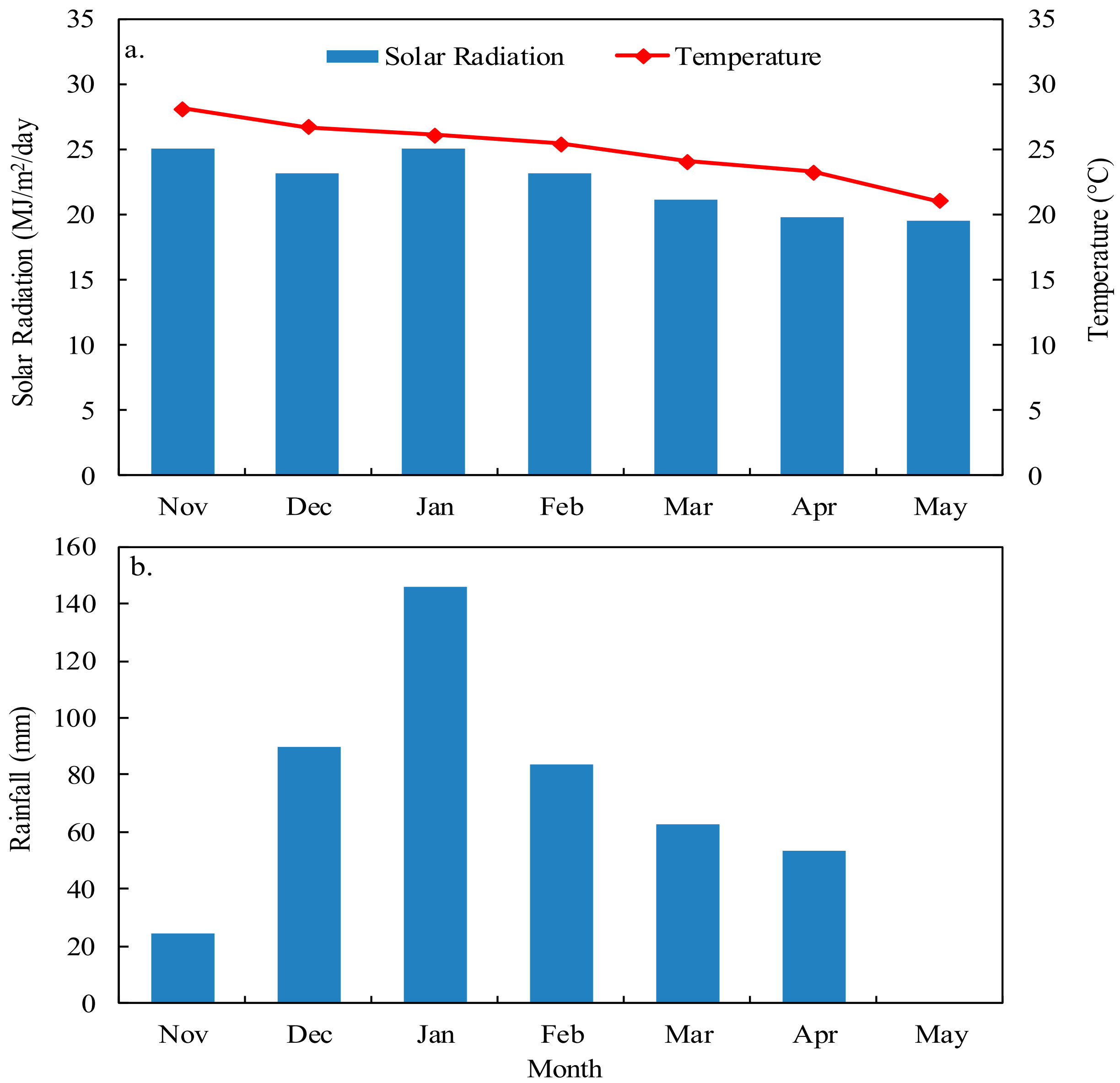

Figure 3. Patterns of the (**a**) monthly average solar radiation and temperature and (**b**) monthly average total rainfall for pooled data of the 2017–2018 and 2019–2020 growing seasons.

3.2. Grain-Yield Dynamics

The cubic polynomial regression models of the grain yields and days of the year used to analyze the yield dynamics of Kantana and Okashana-2 pearl millet varieties are shown in Figure 4. Based on the models, the optimal pearl millet sowing date for the NCR happened to be calendar day 1 (1 January), in which Kantana produced the highest grain yields. The cubic polynomial regression models showed the best fit, with an R^2 of 0.9997 for Kantana and 0.9636 for Okashana-2. For Kantana, the model revealed strong relationships between later sowing regimes and reduced yields (Table 3). The experimental average maximum yield of 9.5 t/ha was attained with Kantana sown on 1 January, which (according to the model) decreased to 82%, 66%, 55% and 47% of the maximum yield as the sowing dates were delayed from the 1 to 7, 14, 21 and 28 January, respectively. The corresponding relative yield of Okashana-2 fluctuated from 64% (1 January) to 67%, 67%, 63%, and 57% of the maximum yield. Kantana sown between 1 and 14 January exhibited a yield advantage of up to 36% over Okashana-2. However, Okashana-2 grain yields were relatively stable across January sowings and even surpassed Kantana's yield by up to 9.4% when sown between 14 January and 1 March. Both Kantana and Okashana-2 varieties had the lowest yields at the last sowing date of 1 March.

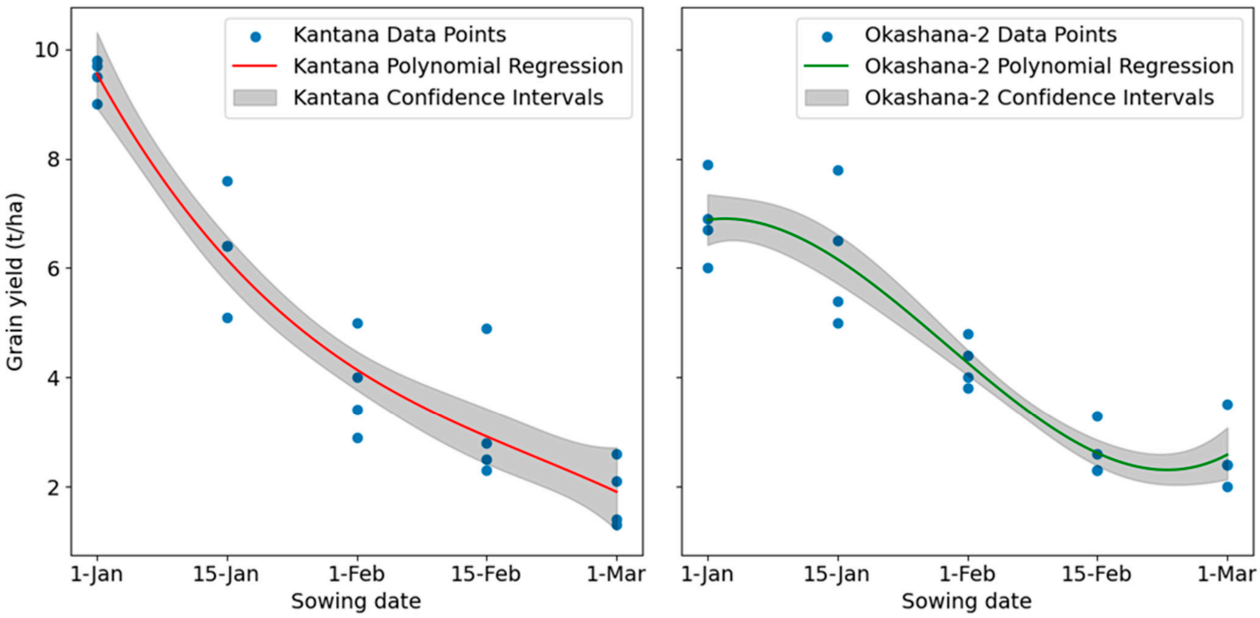

Figure 4. Pooled grain yield response of Kantana (**left**) and Okashana-2 (**right**) pearl millet varieties to sowing date at the University of Namibia—Ogongo Campus.

Table 3. Relative grain yield prediction for Kantana and Okashana-2 pearl millet varieties with the cubic polynomial regression models of days of the year.

Day of the Year	Calendar Date	Relative Yield (%)	
		Kantana	Okashana-2
1	1 January	100	64
7	7 January	82	67
14	14 January	66	67
21	21 January	55	63
28	28 January	47	57
35	4 February	43	50
42	11 February	40	44
49	18 February	38	40
56	27 February	36	38

Data represent combined relative average values for the 2017–2018 and 2019–2020 growing seasons.

The cubic polynomial regression equations for the two varieties are given by:

$$Y_{Kantana} = -0.0004x^3 + 0.0622x^2 - 3.4207x + 103.23, \text{ and}$$

$$Y_{Okashana\text{-}2} = 0.0006x^3 - 0.0581x^2 + 0.9222x + 63.418.$$

3.3. Optimal Variety Sowing Windows

The effects of sowing windows (week 1, week 2, week 3, and week 4 January) on the grain yields of Kantana and Okashana-2 pearl millet varieties are demonstrated in Figure 5. The two varieties had different yield patterns across the sowing windows. For Kantana, the yield substantially declined with every week of delay in sowing, denoting the uniqueness of each sowing window studied. The highest average yield of 7.7 t/ha was attained with the crop sown in week 1, followed by 6.2 t/ha from week 2 and 5.0 t/ha from week 3, while the lowest average yield of 4.2 t/ha was observed from the crop sown in week 4 of January. The reduction in the average grain yield between weeks 1 and 2 was as high as 18%.

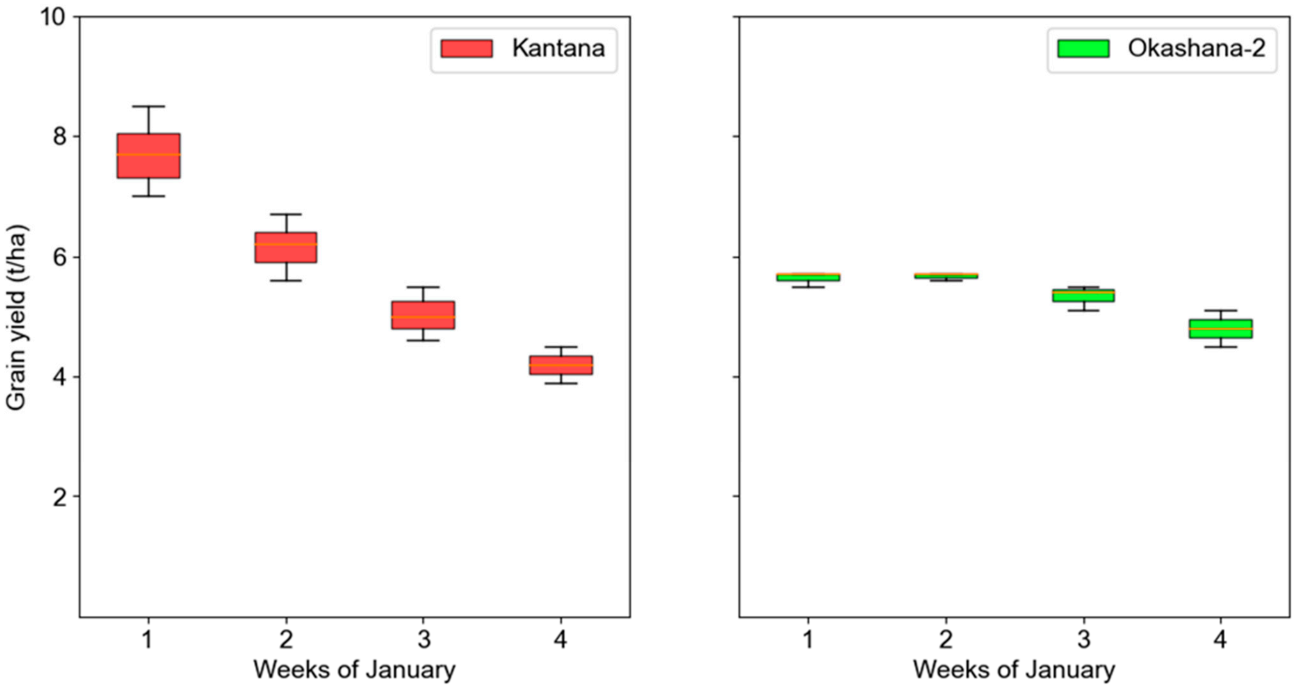

Figure 5. Box plots showing average grain yields of Kantana and Okashana-2 pearl millet varieties influenced by delaying sowing by weeks across January at the University of Namibia—Ogongo Campus.

For Okashana-2, the first three sowing windows had similar grain yield levels; however, such yield levels were higher than the yield obtained from the last sowing window (week 4), implying two distinct sowing windows for this variety. Moreover, Okashana-2 had a lower but relatively stable yield than its counterpart Kantana, producing average yields of 5.6 t/ha, 5.7 t/ha, 5.4 t/ha, and 4.8 t/ha from sowings in weeks 1, 2, 3, and 4 of January, respectively. Thus Okashana-2 yield from week 4 was lower by 6–8% than that of the first three weeks. Based on these results, sowing Kantana during the first week of January resulted in the maximum grain yield, while Okashana-2 maintained its highest yield when it was sown across the first three weeks of January; therefore, their optimal sowing windows would be 1–7 January for Kantana and 1–21 January for Okashana-2.

4. Discussion

4.1. Weather Conditions

The goal of the present study was to analyze rainfall patterns and trends and their implications on the growing season, evaluate pearl millet yield dynamics under different sowing dates and determine the optimal sowing window for Namibia's North-Central Region (NCR) to increase grain production, sustainability, and food security in the region. The descriptive statistics revealed that during the last 30 years, from May 1994 to April 2023, annual rainfall in the NCR was characterized by irregular floods and droughts, with incidents of severe droughts observed mainly during the early and later years of the period studied (Table 1 and Figure 2). However, high rainfalls associated with deluges also occurred between 2008 and 2011. The irregular occurrence of drought and flood events, causing interannual rainfall variability, may be caused by regional and global climatic system changes [27,64,103]. In semi-arid SSA regions, including the NCR, rainfall variability is a natural phenomenon, usually manifested in various ways as a result of the erratic and unpredictable nature of weather conditions in these regions [42,104], resulting in both drought [20,73,74] and flood [42,92,105,106] events.

Like annual rainfall, monthly rainfalls were also highly variable, with the months having the highest rainfalls, i.e., February, March, January, and December, showing the highest variability compared with November and April, which received the lowest rainfall (Table 1). These present results agree with previous studies performed in the NCR, showing variations and variability during the rainy months [42,64,92,107]. In semi-arid SSA regions, rainfall variability is a natural phenomenon, usually manifested in various ways [42,103], including delayed rainy season onset, early rainy season cessation, reduced length of the growing season, and frequent or prolonged intra-seasonal dry spells [20,28,29,108].

Time-series analyses showed that the long-term annual rainfall in the NCR had a nonsignificant negative or downward monotonic trend, and the first four months of the rainy season (November–February) also had downward trends. However, March and April had nonsignificant positive or upward trends (Table 2). Although the decreases in annual and monthly rainfall trends were not statistically significant, they still require close attention. The months with negative trends within the growing season indicate a shift in rainfall distribution patterns such that the November, December, January, and February rainfall is decreasing while the March and April rainfall is increasing. These downward rainfall trends for November–February imply that these months have recently become drier than before, resulting in delayed sowing as farmers would have to wait until they receive good showers that provide sufficient moisture to the soil to facilitate land preparation and sowing. When sowing is delayed, the growing season becomes shorter, decreasing crop growth, development, and final yield [52]. Farmers in other regions have observed, among others, decreasing rainfall amounts, rising temperatures, and shortening of growing seasons' length over the years, causing prolonged droughts, uneven rainfall distributions, and unpredictable onset and ending of rains [20,73,74], which have adverse effects on agricultural productivity, food security, and income.

The downward trend in annual rainfall indicates that total annual rainfall in the region is decreasing. Hence, water would become more limited in the local semi-arid environment of the NCR. Six of the 11 latest years (2013–2023) had rainfall values below the long-term average; additionally, three years were characterized by severe drought—2013, 2019, and 2023 (Figure 2). This situation has implications for local water resources and agricultural production, as drought conditions could intensify, leading to water deficit, poor agricultural production, and food insecurity. The decrease in annual rainfall is also attributed to the reduction in the rainfall of the rainy season months (November–February). Climate-change-related decreases in annual rainfall trends have recently been reported in Namibia [109] and other sub-Saharan African (SSA) countries, such as Botswana [110,111], Zimbabwe [112], Mali [27] and Ethiopia [113,114].

4.2. Crop Performance

The sowing date significantly influences pearl millet performance [76,77]. The results from the grain yield dynamic analyses showed that Kantana, sown earlier by 14 January, had a yield advantage of up to 36% over Okashana-2; however, afterward, the yield dramatically decreased with subsequent delays in sowing (Table 3 and Figure 5). Superior grain production by Kantana under the early sowing dates demonstrates that the variety has a higher yield potential; thus, it can produce more grain yield if it is sown earlier in the season, despite having a more extended growth period than Okashana-2. Kantana is a long-duration variety, taking more days to head than Okashana-2 [101,102], thus maturing later than its counterpart. The results are in line with those of other researchers, such as Nwajei et al. [76] and Nwajei [77], who demonstrated that different pearl millet varieties respond in various ways to sowing dates, and long-duration varieties can produce higher yields when they are sown earlier in the season. They attributed the superior performance of the early-sown crop to the more extended growth period with favorable conditions and better vegetative growth, allowing the accumulation and mobilization of photosynthetic assimilate for grain development.

The results (Table 3 and Figure 5) also revealed that Okashana-2 had more stable grain yields than Kantana, surpassing its counterpart by up to 9.4% when sown between 14 January and 1 March, despite having lower grain yield potential. These results demonstrate that Okashana-2 has mechanisms for setting and sustaining grain yields under variable rainfall conditions, such as alternating dry spells and flash floods during the growing season. According to Mgonja et al. [100] and Monyo et al. [71], Okashana-2 is an improved high-yielding, early-maturing variety developed for drought-prone, low-rainfall regions. Therefore, due to its fast growth characteristics, especially under harsh conditions, Okashana-2 physiologically adjusts to the prevailing moisture conditions. Such adjustment is attained by either setting the grain early when drought or flood stress is initiated or delaying the grain setting when the soil moisture is favorable, allowing more photosynthetic activities for normal plant growth and development, thereby maintaining a certain yield level under the prevailing rainfall conditions. Such yield adjustment may not be possible for the long-duration and late-maturing Kantana [101,102], which requires a longer growing season. Therefore, any delay in sowing means shortening the growing season for Kantana, diminishing its growth and yield.

The more stable yield observed for Okashana-2 may be explained by the fact that the variety is characterized by being a small plant type, suggesting that it has lower water and nutrient requirements than Kantana, which bears bigger plants. For example, the low rainfall during February (Figure 3b) might have created severe moisture stress for Kantana, but not necessarily for the smaller plants of Okashana-2, causing differential growth and yield responses between the varieties. However, the results revealed that local traditional pearl millet varieties do not have as low a yield potential as perceived. However, their yield levels under semi-arid environments are chiefly controlled by the sowing date and available soil moisture during the crop growth cycle.

In Nigeria, the traditional pearl millet variety Gero Badeggi [88] produced a remarkably high grain yield in a sowing date experiment when it was sown earlier in the season [76]. The results of our study show that both Kantana and Okashana-2 varieties had the lowest yields under the last sowing date of 1 March. The reduction in yields as sowing is delayed may be related to the declining growth resources as the last sowing occurred towards the end of summer season. For example, some weather variables such as solar radiation, temperature, and rainfall, which are needed in sufficient amounts to promote normal plant growth, were diminishing as the season was advancing (see Figure 3a,b), slowing plant physiological activities, growth and development, and thus limiting final yields.

4.3. Optimal Sowing Window for the NCR

Figure 5 shows that both Kantana and Okashana-2 produced the highest grain yields when they were sown during the first three weeks of January, with Kantana having a significant maximum yield when sown between 1 and 7 January and Okashana-2 having its highest grain yield potential when sown between 1 and 21 January. The results demonstrate that the sowing of Okashana-2 can be delayed at least by two weeks without a significant reduction in yields, which is attributable to the variety's early-maturity characteristics [71,100].

For Kantana, the results showed the maximum grain yield when it was sown earlier, by 7 January, which may be ascribed to the variety's long growth duration requirement [101,102]. The results also show that Kantana sown in week 1 of January still had a higher grain yield than Okashana-2; however, such a yield was 18% lower than the maximum yield attained by sowing the variety in week 1. This reduction in yield is quite huge; thus, local farmers who prefer Kantana over short-duration varieties are challenged to make tough decisions regarding whether they can still cultivate Kantana in week 2 in January, given such a considerable reduction in yield and the general reduction in and unreliability of local rainfall (Table 2). Alternatively, the farmers should switch to improved short-duration varieties such as Okashana-2 and Kangara [71,100]. Nevertheless, one should consider simultaneous cultivation of both varieties in equal proportions to mitigate potential yield loss due to poor rainfall or sowing an inappropriate variety.

Overall, the results suggest that the optimal pearl millet sowing window for the NCR is the period 1–21 January, such that Kantana can be safely sown from 1 to 7 January, while Okashana-2 can be sown from 1 to 21 January without incurring significant grain yield loss by delaying the sowing date. This method of determining a sowing window for a particular region has previously been used to determine rice-planting windows by Cerioli et al. [115] and Slaton et al. [116].

As local rainfall in the NCR is low and highly unpredictable [42,92,107], both Kantana and Okashana-2 may be sown outside the proposed sowing windows, depending on the availability of rainfall, as farmers would be compelled to produce at least some grains for household food security. This scenario may be highly possible with Okashana-2, whose grain yield from week 4 of January was only 6–8% lower than that of the first three weeks. However, there might be severe yield loss due to the late sowing, particularly for the late-maturing variety Kantana. Therefore, national and regional pearl millet breeding programs should develop or promote extra early-maturing, high-yielding varieties to extend the local sowing window to early February without incurring high yield loss due to the late sowing.

4.4. Agronomic Significance

Namibia's current pearl millet yield level is relatively low [4,75], requiring scientific intervention to improve household food self-sufficiency and national food security. National production data show domestic grain production over the past 10 years (2012–2021) never reached 50% of the national cereal requirements; the shortfalls were covered with imported grains and grain products [4,117]. Although the recently observed on-farm pearl millet yield figures were better than those recorded for the 1993 season [67], such values are remarkably lower than those recorded in our present study. The large gap between the recent on-farm yield levels of 0.71–0.94 t/ha [75] or 0.24 t/ha [4] and the on-station yield of 9.5 t/ha (Kantana) or 6.4 t/ha (Okashana-2) may be related to differences in crop management practices. The present study demonstrated that matching specific varieties to sowing windows during the growing season could improve pearl millet grain production in the NCR (Figure 5). Our results concur with the findings of Minoli et al. [83], who highlighted that adaptive management of crop growing periods by adjusting sowing dates and varieties can improve yields under a changing climate. Therefore, smallholder farmers adopting appropriate production strategies for major crops, such as pearl millet, could increase yields, thus improving household food security and socioeconomic status [118]. Applying the optimal sowing window as a climate smart production strategy could provide maximum pearl millet yield benefit in the NCR. This crop management strategy would be more effective if integrated with other improved production approaches proposed for the local agroecosystem. Such approaches include crop diversification and mixed planting [6,119], ridge-furrow tillage [78,79], and climate-smart agriculture (CSA), including conservation agriculture (CA) [80,120].

Nevertheless, some critical field management strategies for increasing pearl millet yields, such as supplemental fertilization and irrigation and optimal plant population, have not been scientifically determined for local conditions, despite existing scientific evidence that such strategies increase pearl millet productivity [3,121,122]. Nevertheless, it would be wise to sensitize local farmers regarding the beneficial effects of sowing the suitable pearl millet variety at the right time to maximize grain production and enhance farmers' living standards. In a way, the proposed crop management strategy would contribute to improved production efficiency and increased grain production, increased sales of surplus production, and improved farmers' income from agriculture, ultimately leading to an enhanced socioeconomic situation for the farmers in the NCR.

Future studies aiming at improving pearl millet yields in the NCR should focus on determining the crop's fertilizer requirements and optimal plant density to efficiently utilize production inputs and resources. It is also essential to translate the results of this study into economic value to encourage smallholder farmers in Namibia and elsewhere to adopt appropriate crop management techniques and produce surplus grains for food security and income generation.

5. Conclusions

Pearl millet grain production in Namibia's North-Central Region (NCR) can be increased by appropriately matching varieties to sowing time. The cubic polynomial regression models revealed a higher grain yield potential of the landrace variety Kantana compared with the improved Okashana-2 variety under early sowing and a positive relationship between delayed sowing and reduced grain yields for Kantana. Kantana sown between 1 and 14 January exhibited a yield advantage over Okashana-2. By contrast, Okashana-2 sown across January displayed more stable grain yields than Kantana, surpassing those of its counterpart by up to 9.4% between 14 January and 1 March. Both varieties gave the lowest grain yields when sown in March, possibly due to resource decline as the summer growing season approaches cessation. The results suggest that the optimal sowing window for pearl millet in the NCR is 1–21 January, with Kantana better sown 1–7 January and Okashana-2 sown across the entire three weeks. Analyses of time-series rainfall data revealed high annual and monthly rainfall variabilities, with insignificant monotonic negative trends for November–February rainfalls, implying a shortening growing season in the NCR. These results should be crucial for other semi-arid agroclimatic regions where pearl millet is cultivated for grain production. Future studies should investigate the economics of sowing dates to demonstrate to farmers and policymakers the potential financial benefits or losses associated with the different sowing dates and varieties.

Author Contributions: Conceptualization, S.K.A., K.H. and J.S.V.; methodology, K.H. and S.K.A.; software, K.H. and S.K.A.; validation, S.K.A., H.N.N., E.K.S., B.C., L.N.H., S.A., L.S.M.A. and O.D.M.; formal analysis, S.K.A., K.H., H.N.N. and O.D.M.; investigation, S.K.A., J.S.V. and B.C.; resources, S.K.A., O.D.M. and S.A.; writing—original draft preparation, S.K.A.; writing—review and editing, K.H., E.K.S., J.S.V., S.A. and L.S.M.A.; visualization, K.H. and S.K.A.; project administration, S.K.A. and O.D.M.; funding acquisition, S.A., S.K.A. and O.D.M. All authors have read and agreed to the published version of the manuscript.

Funding: The publication of this article has been financially supported by the University of Namibia.

Data Availability Statement: The data for this study are available from the authors on request.

Acknowledgments: The authors thank the University of Namibia—Ogongo Campus students T. Lukas, A. M. Haufiku, B. Angelius, and K. Murangi for assisting with data collection. We also thank the Ogongo Campus Management for availing of facilities and resources for the study. This study did not receive any funds from funding agencies.

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

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