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Relationships between Grain Weight and Other Yield Component Traits of Maize Varieties Exposed to Heat-Stress and Combined Heat- and Water-Stress Conditions

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Abstract: It is necessary to identify the appropriate traits that influence yield in a given environment as part of a breeding programme. The objective of this study was to identify the morphological traits that contribute to maize grain weight (GWt) under abiotic stress conditions. Three drought-tolerant maize varieties were grown under no-stress (NHWS), heat-stress (HS), and combined heat- and water-stress (CHWS) conditions. Data from 19 morphological traits were analysed. The correlation results revealed that eight traits consistently produced a significant positive relationship with GWt under the three growth conditions. The path coefficient analysis revealed that in the NHWS, HS, and CHWS conditions, five traits consistently had a positive direct effect on the GWt. Given the magnitude of the positive direct effects, increasing dry biomass yield, harvest index, and grain number in the NHWS; grain number, harvest index, and ear width in the HS; and harvest index, days till silk appearance, leaf chlorophyll content, and grain number in the CHWS will increase GWt. Under various abiotic stress conditions, maize phenotypic expression varied. Therefore, the identified traits that contributed positively to GWt under various stress conditions should be considered when developing a maize improvement programme in a stress-prone environment.

Keywords: abiotic stress; correlation coefficient; path coefficient analysis; principal component analysis; maize breeding; *Zea mays* L.

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1. Introduction

The second United Nations' Sustainable Development Goal (SDG) aims to eliminate hunger and achieve food security [1]. The realisation of a world without hunger is jeopardised by the growing negative impact of climate change on food production [2]. The recent Intergovernmental Panel on Climate Change report [3] predicted increases in the frequency of concurrent heatwaves and drought on a global scale (high confidence). Abiotic stressors that limit maize (*Zea mays* L.) yield include heat stress and drought caused by high temperatures and limited water resources. These stressors can act alone or in concert to reduce crop yield. Depending on the severity and duration of the stress, maize grain yield loss can range from 15% to more than 80% [4–7]. According to Zhao et al. [8], each degree Celsius increase in temperature will result in a 7.4% reduction in maize grain yield. Besides yield losses, the number of suitable areas for maize production is expected to decrease as global temperatures rise and rainfall levels fall [9].

One of the motivations for breeding high-yielding maize varieties for stress-prone environments is the recognition of the threat posed by climate change to food security. Drought tolerance appears to be favoured more than heat tolerance in breeding programmes, given that more drought-tolerant varieties are released than heat-tolerant varieties [10,11]. As a result, exposing available drought-tolerant varieties to heat-stress conditions can shorten the heat-tolerance breeding period and make it easier to choose heat-tolerant varieties from a pool of drought-tolerant varieties.

The grain yield of a maize variety determines its economic value [12]. However, in maize, selection is often based on yield-related traits that contribute to grain yield rather than selection based solely on grain yield [6,13,14]. Grain yield is a quantitative trait that is related to other traits, and the environment has an impact on its expression. As a result, determining the appropriate traits that influence grain yield in a specific environment is critical to the success of any maize-breeding programme. This study tested the hypothesis that morphological traits that contribute to maize grain yield will vary under different abiotic stress conditions. This information is necessary for maize breeding in the context of climate change. It will also contribute to efforts to increase food security and achieve the second SDG. The objective of this study was to identify the morphological traits that influence maize grain weight under heat and combined heat- and water-stress conditions.

2. Results

2.1. Correlation Coefficient Analysis

The correlation coefficient analysis in the NHWS (no heat or water stress) condition revealed that grain weight (GWt) had the highest significant positive relationship with (CWt) ear weight (Table 1). GWt was found to be positively and significantly correlated with grain number (NoG), dry biomass yield (DBY), harvest index (HI), ear length (CL), number of leaves (NoL), leaf area (LA), stem diameter (SD), ear width (CW), leaf chlorophyll content (LCC), 100-seed weight (SWt), and ear number (NoC). It had significantly negative relationships with days till silk appearance (DS), tassel silk interval (TSI), final plant height (FPH), and days till tassel appearance (DT). In the HS (heat stress with no water stress) condition, GWt had a significant and positive relationship with CWt, NoG, SP, HI, DBY, CW, CL, PH, FPH, LA, SD, and NoL. Its relationships with NoC, TSI, SWt, and LCC were insignificant. Under the CHWS (heat stress with water stress) condition, GWt had a significant and positive relationship with CWt, NoG, DBY, HI, SP, CW, CL, NoL, and FPH. It had a nonsignificant relationship with LCC, LA, SD, TSI, DS, NoC, PH, SWt, and DT. Under the NHWS, HS, and CHWS conditions, eight traits, specifically NoL, DBY, HI, CL, CW, SP, NoG, and CWt, consistently had a significant and positive relationship with GWt, while DT and DS had a negative relationship with GWt.

Table 1. The grain weight correlation coefficient with other maize growth and yield traits under various stress conditions.

Traits	NHWS	HS	CHWS
Number of leaves+	0.704 **	0.299 *	0.486 *
Leaf area+	0.600 **	0.360 *	0.103
Leaf chlorophyll content+	0.482 **	0.002	0.225
Stem diameter+	0.586 **	0.324 *	0.045
Plant height+	0.085	0.475 **	−0.03
Final plant height	−0.386 **	0.399 **	0.484 *
Days till tassel appearance	−0.246 *	−0.352 *	−0.003
Days till silk appearance	−0.430 **	−0.314 *	−0.286
Tassel silk interval	−0.389 **	0.134	−0.389
Dry biomass yield	0.881 **	0.631 **	0.842 **
Harvest index	0.877 **	0.650 **	0.829 **
Ear number	0.359 **	−0.263	−0.082
Ear length	0.790 **	0.598 **	0.538 *
Ear width	0.572 **	0.603 **	0.728 **

Shelling percentage	0.577 **	0.729 **	0.747 **
Grain number	0.903 **	0.921 **	0.927 **
100-seed weight	0.396 **	0.134	−0.006
Ear weight	0.993 **	0.954 **	0.981 **
Grain weight	1	1	1

* = significant at the 0.05 probability level, ** = significant at the 0.01 probability level, n = 48 for each stress condition, + = attribute measured at 10 weeks after planting, NHWS = nonstress, HS = heat stress, and CHWS = heat and water stress.

2.2. Principal Component Analysis

A principal component analysis was used to examine the contributions of the 19 growth, floral, and yield traits in explaining variations in maize plants under various stress conditions. The principal component analysis explained 59.37% (PC1 = 42.96%, PC2 = 16.41%) of the variation under the NHWS condition, 55.12% (PC1 = 37.64%, PC2 = 17.48%) under the HS condition, and 57.14% (PC1 = 37.66%, PC2 = 19.48%) under the CHWS condition (Table 2). For the three stress conditions, six traits, specifically NoL, DBY, CL, NoG, GWt, and CWt, had PC1 scores above 0.2.

Additional traits that loaded above 0.2 under the NHWS condition were HI, LA, and SD. Under the HS condition, they were PH, SP, CW, FPH, and LA, while HI, SP, CW, DS, and TSI were the extra traits with above 0.2 loading under the CHWS condition. The PC2 showed that SD, DT, and DS were constantly loaded above 0.2 under the NHWS, HS, and CHWS conditions. The eigenvalues for the PC1 and PC2 were 8.162 and 3.119 for the NHWS, 7.152 and 3.322 for the HS, and 7.155 and 3.702 for CHWS. The remaining eigenvalues for the NHWS, HS, and CHWS were less than two, except for PC3 in CHWS, which was 2.561.

Table 2. Principal component analysis of 19 maize traits under varied stress conditions.

Traits	NHWS		HS		CHWS	
	PC1	PC2	PC1	PC2	PC1	PC2
Number of leaves+	−0.26296	0.12592	0.25912	0.24752	−0.20990	−0.01855
Leaf area+	−0.22538	0.16858	0.20787	0.10417	−0.15709	−0.04957
Leaf chlorophyll content+	−0.18253	0.17493	0.03402	−0.21334	0.09545	0.39792
Stem diameter+	−0.21024	0.24114	0.14280	0.29094	−0.18232	−0.22384
Plant height +	−0.03190	−0.34015	0.27431	0.21769	−0.09640	0.01222
Final plant height	0.15075	0.31159	0.20805	−0.05292	0.02909	0.44050
Days till tassel appearance	0.09076	0.50739	−0.20770	−0.37127	0.12243	0.41252
Days till silk appearance	0.16629	0.43894	−0.18787	−0.33136	0.25971	0.32844
Tassel silk interval	0.15813	−0.06074	0.09129	0.17049	0.21364	−0.08362
Dry biomass yield	−0.31787	0.19681	0.28336	−0.11548	−0.24458	0.34831
Harvest index	−0.29671	−0.22039	0.18048	−0.31517	−0.32894	−0.00055
Ear number	−0.14364	−0.08226	−0.22735	−0.10875	−0.16180	−0.17835
Ear length	−0.27926	0.15452	0.25392	−0.01927	−0.23845	0.07906
Ear width	−0.19985	0.08010	0.22981	−0.09986	−0.29970	−0.08942
Shelling percentage	−0.18469	−0.27057	0.23467	−0.27131	−0.30179	−0.08120
Grain number	−0.30634	0.00985	0.26843	−0.33075	−0.32963	0.12645
100-seed weight	−0.16087	0.04280	0.17726	0.28025	−0.08076	−0.01250
Grain weight	−0.34392	−0.00304	0.32830	−0.20572	−0.32239	0.23356
Ear weight	−0.34372	0.02946	0.33857	−0.17921	−0.31562	0.25466
Eigenvalue	8.162	3.119	7.152	3.322	7.155	3.702
Percentage variation	42.96	16.41	37.64	17.48	37.66	19.48

+ = attribute measured at 10 weeks after planting, NHWS = nonstress, HS = heat stress, and CHWS = heat and water stress, and PC = principal component axis.

2.3. Path Coefficient Analysis

The path coefficient analysis divided the maize trait correlation coefficients into direct effects and indirect effects. The bold figures in a diagonal arrangement represented the direct effects, and the rest are indirect effects. Under the NHWS, HS, and CHWS conditions, FPH, HI, CL, CW, and NoG all had a direct positive effect on the GWt. Additional direct positive effects were observed in TSI, DBY, and SP under the NHWS condition, whereas NoL, LCC, and DS had direct negative effects on GWt (Table 3). More direct positive effects were found in NoL, LCC, TSI, and SP under the HS condition (Table 4), as well as NoL, LCC, DS, and DBY under the CHWS condition (Table 5). The DS and DBY under the HS condition, as well as the TSI and SP under the CHWS condition, had direct negative effects on GWt.

DBY, followed by HI and NoG, had the greatest direct positive effect on GWt under the NHWS condition. DBY was responsible for the highest indirect effect on GWt through NoL (61.3%), LCC (72%), TSI (57.4%), HI (35.8%), CL (55.6%), CW (53%), and NoG (45.9%). Under the HS condition, NoG, HI, and CW produced the highest direct positive effect on GWt. NoG accounted for the highest indirect positive effect on GWt through FPH (42.1%), DS (32.4%), TSI (39%), DBY (39.7%), HI (39.6%), CL (36.7%), CW (36.1%), and SP (40.3%). Under the CHWS condition, the highest direct positive effect on GWt was from HI, followed by DS and LCC. The highest indirect positive effect on GWt was by HI through NoL (79.7%), FPH (46.5%), DS (186%), TSI (74.6%), DBY (50.1%), CL (56.4%), CW (98.9%), SP (117.6%), and NoG (89.3%).

The residuals from the path coefficient analyses revealed that under the NHWS, HS, and CHWS conditions, the selected traits contributed 98.7%, 92.9%, and 99.45%, respectively, to GWt.

Table 3. Direct (bold diagonal) and indirect effects of selected maize growth and yield traits on grain weight under no stress (NHWS) conditions.

	NoL	LCC	FPH	DS	TSI	DBY	HI	CL	CW	SP	NoG	GWt
NoL	**−0.0246**	−0.0052	−0.0056	0.0021	−0.0044	0.4320	0.2318	0.0031	0.0012	0.0061	0.0677	0.704 **
LCC	−0.0102	**−0.0124**	0.0016	0.0002	−0.0014	0.3467	0.1126	0.0032	0.0011	0.0016	0.0386	0.482 **
FPH	0.0057	−0.0008	**0.0242**	−0.0052	0.0012	−0.1065	−0.2500	0.0000	−0.0003	−0.0093	−0.0447	−0.386 **
DS	0.0063	0.0003	0.0151	**−0.0084**	0.0032	−0.1007	−0.2982	−0.0010	−0.0005	−0.0118	−0.0348	−0.430 **
TSI	0.0134	0.0022	0.0036	−0.0033	**0.0081**	−0.2233	−0.1532	−0.0019	−0.0005	−0.0038	−0.0302	−0.389 **
DBY	−0.0194	−0.0078	−0.0047	0.0015	−0.0033	**0.5482**	0.2699	0.0043	0.0021	0.0064	0.0840	0.881 **
HI	−0.0121	−0.0030	−0.0128	0.0053	−0.0026	0.3138	**0.4716**	0.0032	0.0018	0.0209	0.0913	0.877 **
CL	−0.0141	−0.0074	−0.0001	0.0015	−0.0030	0.4395	0.2812	**0.0054**	0.0018	0.0073	0.0783	0.790 **
CW	−0.0074	−0.0034	−0.0020	0.0010	−0.0011	0.3029	0.2173	0.0025	**0.0039**	0.0077	0.0507	0.572 **
SP	−0.0056	−0.0008	−0.0085	0.0037	−0.0012	0.1318	0.3717	0.0015	0.0011	**0.0265**	0.0568	0.577 **
NoG	−0.0149	−0.0043	−0.0097	0.0026	−0.0022	0.4139	0.3869	0.0038	0.0018	0.0135	**0.1113**	0.903 **
Residual												0.0130

NoL = number of leaves, LCC = leaf chlorophyll content, FPH = final plant height, DS = days till silk appearance, TSI = tassel silk interval, DBY = dry biomass yield, HI = harvest index, CL = ear length, CW = ear width, SP = shelling percentage, NoG = grain number, GWt = grain weight, and ** = significant at the 0.01 probability level.

Table 4. Direct (bold diagonal) and indirect effects of selected maize growth and yield traits on grain weight under the heat-stress (HS) condition.

	NoL	LCC	FPH	DS	TSI	DBY	HI	CL	CW	SP	NoG	GWt
NoL	**0.0404**	−0.0302	0.0127	0.1298	0.0088	−0.0289	0.0004	0.0244	0.0327	0.0134	0.0960	0.299 *
LCC	−0.0176	**0.0694**	0.0013	−0.0681	−0.0237	0.0036	0.0160	−0.0086	0.0019	0.0053	0.0227	0.002
FPH	0.0114	0.0021	**0.0447**	0.0314	−0.0005	−0.0265	0.0527	0.0386	0.0687	0.0081	0.1680	0.399 **
DS	−0.0254	0.0229	−0.0068	**−0.2066**	0.0350	0.0093	0.0363	−0.0264	−0.0227	−0.0281	−0.1018	−0.314 *
TSI	0.0023	−0.0109	−0.0002	−0.0477	**0.1518**	−0.0067	−0.0426	0.0250	0.0292	−0.0184	0.0523	0.134
DBY	0.0207	−0.0044	0.0210	0.0342	0.0179	**−0.0565**	0.1475	0.0543	0.0948	0.0506	0.2507	0.631 **
HI	0.0001	0.0036	0.0075	−0.0240	−0.0206	−0.0266	**0.3134**	0.0325	0.0343	0.0720	0.2573	0.650 **
CL	0.0103	−0.0063	0.0181	0.0572	0.0398	−0.0322	0.1070	**0.0953**	0.0700	0.0191	0.2192	0.598 **
CW	0.0062	0.0006	0.0144	0.0220	0.0208	−0.0251	0.0504	0.0313	**0.2131**	0.0513	0.2180	0.603 **
SP	0.0047	0.0032	0.0032	0.0507	−0.0244	−0.0249	0.1970	0.0159	0.0954	**0.1146**	0.2940	0.729 **
NoG	0.0095	0.0039	0.0184	0.0515	0.0195	−0.0347	0.1975	0.0512	0.1138	0.0825	**0.4083**	0.921 **
Residual												0.0715

NoL = number of leaves, LCC = leaf chlorophyll content, FPH = final plant height, DS = days till silk appearance, TSI = tassel silk interval, DBY = dry biomass yield, HI = harvest index, CL = ear length, CW = ear width, SP = shelling percentage, NoG = grain number, GWt = grain weight, * = significant at the 0.05 probability level, and ** = significant at the 0.01 probability level.

Table 5. Direct (bold diagonal) and indirect effects of selected maize growth and yield traits on grain weight under heat- and water-stress (CHWS) conditions.

	NoL	LCC	FPH	DS	TSI	DBY	HI	CL	CW	SP	NoG	GWt
NoL	**0.0045**	−0.0043	0.0047	−0.0973	0.0889	0.0170	0.3873	0.0701	0.0402	−0.0897	0.0648	0.486 *
LCC	−0.0001	**0.2210**	0.0214	0.1460	−0.0066	0.0194	−0.2340	−0.0003	0.0108	0.0397	0.0078	0.225
FPH	0.0004	0.1008	**0.0469**	0.0425	0.0296	0.0196	0.2252	0.0342	0.0278	−0.0786	0.0355	0.484 *
DS	−0.0014	0.1042	0.0064	**0.3097**	−0.2205	−0.0003	−0.5324	−0.0294	−0.0362	0.1547	−0.0406	−0.286
TSI	−0.0013	0.0047	−0.0045	0.2199	**−0.3105**	−0.0190	−0.2897	−0.0465	−0.0217	0.1215	−0.0415	−0.389
DBY	0.0017	0.0981	0.0210	−0.0019	0.1349	**0.0438**	0.4220	0.0842	0.0489	−0.0795	0.0690	0.842 **
HI	0.0018	−0.0522	0.0107	−0.1666	0.0909	0.0187	**0.9899**	0.0514	0.0876	−0.2907	0.0876	0.829 **
CL	0.0019	−0.0003	0.0096	−0.0542	0.0861	0.0220	0.3035	**0.1677**	0.0509	−0.1038	0.0546	0.538 *
CW	0.0015	0.0199	0.0108	−0.0932	0.0560	0.0178	0.7199	0.0709	**0.1204**	−0.2698	0.0734	0.728 **
SP	0.0012	−0.0268	0.0113	−0.1463	0.1152	0.0106	0.8787	0.0532	0.0992	**−0.3274**	0.0782	0.747 **
NoG	0.0028	0.0164	0.0159	−0.1200	0.1230	0.0288	0.8280	0.0873	0.0844	−0.2443	**0.1048**	0.927 **
Residual												0.0055

NoL = number of leaves, LCC = leaf chlorophyll content, FPH = final plant height, DS = days till silk appearance, TSI = tassel silk interval, DBY = dry biomass yield, HI = harvest index, CL = ear length, CW = ear width, SP = shelling percentage, NoG = grain number, GWt = grain weight, * = significant at the 0.05 probability level, and ** = significant at the 0.01 probability level.

3. Discussion

3.1. Correlation Coefficient Analysis

A positive correlation coefficient between GWt and certain traits (NoL, DBY, HI, CL, CW, SP, NoG, and CWt) indicated that an increase in these traits would increase GWt, whereas a negative coefficient indicated that an increase in these traits would decrease GWt, and vice versa. Under heat stress, the correlation coefficients obtained in this study agreed with those reported by Kandel et al. [15], who found that GWt had a positive relationship with CW, CL, NoG, SP, and SWt but a negative relationship with NoC. A similar significant and positive relationship between GWt with PH, NoG, CL, CW, and SP has been reported [16]. The significant relationship observed with GWt under the NHWS condition was also observed for PH and CL [17]; PH, CL, CW, SP, and SWt [14,18]; and TSI and PH [19] but differed in NoG, DT [20], and DS [19].

In this study, 10 of the 19 studied traits changed their relationship pattern with GWt under three separate stress conditions. This suggests that trait selection will differ depending on abiotic stress, as maize phenotypic expression varies depending on the stress environment.

3.2. Principal Component Analysis

In maize studies, the use of principal component analysis in reducing large data sets to only those variables that explain more variations in a population has been reported [12,13,21,22]. Morrison [23] proposed that eigenvalues with similar values may not provide a new explanation for the variations in the data set. As a result, only principal component axes with distinct eigenvalues should be interpreted [24]. Because the first two principal component axes have distinct eigenvalues, they were used in this study. The high loading of GWt, NoG, and CL in PC1 in this study was consistent with previous maize studies [13,21,22], where PC1 was linked to growth and yield traits, whereas PC2 was linked to floral traits.

The fact that the loading pattern on the PC1 differed across the three stress conditions suggests that the same set of traits did not explain the differences in the maize population under the various stress conditions. This disparity could be due to the different ways that the maize plant reacts to stress stimuli. When drought-tolerant and non-drought-tolerant maize varieties were exposed to water stress, Sah et al. [12] found that the first two PCs explained different proportions of the variation. Using principal component analysis, Inyang et al. [13] found a similar result for drought-tolerant maize varieties.

3.3. Path Coefficient Analysis

The contribution of a group of independent variables (yield-related traits) to a dependent variable (yield) can be determined by using path coefficient analysis. A yield-related trait can directly or indirectly contribute to yield through another yield-related trait. These direct and indirect contributions/effects on yield are determined by partitioning the correlation coefficients between these yield-related traits and yield. The magnitude and direction of a yield-related trait's direct and indirect effects on yield guide the plant breeder's decision to select or not select the yield-related trait. Plant breeders have already been using path coefficient analysis to find traits that contribute to maize grain yield [14,16,18,19,25,26].

Under the NHWS condition, the positive direct effect of FPH, CW, CL, NoG, and DBY on GWt in this study was consistent with Shikha et al. [26] on CL, CW, and PH; Begum et al. [17] on PH and CL; Aman et al. [20] on CL and NoG; and Ali et al. [25] on DBY, PH, and CW. Under the HS condition, Kandel et al. [15] found that SP and NoG had a positive direct effect on GWt. The study by Jodage et al. [16] reported a positive direct effect of NoG, CW, and SP on GWt, which corroborates the findings in this study. However, the negative direct effects of PH and CL found in the study [16] differed from the positive direct effects found in this study.

According to Yahaya et al. [18], different traits had the greatest positive direct effect on GWt in different environments. Uba et al. [14] made a similar observation for maize traits exposed to no stress and water stress. These findings are consistent with the findings of this study, which found that different traits had the greatest positive direct effect on GWt under different stress conditions. The magnitude of a trait effect was classified by Lenka and Misra [27] as low (< 0.2), moderate ($\geq 0.2 < 0.3$), and high (≥ 0.3). Based on this classification, the present study determined that improving DBY and HI under the NHWS condition; NoG, HI, and CW under the HS condition; and HI, DS, and LCC under the CHWS condition will improve GWt.

According to genetic and phenotypic studies, maize has heterotic tendencies for stress-related traits [28]. However, creating maize cultivars that are tolerant to heat and drought and are suited to various geographic settings has proven to be a challenge for maize breeders [29]. In order to boost stress resistance and increase yield in a changing environment, it is necessary to modify maize architectures [29].

This study adds to the growing body of evidence that traits influencing grain weight in maize differ under different abiotic stress conditions. As a result, the identified traits that contribute positively to grain weight under various stress conditions should be taken into account when developing a maize improvement programme in a stress-prone environment.

4. Materials and Methods

4.1. Treatments, Experimental Design, and Cultural Practices

A completely randomised design experiment with four replications was carried out at the North-West University Experimental Farm (25°47′24.1″ S, 25°37′17.3″ E), Mafikeng campus, North West province, South Africa. The province is in a semiarid region with one of the most vulnerable climates in Southern Africa [30], which experiences occasional drought and extreme temperature fluctuations [31].

The relationship pattern of maize traits exposed to heat-stress and water-stress conditions was evaluated by using three drought-tolerant maize varieties (WE3128, WE5323, and ZM1523) as test plants. The treatments were as follows:

I. NHWS (no heat or water stress).
II. HS (heat stress with no water stress).
III. CHWS (heat stress with water stress).

The detailed reports on the cultural practices, soil properties, and stress imposition on NHWS, HS, and CHWS treatments were contained in earlier reports [32,33]. A brief recap follows: three maize varieties were grown in two temperature-ranged structures (plastic greenhouse and net shade house). For the duration of the experiment (December 2018 to February 2020), daily morning and midday temperatures in the two growth structures were recorded (see Figure 1). For the first- and second-season plantings, the weekly average temperature ranges in the HS environment were 16–41 °C and 20–44 °C, respectively, while the NHWS environments had ranges of 15–34 °C and 16–33 °C. The net shade house provided a non-heat-stress environment and was used to house the NHWS treatment, which was also well irrigated. The HS and CHWS treatments were kept in a plastic greenhouse, which provided a heat-stress environment. The HS treatment was well irrigated, whereas the CHWS treatment received half the amount of water that was supplied to HS to induce water stress. Water stress was applied 5 weeks after planting (WAP) until harvest.

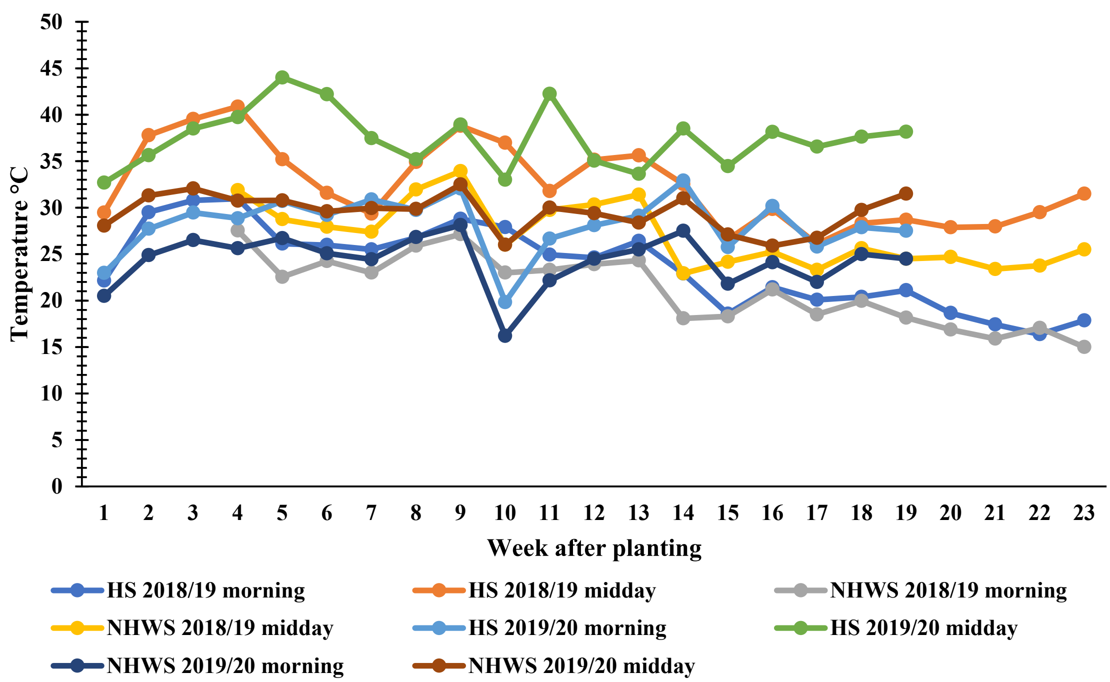

Figure 1. Weekly temperature records for HS and NHWS environments for the two seasons of plantings.

Surface soil (0–20 cm depth) was excavated, air-dried, sieved, and homogenised before being weighed (12 kg) into each plastic planting pot (30 cm top × 28 cm height × 21 cm base) with drainage holes at the base. Three maize seeds were planted per pot, but the seedlings were thinned to one per pot 2 weeks later. No pesticides were used, and the pots were manually weeded. The experiment was conducted during the 2018/2019 and 2019/2020 summer planting seasons.

4.2. Measurement of Plant Traits

Data were gathered from four plants for each treatment. The growth traits were measured at 10 WAP. The number of leaves (NoL) was counted, and the leaf chlorophyll content (LCC) was measured by using a portable chlorophyll content metre (CCM-200plus, Opti-Sciences USA). With a measuring tape, the leaf length (LL) and leaf width (LW) were measured from the leaf base on the maize stalk to the tip and at the widest part, respectively. The leaf area (LA) was calculated by multiplying the product of LL and LW by a constant of 0.75. The plant height (PH) was measured by using a 5 m steel tape placed at the soil surface and read at the tip of the last leaf, while the stem diameter (SD) was measured by using a digital Vernier calliper.

The plants were monitored at the onset of the reproductive phase to determine the number of days till tassel and silk appearances. To calculate the tassel silk interval (TSI), the number of days till silk appearance (DS) was subtracted from the number of days till tassel appearance (DT). The final plant height (FPH) was measured at 20 WAP, and the plants were harvested with sharp secateurs. The harvested ears were removed, counted, and air-dried for 2 weeks in the shade, while the shoots were oven-dried to a constant weight at 65 °C to determine the dry biomass yield (DBY). The ear length (CL) and ear width (CW) were measured by using a measuring tape and a digital Vernier calliper, respectively. Each ear was weighed to determine the ear weight in grams (CWt). Afterwards, the ears were shelled and the grain weight (GWt) determined. The shelling percentage (SP) was calculated as described by [14]:

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

The grains were counted using a Numigral seed counter, and 100 seeds from each plant were weighed to obtain the 100-seed weight (SWt). The harvest index (HI) was calculated as described by [14]:

$$\text{Harvest Index (\%)} = \frac{\text{Grain weight (g)}}{\text{Biological weight (g)}} \times \frac{100}{1} \quad (2)$$

where biological weight is the summation of dry biomass weight and ear weight.

4.3. Data Analysis

The growth and yield traits from the two planting seasons were combined and subjected to Pearson's correlation coefficient and principal component analyses with SPSS Statistics software, version 16.0 (SPSS Inc., Chicago, IL, USA), and GenStat software (VSN Int. Ltd., Hemel Hempstead, UK), respectively. The correlation revealed the relationships between grain weight and the other traits measured. Principal component analysis was used as a data-reduction tool to identify the traits that accounted for the greatest variability in the maize population under the three stress environments. To understand their contribution to grain weight, the top-ranked traits by principal component analysis were subjected to path coefficient analysis as described by Dewey and Lu [34]. The percentages of the traits' direct and indirect effects on GWt were calculated as described by [32]:

$$\text{Direct effect (\%)} = \frac{\text{direct effect of trait A}}{\text{total effect of trait A on the GWt}} \times \frac{100}{1} \quad (3)$$

$$\text{Indirect effect (\%)} = \frac{\text{indirect effect of trait B through trait A}}{\text{total effect of trait B on the GWt}} \times \frac{100}{1} \quad (4)$$

where A and B are random traits.

5. Conclusions

There are varied phenotypic expressions in maize under different abiotic stress conditions. However, increases in eight traits (number of leaves, dry biomass yield, harvest index, ear length, ear width, shelling percentage, number of grains, and ear weight) consistently increased the grain weight under the NHWS, HS, and CHWS conditions. This study observed that five traits (final plant height, harvest index, ear length, ear width, and number of grains) had a positive direct effect on grain weight. Therefore, improvements in dry biomass yield and harvest index under the NHWS condition; the number of grains, harvest index, and ear width under the HS condition; and harvest index, days till silk appearance, and leaf chlorophyll content under the CHWS condition will improve maize grain weight. These identified traits that contributed positively to grain weight under various stress conditions should be considered in the development of a maize improvement programme in a stressful environment.

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