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Variation in Maize Grain Yield Indices When Exposed to Combined Heat and Water Stress Conditions under Different Soil Amendments

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Abstract: Increased yield can be achieved by optimising the growth environment, improving the plant gene pool, or a combination of the two. This study's objective was to evaluate the effect of combined heat and water stress (CHWS) on maize yield, grown in various soil conditions. The experimental design was a four-replicated 3 × 3 × 2 × 3 factorial in a completely randomized design. Three water stress levels, three soil amendments, two soil textural types, and three drought-tolerant maize varieties were combined to create 54 treatment interactions. The result showed that as the severity of the water stress increased, the yield decreased. The near terminal water stress reduced cob weight, grain weight, and grain number by 96, 97, and 97%, respectively. The maize varieties were ranked WE5323 ≥ ZM1523 > WE3128 in terms of average performance and stability. Under heat and moderate water stress, the poultry manure amendment performed well for WE5323 and ZM1523, while the mineral fertilizer amendment performed best for WE3128. Compared to the inorganic amendment, the organic had a greater ameliorative capacity for grain yield under CHWS. For improved grain yield under CHWS, farmers are advised to grow WE5323 and ZM1523 with organic amendments. The findings in this study could improve food security strategies for low-income households living in high-stress environments.

Keywords: drought; food security; rising temperature; sustainability; *Zea mays* L.

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1. Introduction

Africa contributed 81 MT to the global maize (*Zea mays* L.) production of 1148 MT in 2019 [1]. By 2029, global maize output is expected to reach 1315 MT, with Africa contributing less than 10% [2]. However, maize consumption in Sub-Saharan Africa (SSA) is predicted to expand at the fastest rate, accounting for more than half of the additional 23 MT earmarked for human consumption [2]. Due to extreme climate events, projected global increases in maize demand and consumption will coincide with yield declines in SSA [3]. The increase in maize demand will benefit industrialized countries, but it will result in higher poverty rates, malnourished children, and increased food insecurity in most developing countries in SSA. According to FAO [4], approximately 16.7 million people in West Africa are severely food insecure, with the number potentially increasing to 23.6 million if appropriate measures are not taken. The report attributed the food insecurity to significant localized production deficits caused by adverse climate events, as well as the region's long-running conflicts.

Climate change, such as rising temperatures and drought, was expected to become more common and severe in SSA [5–7]. Heat and water stress in maize are caused by rising temperatures and drought, resulting in lower yields. For millions of people in Africa and

Asia, maize is the most important staple food and the most important single source of calories [2]. As a result, increasing maize yield has the potential to improve food security. Maize is a staple crop in some of the world's poorest regions, including Africa, Asia, and Latin America [3].

Thierfelder et al. [8] observed that maize grain improvement can be achieved through improved cultural/management practices, improved varieties, or a combination of the two. Under adverse climate conditions, breeding stress-tolerant varieties remains an important strategy for food security. The lack of a suitable environment, on the other hand, can erode the benefits of breeding. Farmers' maize output has decreased, according to Lunduka et al. [9], as a result of the maize variety chosen and production practices used. Maize yields are reduced when maize is cultivated on marginal land [10]. Variations in soil properties can also affect maize growth and development [11–15].

In stress-free environments, improved soil characteristics from the application of poultry manure have been proven to increase maize grain yield [11]. This is due to increased soil water-holding capacity and fertility [16,17]. Chukwudi et al. [14] found that maize plants grown with organic soil amendment accumulated more dry matter than those grown with inorganic amendment under heat stress. The dry matter partitioning to grain, on the other hand, was influenced by soil amendment and genotype [15].

The response of drought-tolerant maize varieties grown with organic and inorganic soil amendments to combined heat and water stress is poorly understood. While there are studies in soil amendment on maize and climate change on maize, the current study focused on soil amendment under combined heat and water stress. This study hypothesized that substituting poultry manure for conventional mineral fertilizer would affect maize yield under combined heat and water stress conditions. This information will help improve food security strategies for low-income households living in high-stress environments, as well as reduce pollution caused by excessive mineral fertilizer application. The objective of this research was to assess how three drought-tolerant maize varieties responded to combined heat and water stress when grown in different soil amendments and soil types.

2. Materials and Methods

2.1. Description of the Study Site

The experiment took place in a greenhouse at the North-West University Experimental Farm during the summer planting season of 2018/2019 and was repeated in 2019/2020. In the greenhouse, daily morning (08:00 am) and midday (12:00 noon) temperature readings were taken and recorded, the average weekly temperatures computed for plotting line graphs, as presented in Figure 1. The average weekly temperature range was 16.4–40.9 °C in 2018/2019 and 19.8–44 °C in 2019/2020.

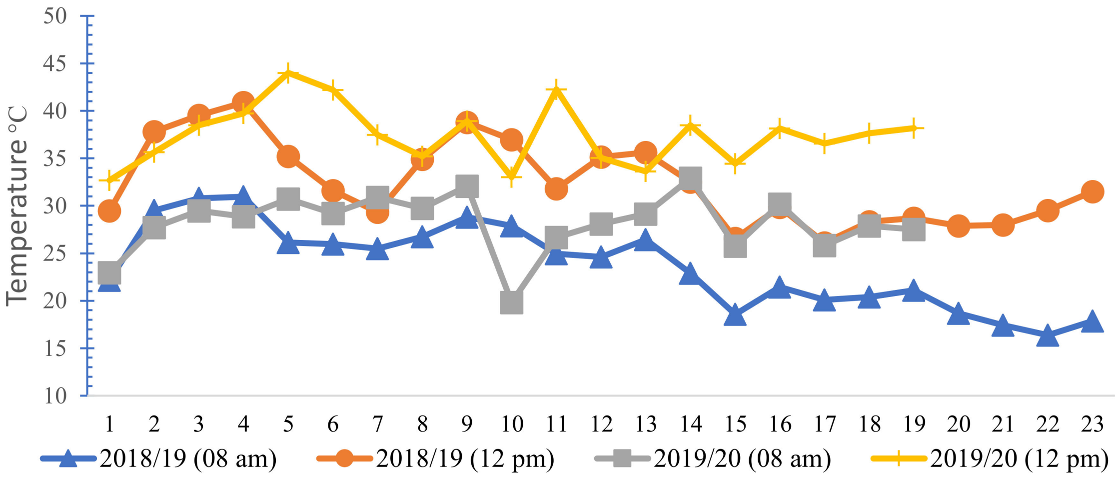

Figure 1. Weekly heat–stressed environment temperature readings under heat-stressed condition during 2018/2019 (Season 1) and 2019/2020 (Season 2) summer planting seasons.

Surface soil (0–20 cm) was obtained from Molelwane (−25.7902166, 25.6187922, 3.5 mi) and Tlapeng (−25.7297143, 25.4324561, 13 mi) towns for the screenhouse experiments. Molelwane and Tlapeng soils are classified as Hutton and Arcadia forms, respectively, by the South African soil classification system [18]. Molelwane soil was composed of 82% sand, 4% silt, and 14% clay (loamy sand), whereas Tlapeng soil was composed of 64% sand, 8% silt, and 28% clay (sandy clay loam). Molelwane soil had a pH (KCl) of 4.98, 11 mg kg^{-1} P (Bray1), 290 mg kg^{-1} K, 390 mg kg^{-1} Ca, 163 mg kg^{-1} Mg, 5 mg kg^{-1} Na, 376 mg kg^{-1} total N, and 0.37% C, while Tlapeng soil had a pH (KCl) of 5.83, 2 mg kg^{-1} P (Bray1), 138 mg kg^{-1} K, 2000 mg kg^{-1} Ca, 1310 mg kg^{-1} Mg, 215 mg kg^{-1} Na, 616 mg kg^{-1} total N and 0.76% C. The organic soil amendment made from poultry manure contained 4.12% nitrogen, 1.45% phosphorus, 1.78% potassium, 8.18% calcium, 1.04% magnesium, and 0.41% sodium. Molelwane and Tlapeng are both towns in South Africa's North West Province. The province is classified as semi-arid, with an average daily minimum and maximum temperatures of 0.9 and 32 degrees Celsius, respectively, and an annual rainfall of 300–600 mm [19].

2.2. Treatments, Experimental Design, and Cultural Practices

The repeated trial used a 3 × 3 × 2 × 3 factorial in a four-replication completely randomised design experiment. Non-water stress (NS, well-watered), moderate water stress (MS), and near terminal water stress (TS) were the three levels of water stress in Factor A. The field capacity of the non-water stress treatment was kept at around 80%. To determine the amount of water used in the moderate water-stress treatment, the amount of water used in the non-water stress (NS) treatment was cut in half. Similarly, the amount of water used in the moderate water-stress treatment was further reduced by half to obtain a near (above) terminal water-stress treatment. The amount of water applied to the MS and TS treatments depended on the initial volume of water that was required to achieve approximately 80% field capacity in the NS treatment on each irrigation day. The MS and TS treatments were applied five weeks after planting (WAP) when the majority of the plants had reached the V4 phenological growth stages.

Factor B consisted of maize varieties obtained from the Agricultural Research Council, Grain-Crops Potchefstroom, South Africa, which include two Water Efficient Maize for Africa hybrids (WE3128 and WE5323) and one open-pollinated variety, ZM1523. The maturity period for these maize varieties was 117–120 days. Factor C was made up of two soils from Molelwane and Tlapeng, with different textural characteristics: loamy sand (LS) and sandy clay loam (SCL), respectively. Factor D represented soil amendment, which included sole poultry manure (PM) and mineral fertiliser (MF) applications, as well as complementary (50:50) poultry manure and mineral fertiliser applications (MPM). NPK (13:7:10 {30}+ 0.5% Zn + 5% S + 3% Ca) and lime ammonium nitrate (28% N) were used as mineral fertilisers, while the poultry manure came from mature layer birds. Chemical characterization of the poultry manure, as described by Okalebo et al. [20], revealed 4.12% N, 1.45% P, 1.78% K, 8.18% Ca, 1.04% Mg, and 0.41% Na. The calculation was based on g/100 g. At a rate of 180 kg N ha^{-1}, each of the soil amendments was applied. The four factors (Table S1) were combined in all possible ways, yielding 54 (3 × 3 × 2 × 3) treatment interactions. However, only the interaction of water stress, maize variety, and soil amendment was discussed, in addition to the main effects of the four factors. The 54 treatment interactions were placed in a plastic greenhouse, where the temperature was set to fluctuate with the temperature outside the greenhouse but was always higher than the temperature outside the greenhouse. The obtained temperature range (Figure 1) is within the temperature bracket exerting heat stress on maize. Temperatures above 32 °C induce heat stress in maize [21–23]. The NS treatments included heat stress without water stress; the MS and TS treatments included both heat and water stress conditions.

Surface soils (0–20 cm depth) were excavated, air-dried, sieved, and homogenised before being weighed into each plastic planting pot (30 cm top × 28 cm height × 21 cm base) with drainage holes. On a polyethene sheet, the 12 kg weighed soil and organic amendments were thoroughly mixed separately and then transferred into each pot based on the treatment. Before sowing the maize seeds, the pots were irrigated to about 80% field capacity and allowed to stand for two weeks to allow the poultry manure to mineralize. Three maize seeds were sown per pot, but two weeks later, the seedlings were thinned to one per pot.

2.3. Measurement of Plant Response Attributes

The cobs were removed, counted, and dried under shade for two weeks after harvest, while the shoots were oven-dried to constant weight at 65 °C for determination of stover dry weight in grams (SDWt). A measuring tape and a digital Vernier caliper were used to determine the length (cm) and width (mm) of the cob. Each cob was weighed in order to determine its gram weight (CWt). The cobs were then shelled and the grain weight (GWt) measured. The shelling percentage (SP) was calculated as described by Chukwudi et al. [15].

$$Shelling\ percentage\ (\%) = \frac{\text{Grain weight (g)}}{\text{Cob weight (g)}} \times 100 \quad (1)$$

The grains were counted (GN) with the Numigral Seed Counter (CHOPIN Technologies, Cedex, France) and 100 seeds from each treatment interaction were weighed to obtain the 100-seed weight (SWt).

2.4. Data Analysis

Using GenStat Software (VSN Int. Ltd., Hemel Hempstead, UK), an analysis of variance (ANOVA) test was run on the collected data, following the procedure for factorial in a completely randomised design. Protected Fisher's Least Significant Difference was used as a post hoc test for mean separation at $p \leq 0.05$. The differences in the maize yield attributes were calculated as described by Chukwudi et al. [15]:

$$\text{Difference } (\%) = \frac{\text{Ta} - \text{Tb}}{\text{Ta}} \times 100 \quad (2)$$

where Ta is the mean of attribute X in treatment A, and Tb is the mean of the same attribute in treatment B.

For the treatment interactions, the GGEBiplot software [24] was used to plot the which-won-where, discriminatory vs. representativeness abilities, and mean vs. stability biplots.

3. Results

3.1. Effects of Water Stress on Biological and Economic Yield Attributes of Maize

Under heat stress, water stress had a significant impact on maize grain yield attributes (Table 1). Water stress had a negative effect on grain yield attributes. As the severity of the water stress increased, the measured yield attributes decreased. All of the measured yield attributes were significantly higher in the non-water stress plants than the moderate and near terminal water-stress plants. Cob length, width, weight, grain weight, grain number, 100-seed weight, shelling percentage, and stover dry weight were all reduced by 79, 74, 96, 97, 97, 63, 72, and 51%, respectively, due to near terminal water stress.

Table 1. Main effects of water stress, maize variety, soil amendment and soil type on maize yield attributes.

Treatments	CN	CL cm	CW Mm	CWt g Plant^{-1}	GWt g Plant^{-1}	SP %	GN	SWt g Plant^{-1}	SDWt g Plant^{-1}
Water stress									
NS	1.3	11.0	31.9	44.7	26.7	51.4	119.8	22.7	74.8
MS	1.0	6.2	22.7	21.0	12.8	39.0	65.4	17.8	47.7
TS	0.4	2.3	8.3	1.9	0.7	14.4	3.9	8.3	36.9
F–LSD$_{(0.05)}$	0.2	1.1	3.1	7.4	5.9	7.9	27.4	2.6	7.3
Maize variety									
WE3128	1.0	6.5	22.9	20.8	11.7	40.8	58.2	16.1	48.9
WE5323	1.1	7.9	23.7	32.7	20.5	39.7	100.3	17.3	58.4
ZM1523	1.1	8.7	25.8	31.0	17.8	39.1	73.2	20.8	57.0
F–LSD$_{(0.05)}$	n.s.	1.1	2.3	7.4	5.9	n.s.	27.4	2.6	7.3
Soil amendment									
MF	1.2	7.8	25.6	25.3	14.8	42.1	65.4	20.4	52.9
MPM	1.1	7.1	22.4	25.0	14.4	34.5	65.6	17.8	57.7
PM	0.8	8.4	24.0	38.0	23.5	42.0	114.0	15.3	55.5
F–LSD$_{(0.05)}$	0.2	1.1	3.1	7.4	5.9	n.s.	27.4	2.6	n.s.
Soil type									
Loamy Sand	1.0	6.5	20.7	22.0	12.3	33.1	53.8	16.5	52.6
Sandy Clay Loam	1.1	8.8	27.0	34.4	21.1	45.3	100.1	19.5	56.3
F–LSD$_{(0.05)}$	0.1	0.9	2.6	6.1	4.9	6.5	22.4	2.1	n.s.

NS = non–stress, MS = moderate–stress, TS = near terminal–stress, MF = mineral fertilizer, MPM = a complementary (50:50) application of mineral fertilizer and poultry manure, PM = poultry manure, CN = cob number, CL = cob length (cm), CW = cob width (mm), CWt = cob weight (g plant^{-1}), GWt = grain weight (g plant^{-1}), SP = shelling percentage (%), GN = grain number, SWt = 100-seed weight (g plant^{-1}), SDWt = Stover dry weight (g plant^{-1}), and n.s.= non-significant.

3.2. Varietal Effects on Biological and Economic Yield Attributes of Maize

Except for the cob number, cob width, and shelling percentage, maize variety had a significant impact on all yield attributes studied (Table 1). Varieties WE5323 and ZM1523 were statistically similar in all attributes except for 100-seed weight, where ZM1523 was significantly higher than WE5323 and WE3128. WE3128 yielded the lowest values in all yield attributes except shelling percentage, and was significantly lower in cob weight, grain weight, and stover dry weight than WE5323 and ZM1523.

The GGEbiplot explained 100% (PC1 = 76.6%, PC2 = 23.4%) of the variation in the maize grain attributes. The long vectors from the biplot origin indicated that the studied maize grain attributes had good discriminatory abilities (Figure 2). Because they have the closest angles to the average-tester axis (the single-arrow straight line), cob weight, stover dry weight, cob length, and grain weight were the most representative attributes.

The mean performance and stability analyses explained the performance of the maize varieties in the selected attributes and the consistency (stability) of the performance across the attributes. The biplot (Figure 3) explained 100% (PC1 = 94.9% and PC2 = 5.1%) of the variation among the three varieties. Figure 3 identified variety WE5323 as the best variety, based on the studied maize attributes, followed by the variety ZM1523. The maize varieties were ranked along the average-tester axis (ATA), that is the single-arrow red line. The average tester was represented by the small circle in the ATA. Varieties within the divide containing the average tester performed well in the attributes studied. Variety WE3128, which appeared after the double-arrow blue line (average of the three maize varieties), performed poorly in the attributes tested. The length of the black line joining the varieties to the ATA indicates the stability of the varieties. The shorter the black line, the higher the stability of the variety.

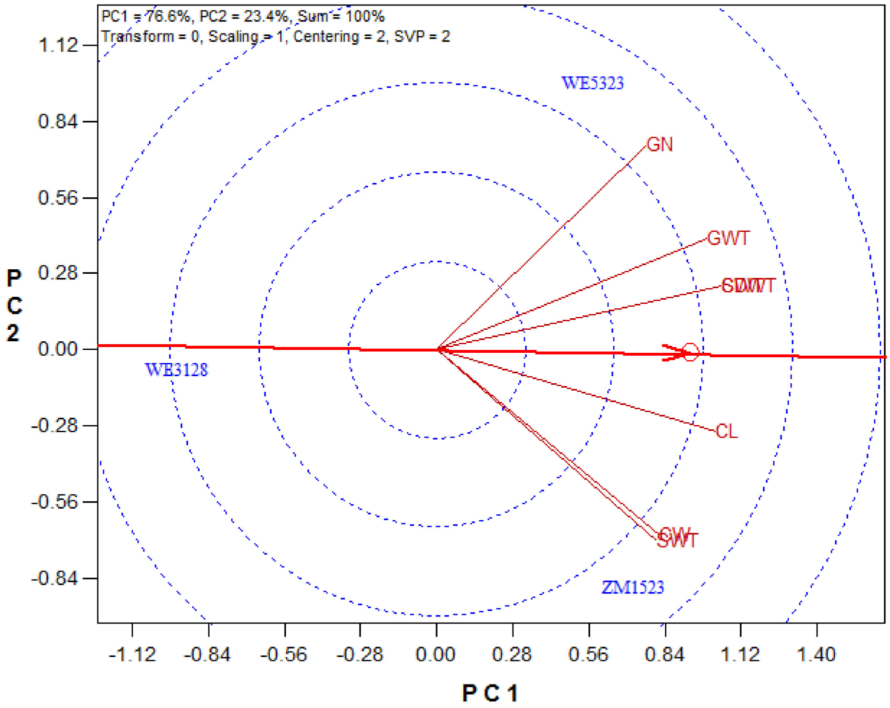

Figure 2. The discriminatory vs representativeness abilities of the maize attributes.

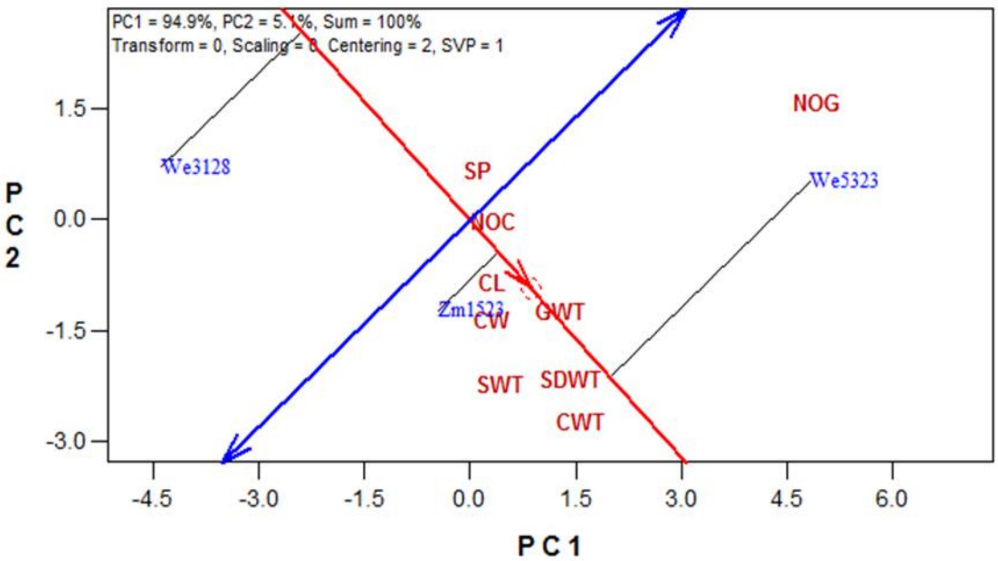

Figure 3. Mean performance and stability of the maize varieties.

3.3. Effects of Soil Amendments on Biological and Economic Yield Attributes of Maize

The number of cobs, cob width, cob length, cob weight, grain weight, grain number, and 100-seed weight of maize were all significantly affected by soil amendment (Table 1). In terms of cob weight, grain weight, and grain number, the PM amendment outperformed the MF and MPM amendments. However, it had a lower cob number and 100-seed weight than the MF amendment.

The GGEbiplot which-won-where view explained 100% (PC1 = 97.3%, PC2 = 2.7%) of the total variation due to soil amendment (Figure 4). The which-won-where analysis reveals treatments (soil amendments) that perform well or poorly in the attributes evaluated, as well as group treatments that are comparable. The treatment that occupies the polygon's vertices is the best in that sector and outperforms the other treatments in the attributes that fall within it. Each of the soil amendments occupied a sector vertex in the biplot. The stover dry weight fell into the MPM sector, while the 100-seed weight and cob width fell into the MF sector. Grain number, grain weight, cob weight, cob number, and cob length were all won by the PM sector. The PM amendment ranked higher than the MF and MPM amendments in terms of mean performance and stability of the soil amendment (Figure 5). The MPM amendment had the shortest black line, indicating that it was the most stable soil amendment. Its position after the double-arrow blue line, on the other hand, indicates that it remained constant in low performance in the attributes tested.

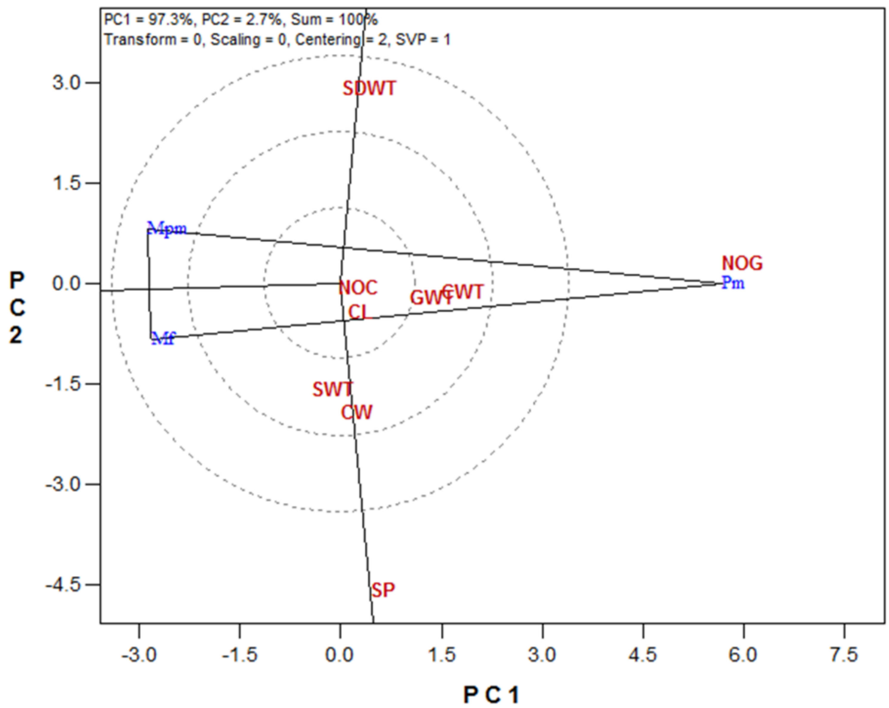

Figure 4. The which–won–where view of the GGEbiplot for soil amendment.

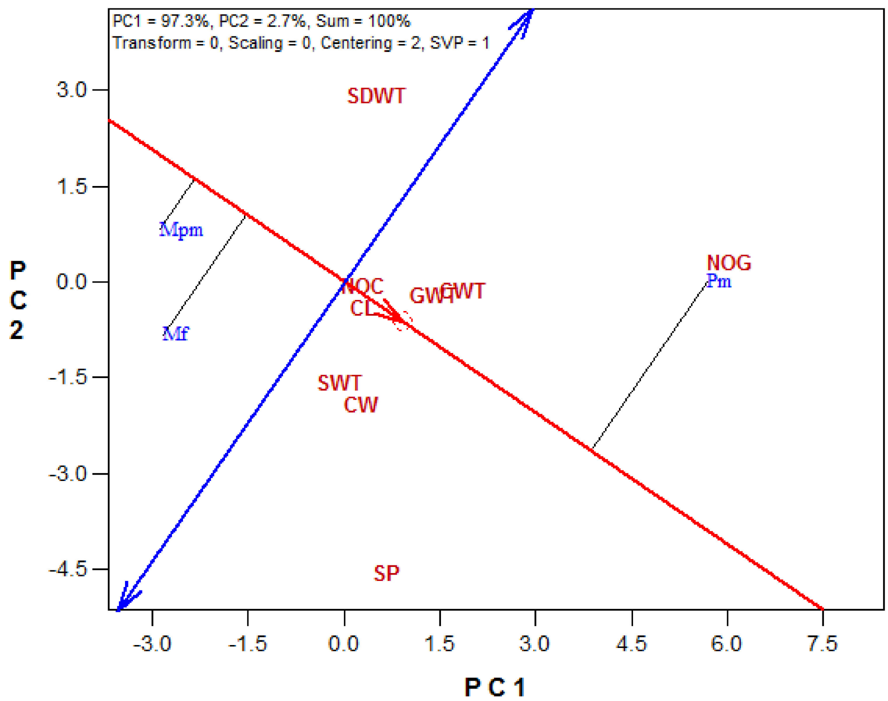

Figure 5. Mean Performance and Stability of the soil amendment.

3.4. Effects of Variation in Soil Textural Types on Biological and Economic Yield Attributes of Maize

Except for cob number and stover dry weight, the sandy clay loam soil outperformed the loamy sand soil in all yield attributes studied (Table 1). It had 35, 30, 56, 72, 37, 86, and 18% higher cob length, cob width, cob weight, grain weight, shelling percentage, grain number, and 100-seed weight, respectively, than loamy sand soil.

3.5. Water Stress, Maize Variety, Soil Amendment, and Soil Type Interactions on Maize Biological and Economic Yield Attributes

The main effects and different treatment interactions, as well as their significance levels for the studied maize attributes, are shown in Table 2. Except for cob number and shelling percentage for maize variety, shelling percentage and stover dry weight for soil amendment, and stover dry weight for soil type, the main effects revealed significant differences for the studied maize attributes. Except for shelling percentage, all of the studied growth attributes showed significant differences due to water stress and soil amendment interaction. For cob length, shelling percentage, and 100-seed weight, there was no significant effect from maize variety × soil amendment interaction. Similarly, for the water stress by soil type interaction, cob length and stover dry weight were not significant. Cob width and 100–seed weight were not affected by the interaction of soil amendment and soil type. The remaining second-order and third-order interactions in all the studied maize attributes were significant, with the exception of the non-significant effect in shelling percentage from the water stress × maize variety × soil amendment interaction and the maize variety × soil amendment × soil type interaction.

Table 2. Main effects, first-, second-, and third-order interactions of maize variety, water stress, soil amendment, and soil type on selected maize grain attributes with significance levels.

Treatment Combination	CN	CL	CW	CWt	GWt	SP	GN	SWt	SDWt
WS	**	**	**	**	**	**	**	**	**
MV	n.s	**	**	**	*	n.s.	*	**	**
SA	**	*	**	*	*	n.s.	*	**	n.s.
ST	**	**	**	**	**	**	**	**	n.s.
WS.MV	**	**	**	*	*	**	*	**	**
WS.SA	**	**	**	*	*	n.s.	*	**	**
MV.SA	**	n.s.	**	*	*	n.s.	*	n.s.	**
WS.ST	**	n.s.	**	*	*	*	*	**	n.s.
MV.ST	**	*	**	*	*	**	*	**	*
SA.ST	**	*	n.s.	*	*	*	*	n.s.	**
WS.MV.SA	**	**	**	*	*	n.s.	*	**	**
WS.MV.ST	*	**	**	*	*	**	*	**	**
WS.SA.ST	*	**	**	**	**	**	**	**	**
MV.SA.ST	*	*	**	*	*	n.s.	*	**	*
WS.MV.SA.ST	**	**	**	**	**	*	**	**	**

CN = cob number, CL = cob length, CW = cob width, CWt = cob weight, GWt = grain weight, SP = shelling percentage, GN = grain number, SWt = 100-seed weight, SDWt = stover dry weight, n.s. = not significant, * = significant at 5% probability level, ** = significant at 1% probability level, WS = water stress, MV = maize variety, SA = soil amendment, and ST = soil type.

Of the studied maize yield attributes, there were significant interactions between water stress, maize variety, and soil amendment. The highest cob number was produced by the NS-WE3-MPM interaction, which was significantly higher than the majority of the other treatment interactions (Table 3). The NS-ZM1-PM interaction produced the longest and widest cob length and width, which was significantly greater than the majority of the other interactions. Cob length and width were measured in the ranges of 2.5–14.0 cm and 7.0–37.2 mm, respectively.

Table 3. Interaction of water stress, maize variety and soil amendment on selected maize yield attributes under heat stress condition.

SN	Treatment Combination	CN	CL cm	CW mm	CWt g Plant^{-1}	GWt g Plant^{-1}	SP %	GN	SWt g	SDWt g Plant^{-1}
N1	NS-WE3-MF	1.2	11.0	30.9	42.4	24.6	49.6	99.0	26.7	79.8
N2	NS-WE3-MPM	2.0	8.3	36.0	33.6	16.1	39.3	81.5	17.9	76.7
N3	NS-WE3-PM	1.0	9.2	30.8	26.6	15.1	58.0	105.3	16.5	59.9
N4	NS-WE5-MF	1.5	10.1	31.4	35.5	20.3	52.7	91.0	22.8	71.8
N5	NS-WE5-MPM	1.3	10.9	33.2	46.2	27.6	53.5	108.2	26.8	82.3
N6	NS-WE5-PM	0.8	12.2	28.4	68.9	49.2	56.4	264.6	14.9	68.9
N7	NS-ZM1-MF	1.2	12.4	32.6	50.6	34.1	59.2	136.7	24.0	59.2
N8	NS-ZM1-MPM	1.6	10.1	27.1	28.4	15.6	44.3	64.0	25.6	91.4
N9	NS-ZM1-PM	1.4	14.0	37.2	68.3	35.6	45.9	133.2	25.5	96.7
M1	MS-WE3-MF	0.7	4.0	20.1	13.9	10.2	48.3	43.3	15.6	36.8
M2	MS-WE3-MPM	0.5	4.0	15.0	6.9	4.0	29.3	14.5	13.8	25.6
M3	MS-WE3-PM	0.5	3.8	14.2	8.3	5.6	33.7	31.0	9.0	36.3
M4	MS-WE5-MF	1.8	4.5	22.1	15.3	7.2	35.6	56.8	15.3	54.9
M5	MS-WE5-MPM	0.7	6.5	17.2	21.6	13.7	24.4	83.0	13.1	43.5
M6	MS-WE5-PM	1.0	9.5	28.7	46.8	31.7	50.4	143.3	21.4	62.4
M7	MS-ZM1-MF	1.3	6.5	26.1	12.5	4.9	33.4	25.3	22.3	46.6
M8	MS-ZM1-MPM	1.5	8.3	25.0	31.4	21.8	45.6	127.5	22.2	50.6
M9	MS-ZM1-PM	1.0	9.0	34.5	37.3	20.7	56.4	76.5	27.2	58.5
T1	TS-WE3-MF	0.5	3.5	12.3	3.8	1.8	24.4	9.0	10.2	33.9
T2	TS-WE3-MPM	0.5	2.5	8.8	2.3	1.0	22.3	4.0	13.0	26.5
T3	TS-WE3-PM	0.5	2.7	7.0	1.8	1.1	30.1	12.0	4.4	33.2
T4	TS-WE5-MF	0.7	3.0	11.5	1.8	0.4	13.3	1.7	14.0	44.9
T5	TS-WE5-MPM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.8
T6	TS-WE5-PM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	35.5
T7	TS-ZM1-MF	1.0	5.5	21.0	4.9	1.4	27.1	6.5	19.5	42.1
T8	TS-ZM1-MPM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.9
T9	TS-ZM1-PM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	35.2
	F-LSD$_{(0.05)}$	0.5	2.6	6.8	21.0	18.6	24.1	86.3	4.8	19.0

CN = cob number, CL = cob length, CW = cob width, CWt = cob weight, GWt = grain weight, SP = shelling percentage, GN = grain number, SWt = 100–seed weight, SDWt = stover dry weight, NS = non–water stress, MS = moderate water stress, TS = near terminal water stress, WE3 = WE3128, WE5 = WE5323, ZM1 = ZM1523, MF = mineral fertilizers, PM = poultry manure, and MPM = a complementary (50:50) application of mineral fertilizer and poultry manure.

Except for NS-ZM1-PM, NS-ZM1-MF, and MS-WE5-PM interactions, the NS-WE5-PM interaction produced the highest cob and grain weights, which were significantly higher than the other treatment interactions. The grain weight varied from 0.4 g plant^{-1} in TS-WE5-MF to 49.2 g plant^{-1} in NS-WE5-PM interaction, while the cob weight varied from 1.8 g plant^{-1} in TS-WE5-PM and TS-WE5-MF to 68.9 g plant^{-1} in NS-WE5-PM interaction. The shelling percentages varied from 13.3% in TS-WE5-MF up to 59.2% in NS-ZM1-MF. In terms of grain number, the NS-WE5-PM interaction was significantly higher than the other treatment interactions.

The GGEbiplot explained 96.6% (PC1 = 90.9%, PC2 = 5.7%) of the variation in treatment interactions. In the which–won–where graph, three of the six sectors were occupied (Figure 6). The treatment interactions were divided into two groups, based on the water stress treatments, with the moderate water stress regime being split into two. The NS-ZM1-MPM (N8) sector won in the 100-seed weight, cob width, shelling percentage, and stover dry weight. The non-water stress treatments and a few moderate water-stress treatments were in the same sector as the cob weight, grain weight, cob length, grain number, and cob number. No attribute fell into the sector that contained the near terminal water-stress treatments and the remaining moderate water-stress treatments.

The treatment interactions were ranked by the average tester coordination view based on their mean performance on the studied attributes (Figure 7). NS-WE5-PM (N6) was the highest-ranking treatment interaction among those who performed better than the population mean, followed by NS-ZM1-PM (N9), NS-ZM1-MF (N7), NS-WE5-MPM (N5), MS-WE5-PM (M6), NS-WE3-MF (N1), NS-WE5-MF (N4), MS-ZM1-MPM (M8), NS- (N8). The results of the other treatment interactions were below the population mean. Due to its long vector from the biplot origin, grain number was the most discriminatory of the maize attributes studied (Figure 8). Because cob weight and grain weight have the closest angles to the average-tester axis, they were the most representative attributes.

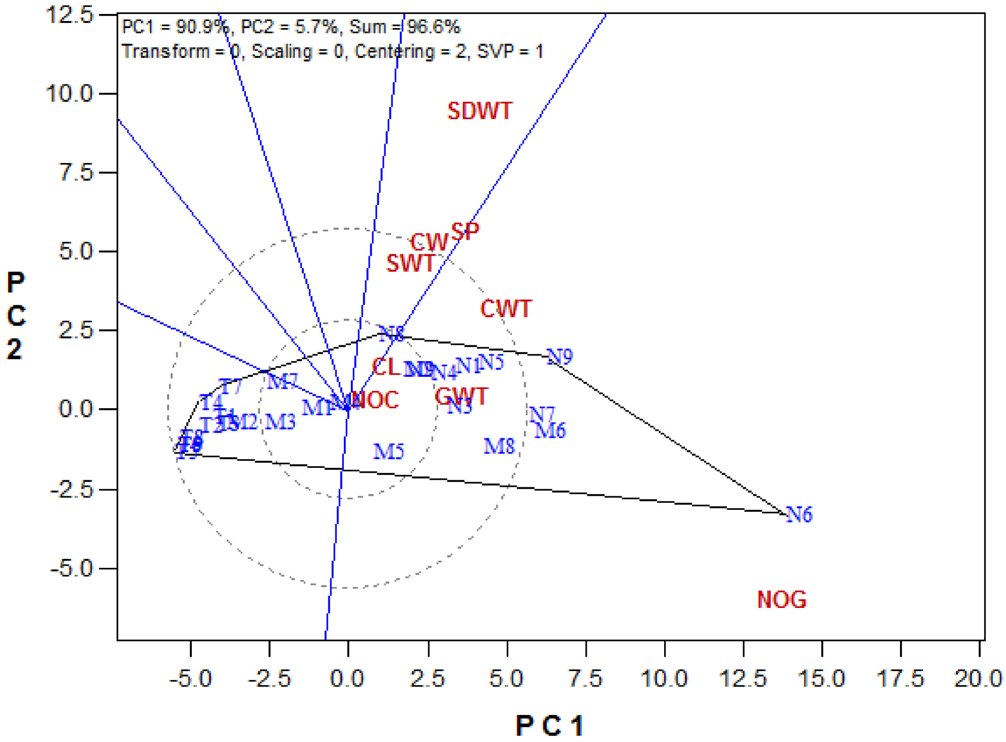

Figure 6. The which–won–where view of the GGEbiplot for the treatment interactions.

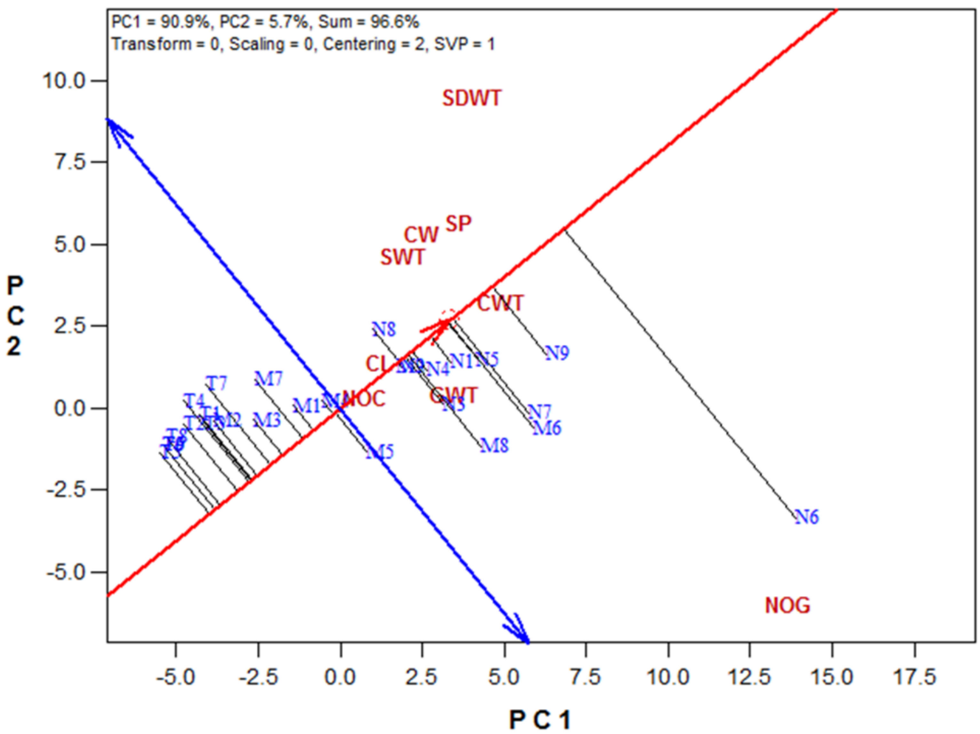

Figure 7. Mean Performance and Stability analysis of the treatment interactions.

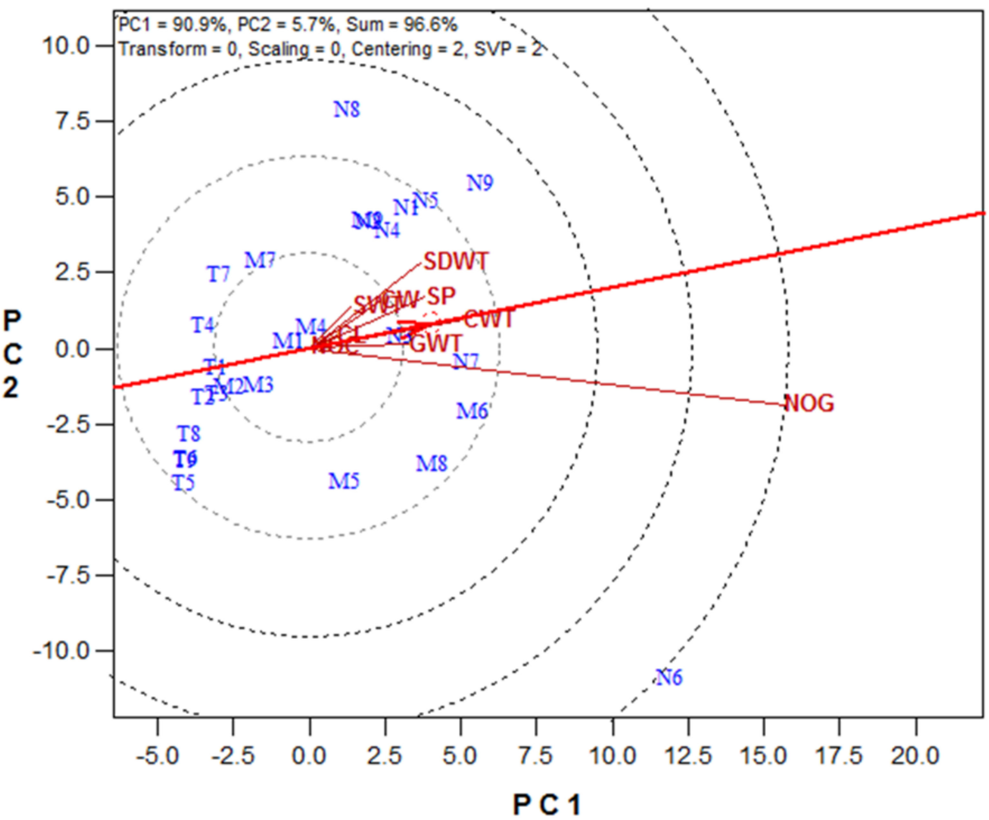

Figure 8. The discriminatory vs representativeness abilities of the maize attributes under combined heat and water stress condition.

4. Discussion

4.1. Effects of Water Stress on Biological and Economic Yield Attributes of Maize

Abiotic stressors are the most common causes of reduced agricultural productivity. Abiotic stressors can act alone or in concert with one another to reduce crop yield [25]. The effect of water stress on maize was investigated in this study under heat stress conditions. In this study, water stress had a depressive effect on the maize grain attributes. As the severity of the water stress increased, a consistent phenomenon of reduced maize grain attributes was observed.

Water stress has a negative impact on plants that is often exacerbated by heat stress. Meseka et al. [26] observed that a combination of heat and water stress reduced more maize grain yield compared to either heat or water stress alone. Depending on the duration and severity of the combined heat and water stress conditions, the reduction ranged from 15% to over 75%. [26–28]. This variation in yield loss due to combined heat and water stress was consistent with the findings of this study, which found differences between the moderate and near terminal water stress treatments.

Heat and water stress in maize have been shown to reduce sink strength via pollen desiccation and fertilisation failures, resulting in low grain number and subsequent cob weight [29]. Grain yield attributes decreased as the water stress progressed in this study. Heat stress disrupts the carbon dioxide reduction and oxygenation cycles in plant leaves, causing severe disruptions when combined with water stress due to stomatal closure [30]. Under combined heat and water stress conditions, there is increased heat energy dissipation via non–photochemical quenching, which leads to degradation of photosynthetic physiology [25]. These stress–induced changes in maize affect its development and could explain the yield losses in this study's moderate and near terminal water stress treatments.

4.2. Varietal Effects on Biological and Economic Yield Attributes of Maize

In stress-prone environments, finding maize varieties that are tolerant to abiotic stresses will ensure food security. Maize varieties have been shown to have varying levels of tolerance to single or combined stress conditions [26,28,31], which is important for breeding and selection. The significant differences in maize yield attributes observed in this study can be attributed to their varying levels of tolerance to combined heat and water stress.

According to Nelimor et al. [28], selection in a stressed maize population based on attributes that account for little variation in the population may be misleading. As a result, the attributes on which selection is based must account for a large proportion of the variation in the population. Various attributes have been recommended as a selection guide under stressful conditions in various studies [28,32–35]. The discriminatory and representative view of the GGEbiplot was used in this study to screen the investigated attributes for their ability to account for differences within maize varieties. The findings indicated that the investigated attributes can account for variations in the genetic expression of maize varieties under combined heat and water stress conditions.

Variety WE5323 was identified as the best variety among the three varieties based on the mean performance and stability analysis of the studied grain attributes, followed by variety ZM1523. These two varieties demonstrated similar tolerance to combined heat and water stress, as evidenced by similarities in the grain attributes studied. The three maize varieties used in this study are drought-tolerant and may be tolerant to both heat and water stress. The evaluation of drought-tolerant maize varieties under combined heat and water stress can aid in the development of maize varieties tolerant to both stress factors [26,31]. To ensure food production in the face of rising global temperatures and diminishing water resources, maize varieties that are tolerant to both heat and water stress must be identified [25].

4.3. Effects of Soil Amendments on Biological and Economic Yield Attributes of Maize

The use of organic fertilisers instead of inorganic fertilisers is seen as a safe option for protecting the environment while maintaining high yields [16]. The use of poultry manure in crop production is a long-term strategy for diversifying agroecosystems, improving soil health, and increasing crop yield [17]. Due to the complex and dynamic nature of soil nitrogen and organic matter, Clark et al. [36] observed that the benefits of organic amendments may not be visible in the short term.

The significant effect of soil amendment was observed in this study under combined heat and water stress conditions. The GGEbiplot which-won-where view revealed that the three amendments influenced the development of different aspects of grain yield. The MF amendment produced the most cobs and the highest 100-seed weight, but the least grain number and weight, indicating a low ameliorative effect on maize under combined heat and water stress conditions. Its low grain number can be attributed to a low seed set, most likely as a result of pollen failure. Lizaso et al. [29] linked reduced grain number in heat-stressed maize to pollen viability.

The few set seeds in the MF amendment received sufficient assimilates, resulting in improved individual ear weights and a higher 100-seed weight than the PM amendment, which was low in 100-seed weight but high in grain number and weight. This study's observation of compensatory seed weight gain in maize under abiotic stress is consistent with previous reports on compensatory weight gains in maize [15,37,38]. When compared to the MPM and MF amendments, the PM amendment had a greater ameliorative capacity for maize grain attributes under combined heat and water stress conditions.

4.4. Effects of Soil Type on Biological and Economic Yield Attributes of Maize

Crop production requires careful site selection to ensure maximum yields. The prevailing climatic conditions, inherent soil properties, and the interaction of climate and soil properties all play a role in site selection. The ability of soil to support plants and provide nutrients and water is often influenced by soil properties. The rate of nitrogen mineralization and release of other nutrients for maize uptake is influenced by the soil's ability to hold and release water [39]. The significantly higher performance of SCL soil over LS soil in maize grain attributes observed in this study can be attributed to differences in their properties. The LS soil was more acidic and contained more exchangeable acidity and sand, whereas the SCL soil contained more clay, silt, total nitrogen, sodium, magnesium, and calcium.

The 72% grain weight loss in LS soil compared to SCL soil observed in this study was consistent with previous studies that found a range of 2.8–71% grain yield reduction in maize due to acidic soil [40,41]. The soil pH range of 5.5–8.0 promotes plant root development, nutrient availability, and microbial activity [42]. SCL had a soil pH of 5.83, while LS had a pH of 4.98.

Clayey soil retains and releases more nutrients and water for plant use than sandy soil. High silt and clay content in soil has been shown in earlier studies to favour high nitrogen uptake in maize [11–13], which corroborated our report of higher yield from SCL soil with high silt and clay content over LS soil. Rao et al. [43] identified low organic matter, nutrient preservation, and water retention capacities as factors causing low productivity in sandy soils.

4.5. Water Stress, Maize Variety, Soil Amendment, and Soil Type Interaction on the Maize Biological and Economic Yield Attributes

Rising temperatures and drought are expected to worsen in SSA, reducing maize output, the region's most staple food [2,5,7,44]. In SSA, the combined effects of heat and water stress limit maize yield and threaten food security. To increase food security in the region, the response of three drought-tolerant maize varieties to combined heat and water stress under different soil amendments was investigated in this study.

The significant differences observed among the treatment interactions point to environmental influence on maize performance, as intravarietal differences were observed when the immediate growth environment was changed. Intravarietal differences for maize grown under various climatic and edaphic conditions have been reported [29,45,46]. The treatment interactions in this study reacted primarily to the water stress treatments, as shown in Figures 6 and 7. As the level of water stress in the maize plant grew, the grain attributes decreased, except for ZM1523 amended with MPM, where moderate water stress (MS-ZM1-MPM) gave higher performance than non-water stressed plants (NS-ZM1-MPM) in some attributes. This phenomenon was consistent across all treatment interactions. The decrease in yield as water stress increased in this study aligned with earlier reports [26–28,31] on the depressive impact of water stress on maize grain yield.

Grain number has the most discriminatory power among the maize attributes studied, while cob weight is the most representative attribute. Lizaso et al. [29] found that maize grain number, followed by grain weight, was the most responsive yield component to heat stress. The grain number determines how many assimilates can be partitioned to the sink. Under a conducive growth condition, a high grain number will result in more assimilate partitioning to the sink, whereas a low grain number will only allow limited assimilate partitioning to the sink.

The cob number and cob length positions in Figure 8 indicated that all treatment interactions performed similarly on them, implying that they may not be good markers for maize selection under combined heat and water stress conditions. According to Yan et al. [47], testers with short vectors that are close to the biplot origin provide little or no information about the genotype difference and should thus be avoided. Superior genotypes can be selected using testers with a long vector and a short angle to the ATA [48]. The grain number has the longest vector and a short angle to the ATA in this study. Cob weight, grain weight, shelling percentage, and stover dry weight are the other maize attributes ranked based on their vector length and angle to the ATA.

The highest means for the aforementioned maize attributes were found in the best three ranked treatment interactions in this study. The non-water stress treatments with three moderate water-stress treatments (M6, M8, and M9) performed better than the population mean when the treatment interactions were ranked. The PM amendment gave the best ranking to varieties WE5323 and ZM1523, while the MF amendment gave the highest ranking to variety WE3128. Under heat and moderate water stress conditions, the PM amendment performed well for varieties WE5323 and ZM1523, while the MF amendment performed best for variety WE3128. The consistent performance of the maize variety × soil amendment interaction under non-water and moderate water stress conditions suggests that the maize varieties may have special preferences for specific soil amendments.

The inclusion of M6, M8, and M9 among the best performing treatment interactions reflects their ability to mitigate the negative impact of combined heat and water stress conditions on maize. PM or MPM amendments were present in these three treatment interactions. Poultry manure has been shown to improve soil health and fertility in non-stress conditions [16,17] and can improve maize yield in stress conditions, as demonstrated in this study. Plants exposed to higher nitrogen supply had higher photosynthesis capacity and tolerance to photo-oxidative damage than those exposed to low nitrogen supply under environmental stress conditions [49]. Nutrient availability and accessibility promote plant structure integrity and key physiological processes that result in high biomass production [50,51].

5. Conclusions

The differences in yield attributes across the three water stress levels reveal that heat-stressed maize plants react even more to added water stress. As the severity of the water stress increased, the yield attributes decreased. Due to near terminal water stress, there were 79%, 74%, 96%, 97%, 63%, 72%, and 51% reductions in cob length, width, weight, grain weight, grain number, 100-seed weight, shelling percentage, and stover dry weight, respectively. The maize varieties were ranked WE5323 ≥ ZM1523 > WE3128 in terms of average performance and stability. In terms of cob weight, grain weight, and grain number, the PM amendment outperformed the MF and MPM amendments significantly. Except for cob number and stover dry weight, the sandy clay loam soil outperformed the loamy sand soil in all yield attributes studied. The GGEbiplot explained 96.6% of the variation in treatment interactions (PC1 = 90.9%, PC2 = 5.7%). In the treatment interaction ranking, the non-water stress treatments with three moderate water-stress treatments (M6, M8, and M9) performed better than the population mean. Poultry manure improved the yield of varieties WE5323 and ZM1523 under heat and moderate water-stress conditions, indicating that it has ameliorative properties in reducing the negative impact of combined heat and water stress on maize. These results were comparable to non-water stress treatments. WE5323 and ZM1523 are preferred over WE3128 under combined heat and water stress. The findings in this study could improve food security strategies for low-income households living in high-stress environments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14095150/s1, Table S1. Treatment description.

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