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Assessment of Nitrogen Use Efficiency in Algerian Saharan Maize Populations for Tolerance under Drought and No-Nitrogen Stresses

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Abstract: Increasing drought incidence and infertile soils require the improvement of maize for nitrogen use efficiency (NUE) under drought conditions. The objectives were to assess tolerance and genetic effects of Algerian populations under no-nitrogen and water stress. We evaluated a diallel among six Algerian maize populations under no-nitrogen vs. 120 kg/ha N fertilization and drought vs. control. Variability was significant among populations and their crosses for NUE under drought. Additive genetic effects could be capitalized using the populations BAH and MST, with high grain nitrogen utilization efficiency (NUtE). The most promising crosses were SHH × AOR with no-nitrogen supply under both water regimes for NUtE, AOR × IGS, under water stress for partial factor productivity (PFP), and well-watered conditions with nitrogen supply for protein content; AOR × IZM for agronomic nitrogen use efficiency (AE) under water stress; and AOR × BAH for grain nutrient utilization efficiency (NUtE) under well-watered conditions with nitrogen. These parents could be promising for developing drought-tolerant or/and low nitrogen hybrids to improve these traits. Maximum heterosis could be exploited using those populations and crosses. Reciprocal recurrent selection could be used to take advantage of additive and non-additive gene effects found based on estimations of genetic parameters.

Keywords: Algerian maize; NUE; nitrogen utilization; grain protein; nitrogen deficiency; drought; heterosis; varietal effect

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1. Introduction

Maize (*Zea mays* L.) is one of the world's most widely cultivated crops with an area around 202.72 million hectares, providing food and animal feed as well as being a source of biofuel [1]. Maize is a major staple food crop in sub-Saharan Africa and Latin America, providing more than 30% of the total calories and protein in 11 countries [2,3].

In recent decades, global climate change has brought more and more frequent heat-waves and severe droughts [4]. Climate models predict that the frequency and intensity of drought will intensify in the years ahead in response to anticipated climate change (CC) [5]. Climate change is expected to affect rains and raise average temperatures, threatening the availability of fresh water for agricultural production [6], and it is one of the primary culprits behind the restraint in the increase of cereal crop yields [7]. In most low-rainfall areas of the Middle East, North Africa, and Central Asia, most of the exploitable water is already very scarce, with 80–90% of this water destined for agriculture. Rivers and aquifers are, therefore, operating beyond their sustainable levels [8]. Under these scenarios of (CC) and development, world cereal production is estimated to decrease between 1% and 7%

depending on the general circulation model (GCM) climate scenario [9]. Increasing yields under stressful environments will require novel approaches to be implemented in gene discovery and plant breeding that will significantly increase both production per unit of land area and resource use efficiency [10,11].

Furthermore, the growing population will increase food demand, and more water will be required for crop irrigation [12]. Therefore, environmental changes will become an explicit threat to global food security, especially in Africa [13–16]. In addition, the most affected countries by this impact are those in sub-Saharan Africa [15].

The predicted climate change threatens food security in the coming years in Algeria [17]. It is projected in Algeria by the future horizon of 2030: (i) an increase in temperatures of +0.9 to +1.3 °C and their variability; (ii) intensification of the frequency of heatwaves, and (iii) an accentuation of the variability of precipitations, which will result in an increase in dry and wet episodes by +10% and will be accompanied by a decrease in precipitation of −9 up to −14% [18]. Low precipitation and its uneven distribution in Algeria, along with fast population and agriculture activity increase and, particularly, recent droughts have made water availability one of the country's most pressing challenges [19].

Drought also affects fertilization, particularly nitrogen (N) uptake by the plant, which is a paramount macronutrient for plant growth, development, and production. The high and relatively rapid nutrient requirement is an important characteristic of maize, and its production consumes over one-fifth of all nitrogen produced [20], resulting in marked increases in yield [21]. In addition, as a C4 plant, maize accumulates biomass efficiently under abundant N supply with high photosynthetic efficiency [22,23]. However, in the last 40 years, the amount of synthetic nitrogen (N) applied to crops has risen drastically [24]. Excessive application of nitrogen fertilizer is not only costly but also damaging to the environment, causing for example soil acidification and air and water pollution [25–28]. Since the plants can take only up to 30 to 40% of the applied N, more than 60% of the N added to the soil is lost through a combination of leaching, surface run-off, denitrification, volatilization, and microbial consumption [20,29,30]. Furthermore, production and application of N fertilizers consume huge amounts of energy [31].

In this context, after drought, a major challenge to smallholder farmers in sub-Saharan Africa is low-fertility soils and inability to apply nitrogen fertilizer externally due to the high cost [32–34]. Ribeiro et al. [35] reported also that this occurs because of farmers' low purchasing power for nitrogen fertilizer in developing countries, which results in most maize farming conducted under nitrogen deficiency conditions. Thus, a strategy for maximizing economic return while minimizing environmental impact is improving nitrogen use efficiency (NUE) [20,22,36,37]. It is estimated that a 1% increase in NUE could save $1.1 billion annually [30]. In order to face this challenge, we need crops that are able to efficiently uptake, utilize, and remobilize the nitrogen available to them [38].

The breeding goal for high NUE is to maintain or increase productivity with less N applied [39]. Then, the alternative to increase yield without raising the production cost and minimizing the dependence on agricultural inputs is the development of maize genotypes presenting high NUE under low N level conditions, allowing the development of sustainable agriculture [21,30,31,33,40]. Moreover, compared to inefficient cultivars, a nitrogen-efficient cultivar may produce a higher yield at low N and/or at high N applications. In general, a cultivar that attains higher yields at relatively low N inputs is referred to as an N-efficient genotype [41].

Maize suffers from a wide range of production constraints, the most important being the increasing drought incidence and infertile soils [42,43]. Thus, nitrogen and water, separately or in combination, are two of the most critical factors in maize production worldwide [44,45] underlying poor growth and yield in maize [46]. Nitrogen deficiency can cause several adverse effects on maize growth, development, and final yield [45] by increasing kernel abortion resulting in about 85% of the abortion during the first 20 days after flowering, which reduces final grain number [47,48]. In addition, Gou et al. [49] reported that under water deficits, N supplies can enhance drought resistance of crops by protecting photosynthetic apparatus, activating antioxidant defense systems, and improving osmoregulation. Uptake of nitrogen and NUE may fall due to water stress during the early growth stage. Then, maize drought-tolerant cultivars produced consistently higher yields because they had either high nitrogen uptake or nitrogen utilization efficiency [50]. Conventionally, breeders develop stress-tolerant maize populations, improve such populations through recurrent selection, and extract from the improved populations experimental cultivars and/or inbred lines for hybrid production [51]. However, breeding for low N and drought have common traits indicating a common adaptive mechanism, and thus, developing maize genotypes with tolerance to stresses and with high yield performance across environments will favor the subsistence of farmers in Africa [45].

There are various ways to define nitrogen use efficiency (NUE) [39,52]. At the crop level, NUE is defined as the ratio of grain yield to supplied N fertilizer [53,54] and depends on N uptake from the soil, internal utilization, and the subsequent partitioning and remobilization of N to the grain [36,55]. Nitrogen use efficiency is contributed to by N utilization efficiency and N uptake efficiency [53]. Among the several definitions of NUE is agronomic nitrogen use efficiency (AE), which is the relative yield increase per unit of N applied [56]. It gives an indication of how much productivity improvement was gained via the use of nitrogen fertilizers [57].

Breeding for high NUE and tolerance to low-N stress requires the availability of adequate genetic variability for the target traits [40], which can be found in the maize germplasm that has not been evaluated for NUE [30]. On the other hand, the magnitude of additive and non-additive effects on the trait control is not yet well understood. Considering all these points, a diallel analysis is a potential tool for the identification of desirable parents with information about the magnitude and nature of the genetic effects controlling the trait [58,59]. If the heritability of the trait is moderate–high, a successful recurrent selection program is expected to increase the mean performance of individuals and also maintain the genetic variability within the population to facilitate continuous improvement in advanced cycles of selection [51,60,61].

Little is known about the effects of drought and low N in Algerian maize populations. However, Stephen et al. [62] reported that a large genetic diversity resides in the African maize landraces which could be conserved and exploited for maize improvement. In addition, Saharan maize may be a great donor of alleles of stress tolerance because of its adaptation to biotic and abiotic stress. In this way, there is a high diversity in Algerian maize that may provide new alleles for drought conditions reported by a few authors in their previous phenotypic [63–66] and genetic [67–69] studies using the collection of some maize populations from a subtropical area in the Algerian Sahara. Furthermore, their high genetic divergence was found in the heterotic patterns study of Cherchali et al. [70], who suggested the incorporation of this material in breeding programs. Then, a diallel among six Algerian maize populations under drought and no-nitrogen fertilization was evaluated by Riache et al. [71] to select the most productive genotypes, but they did not study the nitrogen use efficiency.

The objectives of the present study were: (i) to estimate the varietal and heterosis effect of Algerian Saharan maize populations and their crosses for nitrogen use efficiency traits under no-nitrogen fertilization and drought conditions and (ii) to select the most promising populations and crosses for breeding for stress tolerance.

2. Materials and Methods

2.1. Experimental Site and Weather Data

The 2-year field experiment was carried out during 2018 and 2019 at the National Higher Agronomic School (ENSA), in Algiers, Algeria (36°43′16′′ N, 3°09′03′′ E, 36 m altitude, with an annual rainfall of 600 mm).

The meteorological data were as follows (Table 1): minimum temperature varied from 10.6 (April) to 20.3 (July) in 2018 and from 9.6 (April) to 21.2 (July); total rainfall was 189 mm in 2018 and 76 mm in 2019 during the cropping period [72].

Table 1. Means of monthly temperatures and precipitations of the experimental field during the cropping period 2018–2019 in Algiers [72].

	2018				2019			
Months	**P (mm)**	**Min. (°C)**	**Max. (°C)**	**Moy. (°C)**	**P (mm)**	**Min. (°C)**	**Max. (°C)**	**Moy. (°C)**
April	103	10.6	21.9	16.3	47	9.6	21.2	15.4
May	54	12.1	22.7	17.4	19.1	11.4	25.2	18.3
June	32	15.1	28.2	21.7	8.4	16.7	29.4	23.1
July	0	20.3	32.4	26.4	1.5	21.2	34.1	27.7
Total	189	58.1	105.2	81.65	76	58.9	109.9	84.4

P: precipitations; Min.: minimal temperature; Max.: maximal temperature; Moy.: mean temperature.

2.2. Germplasm

The current study used six Algerian maize populations representative of the collection of maize germplasm reported by Djemel et al. [63] (Table 2). The six populations were crossed (15 hybrids) following a diallel mating design without reciprocals in 2013 [64]. These populations were studied by Aci et al. [67] based on genetic distances and geographic origin. Sixty pairs of plants were used to produce 60 crosses for each pair of populations, and for each hybrid, a bulk of all kernels was made [70].

Table 2. Classification of the six maize populations from Algeria used in this diallel matting design based on geographic origin [70].

Population	**Location, Province, Area**
AOR	Aougrout, Adrar, Center
BAH	Bechar, West
IGS	Ain Salah, Tamanrasset, South
IZM	Inzgmir, Adrar, Center
MST	K'sar M'sehel, Timimoune, Adrar, Center
SHH	Sidi Maamar, Saida, North

2.3. Crop Management

2.3.1. Experimental Material and Treatments

The evaluated genotypes in both years were the six parents and their fifteen crosses along with the two synthetic varieties EPS20 (originated from eight Reid inbred lines), EPS21 (originated from eight non-Reid inbred lines), and their respective cross EPS20 × EPS21, as a check of the Reid × non-Reid heterotic pattern. Finally, we used EP17 × EP42, a flint × flint hybrid from Spain, as a check from the European Flint germplasm, in conditions of drought and no-nitrogen fertilization.

Treatments were arranged in a split-split plot design with two main plots representing the water regimes (water stress and well-watered as control) and two subplots that included the two nitrogen treatments 0 kg/ha and 120 kg/ha of nitrogen. Finally, the genotypes were randomized within each subplot, in experimental units consisting of one 6-m row with 0.7 m row spacing. Three repetitions were used for each trial.

2.3.2. Crop Husbandry

Maize seeds were sown manually on 18 May 2018 and 3 May 2019, respectively. Plants were harvested by hand on 2nd and 7th of September in 2018 and 2019, respectively. The sowing density was 70,000 plants/ha with inter-hills spaces of 0.2 m. Weeding was done manually when necessary and was closely monitored to avoid competition.

In each growing season, from sowing to post-flowering, around 600 mm of irrigation water was applied to the maize crop under control conditions and 300 mm under drought.

Every week, a drip irrigation system was used to irrigate the trials, and the exact quantity was removed when the trials received water from rainfall.

For the physico-chemical properties of the soil, five soil samples were collected before sowing at a depth of 30 cm randomly from across the whole field following a diagonal and then mixed. The results of bulked samples analysis revealed that the test site was silty with a low organic matter content (1.53%) which contained 110 ppm of total nitrogen and was moderately poor (20 ppm) in inorganic nitrogen (N min) in both years. The electrical conductivity was 11.54 meq/100 g, total carbon 0.89%, pH-KCl 6.52, and pH-H_2O 7.09.

Plots received a nitrogen supply depending on these results, which estimated the nitrogen fertilizer rate. Consequently, 120 kg of N per ha in the form of urea was hand applied in two splits with 1/3 (40 kg/ha) at the three-leaf growth stage and 2/3 (80 kg/ha) at the six-leaf growth stage.

2.3.3. Data Recording

Grain Sampling and Determination of Total N Concentration

At maturity, five plants from each single-row plot were sampled, cobs manually threshed, and then a bulk of grains was made to prepare the samples for each genotype under each treatment from the plots. These fresh grains were oven-dried at 60 °C for 48 h until a constant mass was obtained, and the dry weights were recorded and used for calculation of the dry matter yield. The yield of corn grain was adjusted to a 14% moisture content as previously measured and published [71]. The kernels were ground and sifted through a 1 mm mesh screen. The total N content of the samples was determined using the micro-Kjeldahl as per the procedures prescribed by Kirk [73].

The equations for calculating the nitrogen parameters were introduced as follows:

$$AE = \frac{Y_f - Y_0}{F} \tag{1}$$

where AE is the agronomic efficiency of the applied nutrient (kg yield increase per kg nutrient applied) and means the contribution of fertilizer N towards yield, compared to a non-fertilized control. F is the amount of (fertilizer) nutrient applied (kg/ha). Y_f is the crop yield with the applied nutrients (kg/ha). Y_0 is the crop yield (kg/ha) in a control treatment with no nitrogen [54].

$$PFP = \frac{Y_f}{F} \tag{2}$$

where PFP is the partial factor productivity (kg harvested product per kg nutrient applied) and means the expression of yield per unit of fertilizer N applied. F is the amount of (fertilizer) nutrient applied (kg/ha). Y_f is the crop yield with the applied nutrients (kg/ha) [54].

$$NUtE = \frac{Y}{GNUpt} \tag{3}$$

Grain nitrogen utilization efficiency was recorded using the formula proposed by Fiez et al. [74] and adapted to grain only, where NUtE represents the N utilization efficiency in kg/kg, Y is the crop yield in the single-row plot, and GNUpt is the grain total nitrogen uptake, calculated as follows:

$$GNUpt = Y \times \frac{GN}{100}$$

where Y represents the crop yield in the single-row plot in kg/ha, and GN is the N concentration in maize grain.

$$PC = GN \times 6.25 \tag{4}$$

where PC represents the protein content in grain in %, and GN is the grain N, indicating the total N concentration in the maize grain; 6.25 is the conversion factor for maize to estimate the protein content [75].

2.3.4. Statistical Analysis

The data over environments and conditions and individual analysis by each condition over the environments were subjected to combined analyses of variance using the PROC MIXED procedure of SAS 9.4 software [76] in order to assess the performance of the maize genotypes under drought and low N.

Combined analyses of variance for each trait were performed according to the split-split plot design, considering the effects of genotypes (populations per se and crosses) and treatments (water regime and nitrogen) as fixed and the effects of environments and repetitions as random.

Fischer's analysis of variance (ANOVA) was computed, and comparison among mean values of maize genotypes under drought and no-nitrogen fertilization was performed using the least significant difference (LSD) at 5% level of probability.

Genetic analysis was performed to estimate varietal effects and heterosis effects (average heterosis, varietal heterosis, and specific heterosis) and their interaction with the environment, using method II of Gardner and Eberhart [77], adapted for a partial diallel, in the diallel crosses for each water $\times$ nitrogen treatment combination, excluding the checks, according to the following model:

$$\text{Yij} = \text{E} + \text{b(e)} + \mu\text{v} + 1/2(\text{vi} + \text{vj}) + \frac{1}{2}\,(\text{evi} + \text{evj}) + \text{k}\,(\text{hij} + \text{ehij}) + \text{Error}$$

where Yij is the average value obtained for each variety (i = j) or for a cross (i $\neq$ j); E is the environment effect; b(e) is the effect of repetition within environment; μv is the mean of n parental genotypes; vi and vj are the varietal effects for i and j, respectively; k = 0 when I = j and k = 1 when i $\neq$ j; hij is the overall heterosis effect; evi is the interaction effect of environment and population i, and ehij is the interaction of environment and heterosis of populations i and j. Error is the experimental error. The varietal effect was calculated as the difference between the mean performance of each parent and the mean of all parents, whereas the heterosis effect was calculated as the difference between the mean of two parental populations and their cross. In addition, hij is the deviation from mean heterosis observed in the cross of populations i and j, partitioned into these components:

$$\text{hij} = \text{h} + \text{hi} + \text{hj} + \text{sij}$$

where h is the average heterosis of all crosses calculated as the difference between the mean of all crosses and the mean of all parents; hi and hj are the parental heterosis contributed by the variety i and j in its crosses measured as a deviation from the average heterosis, and sij is the specific combining ability effect of the cross between ith and jth parents. The DIALLEL-SAS05 program of Zhang et al. [78] was used to analyze all data.

3. Results

3.1. Analyses of Variance and Comparisons of Means

Combined analysis of variance for AE and PFP revealed non-significant differences between environments, and most interactions between the environment and other factors were not significant (Table 3). Differences among the genotypes and the interaction genotypes $\times$ irrigation were significant only for PFP. However, the irrigation effects were significant for both traits.

Combined analysis of variance for grain protein content and grain NUtE revealed significant differences only among genotypes for grain NUtE (Table 4). For grain protein content and grain NUtE, under well-watered conditions, significant differences were recorded only without nitrogen supply among genotypes. The ENV $\times$ genotypes interaction was not significant. Under water stress conditions, differences were not significant among genotypes and the ENV $\times$ genotypes interaction was not significant for both traits with both nitrogen levels (Table 4). For AE and PFP, differences among genotypes were significant for all traits under both water regimes except for AE under well-watered conditions (Table 3). Therefore, differences among genotypes for efficiently using nitrogen and produce proteins, was significant under drought conditions. Furthermore, these results indicate that the genetic diversity for yield per unit of fertilizer applied has significant genotype × environment interaction and is affected by irrigation.

Table 3. Analysis of variance combined across environment of agronomic efficiency (AE) and partial factor productivity (PFP) analyzed in the diallel systems with six Algerian maize populations evaluated along with four checks in two environments in Algiers under both managed drought and nitrogen deficiency.

Source of Variation	df	Combined Across Treatments		Well-Watered		Water Stress	
		AE (kg of Grain/kg of N)	PFP (kg of Grain/kg of N)	AE (kg of Grain/kg of N)	PFP (kg of Grain/kg of N)	AE (kg of Grain/kg of N)	PFP (kg of Grain/kg of N)
Environment (ENV)	1	0	155.63 ns	65.29 ns	411.76 ns	0.27 ns	5.54 ns
Irrigation	1	3504.95 *	40995.91 *				
Irrigation × ENV	1	27.35 ns	251.07 ns				
Genotypes	24	67.97 ns	306.074 ***	136.68 ns	448.25 ***	52.96 *	57.67 **
Genotypes × ENV	24	50.53 ns	29.415ns	122.06 ns	43.57 ns	23.07 ns	17.52 ns
Genotypes × Irrigation	24	102.58 ns	165.52 ***				
Genotypes × Irrigation × ENV	23	85.84 ns	30.10 ns				

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively; ns: not significant.

Under water stress conditions with no nitrogen supply, grain protein content varied from 9.13% to 11.21% (Table 5). AOR × IZM was the cross with the highest grain protein content (11.21%), followed by IZM × BAH (11.15%) and crosses involving IGS with BAH (11.12%), SHH (11.09%), and IZM (10.81%) and AOR × MST, thus, they are not significantly different. Under water stress conditions with nitrogen fertilization, the population MST had the highest grain protein content value (12.38%) and was not significantly different from the cross MST × BAH, while BAH had the lowest value (9.08%). Under well-watered conditions, with both N levels, AOR and EPS20 × EPS21 had the highest grain protein content value among the populations and crosses, respectively. On the other hand, EP17 × EP42 had the lowest grain protein content value for the checks with both N levels. Grain protein content mean values varied from 9.1% (IGS × MST) to 12.09% (AOR × IGS) with nitrogen supply and from 7.89% (SHH × AOR) to 10.22% (SHH × IZM) with no nitrogen fertilizer.

For grain NUtE, under water stress, BAH had the highest values with both N levels while SHH × IZM (with nitrogen fertilizer) and SHH × AOR (with no nitrogen fertilizer) were the crosses with the highest values (70.60 kg/kg and 69.03 kg/kg, respectively). Over eight crosses following SHH × AOR were not significantly different (Table 5). Under well-watered conditions, SHH × AOR (80.87 kg/kg) followed by MST (79.15 kg/kg) and EP17 × EP42 (79.15 kg/kg) had the highest grain NUtE values with no-nitrogen fertilizer. The four crosses following SHH × AOR were not significantly different. AOR × BAH (70.20 kg/kg) was the best cross with nitrogen fertilizer followed by SHH × IZM (69.39 kg/kg) and IGS × MST (68.94 kg/kg), and four other crosses not significantly different. In addition, BAH had the highest grain NUtE value for the parental populations. EPS20 × EPS21 was the worst check under both N levels while EP17 × EP42 was the best. On average, nutrient utilization efficiency increases with irrigation, especially without N fertilization, while protein content increases with water stress and N fertilization as a low effect; however, there is genotypic diversity for these responses.

Table 4. Analysis of variance combined across environment of grain protein content (PC) and nutrient utilization efficiency (NUtE) analyzed in the diallel systems with six Algerian maize populations evaluated along with four checks in two environments in Algiers under both managed drought and nitrogen deficiency.

Source of Variation	df	Combined Across Treatments		Well-Watered				Water Stress			
				With Nitrogen		Without Nitrogen		With Nitrogen		Without Nitrogen	
		PC (%)	NUtE (kg/kg)	PC (%)	NUtE (kg/kg)	PC (%)	NUtE (kg/kg)	PC (%)	NUtE (kg/kg)	PC (%)	NUtE (kg/kg)
Environment (ENV)	1	53.21 ns	2429.37 ns	34.305 ns	1430.84 ns	34.02 ns	1998.19 ns	34.59 ns	1303.46 ns	5.43 ns	243.84 ns
Irrigation (Ir)	1	84.06 ns	3652.69 ns								
Irrigation × ENV	1	15.55 ns	885.54 ns								
Nitrogen (N)	1	18.41 ns	612.60 ns								
Nitrogen × ENV	1	18.31 ns	569.83 ns								
Irrigation × Nitrogen	1	12.24 ns	713.32 ns								
Genotypes (G)	24	2.33 ns	85.14 *	2.432 ns	83.29 ns	1.78 *	109.31 *	2.61 ns	101.63 ns	1.082 ns	38.48 ns
G × ENV	24	1.37 ns	39.78 ns	1.487 ns	53.61 ns	0.74 ns	45.27 ns	1.80 ns	59.13 ns	1.57 ns	58.61 ns
G × N	24	2.25 ns	111.59 ns								
G × Ir	24	2.09 ns	87.28 ns								
G × Ir × N	24	1.14 ns	46.81 ns								
G × N × ENV	24	1.54ns	62.20 ns								
G × Ir × ENV	24	1.46ns	67.14 ns								
G × Ir × N × ENV	22	1.27ns	50.80 ns								

* Significant at the 0.05 probability level; ns: not significant.

Table 5. Means [a] of grain protein content (PC) and nutrient utilization efficiency (NUtE) analyzed in the diallel systems with six Algerian maize populations evaluated along with four checks in two environments in Algiers under drought and nitrogen deficiency.

	NUtE (kg/kg)				PC (%)			
	Water Stress		Well Water		Water Stress		Well Water	
Populations	Without N	With N	Without N	With N [c]	Without N	With N	Without N	With N
Algerian populations								
AOR	60.41 ab	53.86 fg	63.45 gh	59.65 bcd	10.53 ab	11.98 ab	10.04 ab	10.79 abc
BAH	64.56 ab	69.51 ab	75.3 abcde	65.86 abc	9.71 ab	9.08 g	8.42 efgh	9.61 bcd
IGS	57.12 b	66.09 abcde	65.89 efgh	65.34 abc	10.96 a	10.06 cdefg	9.54 abcde	9.74 bcd
IZM	59.99 ab	56.68 cdefg	64.86 fgh	64.28 abcd	10.53 ab	10.93 abcde	9.84 abc	9.73 bcd
MST	61.81 ab	51.26 g	79.15 ab	60.3 abcd	10.62 ab	12.38 a	8.15 fgh	10.52 abcd
SHH	59.63 b	62.26 abcdef	73.62 abcdef	61.77 abcd	10.51 ab	10.31 cdefg	8.58 defgh	10.23 abcd
Population crosses								
AOR × BAH	63.73 ab	59.26 bcdefg	69.74 bcdefgh	70.2 ab	9.87 ab	10.6 bcdefg	9.04 abcdefgh	8.96 cd
AOR × IGS	61.11 ab	64.41 abcde	68.07 defgh	52.57 d	10.25 ab	9.88 defg	9.51 abcde	12.09 a
AOR × IZM	55.9 b	58.71 cdefg	66.09 efgh	64.42 abcd	11.21 a	10.76 abcdef	9.47 abcde	9.92 bcd
AOR × MST	58.28 b	60.9 abcdefg	63.94 gh	62.81 abcd	10.76 a	10.52 bcdefg	9.96 ab	10.15 abcd
IGS × BAH	58.51 b	64.36 abcdef	66.78 efgh	59.83 bcd	11.12 a	10.12 cdefg	9.44 abcde	10.61 abcd
IGS × MST	62.46 ab	60.05 bcdefg	70.39 bcdefgh	68.94 abc	10.08 ab	10.44 bcdefg	8.97 bcdefgh	9.1 cd
IZM × BAH	56.71 b	55.18 efg	70.23 bcdefgh	67.78 abc	11.15 a	11.36 abcd	8.99 abcdefgh	9.53 bcd
IZM × IGS	58.41 b	56.2 efg	68.51 cdefgh	66.43 abc	10.81 a	11.15 abcde	9.17 abcdefg	9.45 bcd
IZM × MST	62.8 ab	63.57 abcdef	64.21 fgh	67.41 abc	10.28 ab	10.16 cdefg	9.98 ab	9.39 bcd
MST × BAH	63.72 ab	56.28 efg	68.08 defgh	63.29 abcd	9.89 ab	11.57 abc	9.19 abcdefg	10.19 abcd
SHH × AOR	69.03 a	56.98 efg	80.87 a	63.17 abcd	9.13 b	11.05 abcde	7.89 h	9.99 bcd
SHH × BAH	60.03 ab	55.99 defg	71.6 abcdefgh	60.04 abcd	10.59 ab	11.05 abcde	8.86 bcdefgh	10.55 abcd
SHH × IGS	56.69 b	68.5 abc	68.31 cdefgh	68.76 abc	11.09 a	9.5 efg	9.16 abcdefg	9.2 cd
SHH × IZM	63.98 ab	70.6 a	61.99 h	69.39 abc	9.81 ab	9.11 fg	10.22 a	9.23 cd
SHH × MST	60.32 ab	67.63 abcd	64.47 fgh	61.89 abcd	10.38 ab	9.56 efg	9.74 abcd	10.32 abcd

Table 5. *Cont.*

	NUtE (kg/kg)				PC (%)			
	Water Stress		Well Water		Water Stress		Well Water	
Populations	**Without N**	**With N**	**Without N**	**With N** [c]	**Without N**	**With N**	**Without N**	**With N**
				Checks				
EPS20	-	60.06 abcdefg	72.81 abcdefg	64.06 abcd	-	10.36 bcdefg	8.62 cdefgh	9.95 bcd
EPS20 × EPS21	65.08 ab	59.65 bcdefg	67.29 efgh	57.34 cd	9.79 ab	10.56 bcdefg	9.39 abcdef	11.38 ab
EPS21	-	61.69 abcdefg	77.51 abcd	69.48 abc	-	10.31 bcdefg	8.07 gh	9.18 cd
EP17 × EP42	61.57 ab	-	79.06 abc	72.2 a	10.19 ab	-	7.93 gh	8.72 d
Means	60.70	60.82	69.69	64.29	10.41	10.53	9.13	9.94
$LSD_{(0.05)}$	10.82	15.31	12.78	13.23	1.79	2.36	1.64	2.18

[a] For each trait, means followed by the same letter in the row are not significantly different; [c] Nitrogen.

General means of partial factor productivity (PFP) varied from 7.35 kg/kg under water stress conditions to 31.04 kg/kg under well-watered conditions (Table 6). The reduction of PFP caused by drought was variable across genotypes, being more drastic for the flint hybrid EP17 × EP42 and milder for AOR × IZM, followed by IGS × BAH, AOR × IGS, and the Reid check EPS20. Under water stress conditions, AOR × IGS (14.11 kg/kg) followed by AOR × IZM (11.53 kg/kg) had the highest PFP values. AOR (8.68 kg/kg) had the highest PFP value, while IZM (3.61 kg/kg) had the lowest value, which was not significantly different from the values of the checks. Under well-watered conditions, EP17 × EP42 (49.52 kg/kg) followed by SHH × IGS (42.41 kg/kg) and AOR × IGS (40.77 kg/kg) had the highest PFP values, while the lowest PFP value was for EP2S0. BAH (29.53 kg/kg) and IGS (29.23 kg/kg) had the highest PFP value, and they were not significantly different.

Table 6. Means [a] of agronomic efficiency (AE) and partial factor productivity (PFP) analyzed in the diallel systems with six Algerian maize populations evaluated along with four checks in two environments in Algiers under drought and nitrogen deficiency.

	AE (kg of Grain/kg of N)		PFP (kg of Grain/kg of N)	
Populations	**Water Stress**	**Well Water**	**Water Stress**	**Well Water**
		Algerian populations		
AOR	4.36 abc	9.81 bcdef	8.68 bcdef	26.32 ghijk
BAH	2.05 abc	8.25 bcdef	8.67 bcdef	29.53 efghij
IGS	−0.37 bcd	3.38 cdef	5.22 efg	29.23 efghij
IZM	−0.62 bcd	9.25 bcdef	3.61 fg	23.42 ijk
MST	−0.14 abcd	1.49 def	3.9 fg	18.68 k
SHH	0.38 abcd	0.74 ef	5.29 defg	22.54 jk
		Population crosses		
AOR × BAH	0.68 abcd	8.36 bcdef	9.33 abcde	31.28 defghi
AOR × IGS	6.18 a	8.98 bcdef	14.11 a	40.77 bc
AOR × IZM	5.64 ab	3.48 cdef	11.53 ab	31.67 defgh
AOR × MST	−0.06 abcd	6.03 bcdef	5.33 defg	31.75 defgh
IGS × BAH	5.34 ab	12.78 abc	12.26 ab	35.24 bcdef
IGS × MST	2.07 abc	8.02 bcdef	8.34 bcdef	33.8 cdefg
IZM × BAH	−1.95 cd	14.94 ab	6.39 cdefg	38.51 bcd
IZM × IGS	−0.02 abcd	8.92 bcdef	6.6 cdefg	35.2 bcdef
IZM × MST	1.09 abcd	2.36 def	7.88 bcdef	28.7 fghij
MST × BAH	2.58 abc	4.87 bcdef	8.09 bcdef	25.73 hijk
SHH × AOR	−4.8 de	7.6 bcdef	6.08 cdefg	33.42 cdefgh
SHH × BAH	1.76 abc	11.36 abcd	9.5 abcde	36.85 bcde
SHH × IGS	2.94 abc	11.25 abcd	10.23 abcd	42.41 ab
SHH × IZM	1.07 abcd	9.31 bcdef	10.37 abc	35.81 bcdef
SHH × MST	4.43 abc	10.35 abcde	10.34 abc	34.47 cdef
		Checks		
EPS20	-	−0.24 f	2.08 g	5.85 l
EPS20 × EPS21	1.2 abcd	13.34 abc	5.45 cdefg	32.69 defgh
EPS21	1.9 abcd	13.43 abc	2.35 g	22.52 jk
EP17 × EP42	−10.92 e	20.95 a	2.00 g	49.52 a
Means	1.03	8.36	7.35	31.04
$LSD_{(0.05)}$	7.06	12.12	6.01	8.10

[a] For each trait, means followed by the same letter in the row are not significantly different.

For AE, general means decreased under water stress (Table 6). The reduction of AE caused by drought followed similar patterns as for PFP, being more drastic for EP17 × EP42; on the other side, AE was negative for AOR × IZM because the yield was lower with nitrogen fertilization than without it. Other genotypes with mild effect of drought on AE were AOR × IGS, MST × BAH, IZM × MST, SHH × MST, and IGS × BAH. AOR was the population with the highest AE values under both water regimes. Under water stress conditions, AOR × IGS (6.18 kg/kg) followed by AOR × IZM (5.64 kg/kg) and IGS × BAH (5.34 kg/kg) were the crosses with the highest AE. EP17 × EP42 was the worst check under water stress (−10.92 kg/kg) and the best under well-watered conditions (20.95 kg/kg). The negative values were because yields with nitrogen fertilizer were lower than those with no-nitrogen fertilizer. The highest AE values for the crosses under well-watered conditions were found for IZM × BAH followed by IGS × BAH. Therefore, the effects of fertilization on productivity were variable among genotypes and were significantly affected by irrigation, some Algerian populations being particularly promising as sources of stress tolerance.

3.2. Varietal and Heterosis Effects among Algerian Maize Populations

Analysis of diallel crosses was made separately for each treatment (Tables 7 and 8). Combined analyses over environments for grain protein content (PC) and grain NUtE revealed significant differences among environments under all the treatments for the two traits (Table 7). Entries were significantly different for both traits under water stress with nitrogen supply and under well-watered conditions with no-nitrogen supply. Under well-watered conditions, specific heterosis was significant for PC and grain NUtE with nitrogen supply. With no-nitrogen fertilizer, variety heterosis was significant for PC, and average heterosis was significant for grain NUtE. Under water stress, variety heterosis × ENV interaction was significant for both traits with nitrogen supply. In the absence of nitrogen supply, specific heterosis was significant for PC and variety × ENV for grain NUtE.

Table 7. Mean squares for grain protein content (PC) and nutrient utilization efficiency (NUtE) *from analysis II of* Gardner and Eberhart [77] of the diallel made with six Algerian maize populations evaluated along with four checks in two years in Algiers under drought and nitrogen deficiency.

		Well-Watered			
Sources of Variation	**df**	**With Nitrogen**		**Without Nitrogen**	
		PC (%)	**NUtE (kg/kg)**	**PC (%)**	**NUtE (kg/kg)**
Environment (ENV)	1	35.95 ***	1456.00 ***	33.54 ***	1952.49 ***
Rep (ENV)	2	3.2	96.28	6.5 **	464.66 ***
Entry	20	2.09	72.05	1.6 *	101.33 *
ENV × Entry	20	1.34	48.18	0.75	46.41
Variety	5	1.70	53.26	1.84	99.47
Heterosis	15	2.22	78.32	1.52	101.95
Average heterosis	1	0.63	43.60	0.77	79.92 *
Variety heterosis	5	0.77	34.06	1.83 *	134.06
Specific heterosis	9	3.21 **	106.76 *	1.43	86.56
Variety × ENV	5	0.78	24.76	0.54	33.32
Heterosis × ENV	15	1.52	55.99	0.83	50.77
Average heterosis × ENV	1	2.92	108.16	0.15	0.26
Variety heterosis × ENV	5	3.01	109.81	0.31	45.37
Specific heterosis × ENV	9	0.54	20.29	1.18	59.38
Error					
Df		40	40	40	40
MS		1.81	64.75	0.82	47.03

Table 7. *Cont.*

Sources of Variation	df	Water Stress			
		With Nitrogen		Without Nitrogen	
		PC (%)	NUtE (kg/kg)	PC (%)	NUtE (kg/kg)
Environment (ENV)	1	36.13 ***	1343.12 ***	5.36 *	231.70 *
Rep (ENV)	2	24.03 ***	1222.67 ***	7.99 **	304.38 **
Entry	20	3.08 *	118.78 *	1.2	41.69
ENV × ENTRY	20	1.89	61.26	1.67	61.08
Variety	5	3.68	136.09	0.93	35.49
Heterosis	15	2.82	107.29	1.29	43.76
Average heterosis	1	2.54	43.97	0.04	0.62
Variety heterosis	5	4.56	155.09	0.87	19.51
Specific heterosis	9	1.89	89.00	1.67 *	62.03
Variety × ENV	5	1.07	40.50	2.75	94.54 *
Heterosis × ENV	15	2.4	84.25	1.31	49.92
Average heterosis × ENV	1	1.36	29.66	3.56	90.14
Variety heterosis × ENV	5	5.44 **	181.88 *	2.27	88.85
Specific heterosis × ENV	9	0.82	37.09	0.52	23.83
Error					
Df		38	37	40	40
MS		1.37	55.10	1.24	42.15

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

Table 8. Mean squares for agronomic efficiency (AE) and partial factor productivity (PFP) from analysis II of Gardner and Eberhart [77] of the diallel made with six Algerian maize populations evaluated along with four checks in two years in Algiers under drought and nitrogen deficiency.

Sources of Variation	df	Water Stress		Well-Watered	
		AE (kg of Grain/kg of N)	PFP (kg of Grain/kg of N)	AE (kg of Grain/kg of N)	PFP (kg of Grain/kg of N)
Environment (ENV)	1	0	17.13	8.18	268.14 *
Rep (ENV)	4	276.35 ***	330.11 ***	322.74 **	54.68
Entry	20	42.64	44.25 **	86.14	219.86 ***
ENV × ENTRY	20	22.34	16.18	83.28	33.13
Variety	5	14.82	27.47 *	89.32	234.96 *
Heterosis	15	50.88	47.73 *	85.09	214.83 ***
Average heterosis	1	11.99	229.58	232.24	2281.66 *
Variety heterosis	5	28.82	17.06	130.78	80.96
Specific heterosis	9	67.51	44.4	43.18	59.55
Variety × ENV	5	8.22	4.66	90.79	29.09
Heterosis ×ENV	15	27.17	21.13	85.35	34.48
Average heterosis × ENV	1	7.75	20.84	103.47	2.03
Variety heterosis × ENV	5	10.67	11.43	73.82	30.21
Specific heterosis × ENV	9	38.44	26.45	89.64	40.45
Error					
Df		78	78	79	80
MS		33.29	19.92	76.62	40.36

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

Combined analyses over environments for AE and PFP revealed significant differences among environments only for PFP under well-watered conditions (Table 8). The effect of entries, variety, and heterosis were significantly different only for PFP under both water regimes. Finally, average heterosis was significant for PFP under well-watered conditions.

Average heterosis was significant and positive only for PFP under both water regimes, indicating the existence of heterosis in this set of diallel crosses (Table 9). Furthermore, drought reduced heterosis for PFP, being one third of the heterosis found under well-watered conditions. Similarly, for AE, the average heterosis under drought conditions was about one third of that under well-watered conditions. However, the other genetic parameters, namely, varietal effect and varietal and specific heterosis, did not follow a consistent trend, as the values under drought conditions were lower or higher than under well-watered conditions, depending on the genotype. Therefore, heterosis and its components were more important than variety and environmental effects, indicating that dominance was more important than additive genetic effects.

Table 9. Genetic parameters for agronomic efficiency (AE) and partial factor productivity (PFP) from the analyses of [61,77] (varietal effect, varietal heterosis, specific heterosis, and average heterosis) for two traits in the diallel made among six Algerian maize populations evaluated in two years in Algiers under both managed drought and nitrogen deficiency.

	AE (kg of Grain/kg of N)		**PFP (kg of Grain/kg of N)**	
Populations	**Water Stress**	**Well-Watered**	**Water Stress**	**Well-Watered**
		Varietal effect		
AOR	3.26	4.32	2.65	1.37
BAH	0.95	2.77	2.63	4.58 *
IGS	−1.47	−2.11	−0.81	4.28
IZM	−1.02	3.76	−1.71	−1.54
MST	−1.01	−4.00	−2.01	−6.27 *
SHH	−0.72	−4.75	−0.74	−2.42
		Varietal heterosis		
AOR	−1.96	−4.45	−1.09 **	−1.43
BAH	−0.62	0.79	−1.28	−3.35 *
IGS	2.62	2.92	1.92	1.75
IZM	−0.28	−2.75	0.19	0.28
MST	0.79	−0.71	−0.37	−1.22
SHH	−0.54	4.22	0.64	3.98 *
		Specific heterosis		
AOR × BAH	−0.64	−1.15	−0.02	−1.29
AOR × IGS	2.84	0.91	3.27 *	3.25
AOR × IZM	4.97 *	−1.86	2.88	−1.47
AOR × MST	−1.80	2.54	−2.63	2.48
IGS × BAH	1.80	0.25	1.62	−1.95
IGS × MST	−1.89	0.37	−0.9	−0.11
IZM × BAH	2.81	−5.14	2.06	−5.70 **
IZM × IGS	−2.91	−0.57	−3.34 *	−2.56
IZM × MST	−0.20	−2.55	0.83	−0.82
MST × BAH	0.65	−3.08	0.34	−3.22
SHH × AOR	−5.36 **	−0.45	−3.51 *	−2.98
SHH × BAH	1.00	−1.16	0.12	0.76
SHH × IGS	0.16	−0.96	−0.65	1.38

Table 9. *Cont.*

	AE (kg of Grain/kg of N)		PFP (kg of Grain/kg of N)	
Populations	**Water Stress**	**Well-Watered**	**Water Stress**	**Well-Watered**
SHH × IZM	0.96	−0.16	1.68	−0.84
SHH × MST	3.25	2.73	2.36	1.68
Average heterosis	0.70	3.01	3.06 **	9.42 ***

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

For AE, under water stress, significant and positive specific heterosis (4.97 kg/kg) was found in AOR × IZM and negative (−5.36 kg/kg) in SHH × AOR. None of the populations had significant varietal effects or varietal heterosis for agronomic efficiency.

For PFP, under water stress, specific heterosis was significant and positive (3.27 kg/kg) for AOR × IGS and negative for IZM × IGS (−3.34 kg/kg) and SHH × AOR (−3.51 kg/kg). Varietal heterosis was significant and negative (−1.09 kg/kg) for AOR. Under well-watered conditions, a significant and positive varietal effect (4.58 kg/kg) was found in BAH and negative (−6.27 kg/kg) for MST. Furthermore, varietal heterosis was significant and positive (3.98 kg/kg) for SHH and negative (−3.35 kg/kg) for BAH. Specific heterosis was significant and negative (−5.70 kg/kg) for IZM × BAH.

Average heterosis was not significant for grain protein content and grain NUtE (Table 10). For grain protein content, under water stress, BAH had a significant and negative varietal effect (−1.75%), while MST had a positive value (1.55%), with nitrogen fertilizer. BAH recorded a significant and positive (1.44%) varietal heterosis. Under well-watered conditions, with no-nitrogen fertilizer, varietal heterosis was significant and positive (0.80%) for MST and specific heterosis was significant and negative (−1.09%) for SHH × AOR. Under a well-watered regime with nitrogen fertilizer, significant and positive specific heterosis for AOR × IGS (1.57%) was observed, whilst AOR × BAH (−1.41%) had a negative value.

Table 10. Genetic parameters for grain protein content (PC) and nutrient utilization efficiency (NUtE) from the analyses of Gardner and Eberhart [61] (1966) (varietal effect, heterosis effect, specific heterosis, and average heterosis) for two traits in the diallel made among six Algerian maize populations evaluated in two years in Algiers under both managed drought and nitrogen deficiency.

	PC (%)				NUtE (kg/kg)			
	Water Stress		**Well-Watered**		**Water Stress**		**Well-Watered**	
Populations	**Without N** [b]	**With N**	**Without N**	**With N**	**Without N**	**With N**	**Without N**	**With N**
				Varietal effect				
AOR	0.05	1.15	0.94	0.68	−0.18	−5.88	−6.93	−3.22
BAH	−0.77	−1.75 *	−0.67	−0.49	3.98	9.78 *	4.92	2.99
IGS	0.49	−0.53	0.45	−0.36	−3.46	4.77	−4.49	2.47
IZM	0.05	0.1	0.75	−0.37	−0.60	−2.72	−5.52	1.42
MST	0.14	1.55 *	−0.94	0.42	1.22	−8.48	8.77 *	−2.56
SHH	0.03	−0.52	−0.52	0.12	−0.96	2.53	3.24	−1.10
				Varietal heterosis				
AOR	−0.25	−0.42	−0.64	0.05	1.13	1.25	5.37	−0.68
BAH	0.50	1.44 *	0.09	0.32	−2.29	−8.27 *	−1.13	−1.79
IGS	0.06	−0.01	−0.29	0.40	0.05	−0.76	2.48	−2.68
IZM	0.25	0.04	−0.05	−0.32	−1.23	0.67	0.24	2.57
MST	−0.26	−0.76	0.80 *	−0.31	0.31	4.59	−6.89 *	1.79

Table 10. *Cont.*

	PC (%)				NUtE (kg/kg)			
	Water Stress		Well-Watered		Water Stress		Well-Watered	
Populations	**Without N** [b]	**With N**	**Without N**	**With N**	**Without N**	**With N**	**Without N**	**With N**
SHH	−0.30	−0.29	0.09	−0.13	2.02	2.51	−0.08	0.79
Specific heterosis								
AOR × BAH	−0.45	−0.55	0.15	−1.41 *	2.21	2.92	−1.71	8.31 *
AOR × IGS	−0.25	−0.44	0.44	1.57 **	0.97	3.07	−2.3	−8.16 *
AOR × IZM	0.73	0.08	0.01	0.13	−4.4	−0.31	−1.52	−1.04
AOR × MST	0.75	−0.09	0.49	−0.05	−4.46	0.83	−3.68	0.13
IGS × BAH	0.27	−0.6	0.46	0.40	−0.29	4.71	−3.02	−2.89
IGS × MST	−0.46	0.26	−0.6	−0.93	2.44	−3.33	4.43	5.41
IZM × BAH	−0.32	−0.27	0.39	−0.06	2.25	2.16	−3.19	−0.33
IZM × IGS	−0.20	0.90	−0.39	−0.17	0.83	−6.14	2.56	0.13
IZM × MST	−0.24	−0.38	0.02	0.09	2.62	2.50	1.01	−0.84
MST × BAH	−0.47	0.56	−0.19	0.31	2.32	−2.09	1.03	−1.39
SHH × AOR	−0.78	1.01	−1.09 *	−0.24	5.67 *	−6.51	9.21 *	0.76
SHH × BAH	0.33	0.32	−0.03	0.64	−1.99	−3.38	0.51	−4.36
SHH × IGS	0.65	−0.12	0.09	−0.87	−3.95	1.69	−1.68	5.51
SHH × IZM	−0.61	−0.87	0.75	−0.11	3.19	6.11	−5.25	1.41
SHH × MST	0.42	−0.34	0.27	0.58	−2.92	2.09	−2.79	−3.32
Average heterosis	−0.05	−0.39	0.21	−0.19	0.19	1.67	−2.16	1.59

*, ** Significant at the 0.05 or 0.01 probability levels respectively. [b] N = Nitrogen.

For grain NUtE, under water stress conditions, SHH × AOR exhibited significant and positive specific heterosis (5.67 kg/kg) with no-nitrogen fertilizer. With nitrogen supply, BAH showed a significant and positive varietal effect (9.78 kg/kg) and significant and negative varietal heterosis (−8.27 kg/kg). Under well-watered conditions, with no-nitrogen fertilizer, a significant and positive value of varietal effect (8.77 kg/kg) was observed for MST and of specific heterosis (9.21 kg/kg) for SHH × AOR, whilst MST exhibited significant and negative varietal heterosis (−6.89 kg/kg). Under the same water regime, significant specific heterosis was found with a negative value (−8.16 kg/kg) for AOR × IGS and positive value (8.31 kg/kg) for AOR × BAH. Therefore, some Algerian populations have promising varietal and heterosis effects for grain protein content and nutrient utilization efficiency, and some crosses were valuable for their specific heterosis effects, mainly with fertilization, and they varied with irrigation.

4. Discussion

The significant variation observed among genotypes for most traits revealed the existence of adequate genetic variability for nitrogen use efficiency (NUE) and protein content among Algerian maize populations per se and their crosses under drought and low nitrogen conditions. The potential for genetic improvement in nitrogen use efficiency depends on the magnitude and nature of differences among varieties as stated by previous researchers [79]. Identification of sources of stress tolerance are the basic task for releasing stress-tolerant lines and their utilization in the development of productive hybrids is a sustainable means of developing climate-resilient maize varieties, as previously reported [80]. In accordance with our results, the Algerian maize populations per se and their crosses had a large amount of variability in the studies of Cherchali et al. [70] and Riache et al. [71]. Naggar et al. [81] reported that such high variability suggested that the germplasm was adapted to a wide range of environmental conditions. As reported by Abu et al. [82], the wide genetic variability observed suggested that the inbred lines could be important sources of beneficial alleles for low nitrogen breeding programs in sub-Saharan Africa. However, in order to release inbred lines, sources of tolerance have to be identified among adapted populations, and Algerian maize has a wide adaptability to temperate regions and a high degree of genetic diversity and could provide valuable alleles for maize improvement in temperate environments [63,67]. In addition, the magnitude and type of genetic variability are of prime importance to breeders in determining whether or not to improve a breeding population and the most efficient method [61]. The amount of genetic variability determines the limits of selection for improvement, while the type of variability helps the breeder to determine the most appropriate breeding method to use for the genetic improvement of a population [61]. However, diversity exploitation in maize hybrid breeding allows breeders to develop cultivars with high heterosis, specific, and/or general adaptation to prevailing biotic and abiotic conditions [83].

Genetic diversity provides the capacity for plants to meet changing environments. It is fundamentally important in crop improvement [84]. As Tefera [85] reported, genetic diversity is the foundation for the sustainable development of new varieties for present and future challenges which arise due to the various biotic and abiotic stresses. The Mediterranean region, especially the Middle East and North Africa, ran out of renewable freshwater decades ago. The region is characterized by an extremely variable climate and considered as one of the driest agricultural regions on Earth, containing only 1% of the world's freshwater resources [86].

Moreover, there is huge yet unexploited genetic diversity in maize landraces as a product of thousands of years of evolution under domestication and hybridization [87]. Landraces adapted to local growth conditions could play a significant role in this process [88] and even the smallest participation of local germplasm can have a great impact on the final result [89]. Landraces are a potential source of original traits and new variability [90] desirable to be used in plant breeding programs. There is no doubt that the landraces are adapted to a specific environment and region [91]. Furthermore, the main reason to use landraces is to bring novel favorable alleles to a breeding population [92]. The local landraces are rich in diverse genetic materials and are a good source of important genes such as resistance to biotic and abiotic stresses and quality traits [91] and have a better capacity to absorb and utilize N under low N fertilization conditions [93].

The effects of irrigation and fertilization on protein content were not consistent across genotypes, as the proportion of proteins under water stress or without nitrogen compared with that under control conditions was higher or lower depending on the genotypes. Protein content was higher under drought conditions with nitrogen fertilization compared with no nitrogen for half of the genotypes and lower for the other half. Nevertheless, some general trends were shown, as protein content decreased without nitrogen compared to with nitrogen fertilization under control conditions. Furthermore, without nitrogen fertilization, protein content was higher for all genotypes under drought, compared with well-watered conditions. Similarly, with nitrogen fertilization, protein content was higher for most genotypes under drought, compared with well-watered conditions.

The ranges of variability increased among populations under water stress, as the partial factor productivity (PFP) values of AOR and BAH duplicated that of IZM under water stress and were even larger for the crosses (Table 5). However, PFP values decreased under water stress. As reported by Wang et al. [94], the nitrogen PFP and nitrogen AE decreased when subjected to drought stress. In the same way, in the study of Qiu et al. [95], all three sites of each N rate had lower PFP in one year than in the two other years as the result of drought condition. As reported also Wang et al. [94], drought stress inhibited the uptake of N in plants, while reducing PFP for the maize under the same N conditions.

As a consequence of lower N use efficiencies, additional N is retained in the soil; thus, N fertilizer levels could likely be reduced for the next crop season.

The negative values of nitrogen agronomic efficiency could be explained by the fact that, on average, yields under water stress with no-nitrogen fertilizer had higher values than those with nitrogen fertilizer. As reported by Wang et al. [96], maize plants in treatment under moderate water stress with low nitrogen showed an optimal root distribution, characterized by a larger and deeper penetration scale with higher root length density throughout the soil layers, and thus showed fewer drought responses and obtained the higher NUE.

Maize kernels of current commercial varieties contain 70–75% starch, 8–10% protein, and 4–5% oil [97]. The general means performance of grain protein content increased under water stress and when nitrogen supply was applied. Das et al. [32] reported that protein content was also significantly reduced by 25% under low N. However, protein content of the grain endosperm increased markedly as available N in the soil increased [98–100]. This is because N plays a key role in metabolism, notably in protein synthesis, and thus strongly influences both grain production and grain protein content [101]. Worku et al. [102] reported the favorable effect of nitrogen fertilizer in the synthesis and storage of cereal chemical compound grains as protein, lipids, and carbohydrate concentrations during the course of maize. Furthermore, drought accelerates leaf senescence and reduces the photosynthetic area and period, often limiting the amount of assimilate, which results in lower grain yields but higher grain protein content [103–105].

Mean squares of the genetic variability observed in nitrogen utilization efficiency (NUtE) increased under no-nitrogen fertilizer and decreased under water stress conditions. NUtE followed patterns opposite to those of the protein content. Indeed, under drought conditions, NUtE was lower without than with nitrogen fertilization for those genotypes showing the opposite trend for PC; under well-watered conditions, NUtE was lower without than with nitrogen fertilization for most genotypes.

Elvio and Rinaldi [106] reported that sufficient available soil water led to better uptake and utilization of N in cell metabolic processes and increased crop biomass and yield. Omoigui et al. [107] observed a higher NUtE and NUE under low nitrogen and suggested that the good adaptation to these conditions was attributed to improved N utilization efficiency. Moll et al. [53] also found that N utilization efficiency played a dominant role in determining grain yield at low N. According to Arisede et al. [108], at low N input, variation in NUtE was more important than at high N input, because when nitrogen is not limiting uptake, efficient utilization is not as critical as when N is limiting. Dhugga and Waines [109] argued that decreased NUE at high N to higher volatilization losses was because the plant was unable to assimilate all N taken up. It is well accepted that NUE is high at low N rates and decreases with increasing N rates [110].

Nitrogen use efficiency (NUE) is generally defined as the ability of a genotype to produce superior grain yield under low soil N conditions in comparison with other genotypes [111]. Understanding the mechanisms regulating NUE processes is crucial for the improvement of NUE in crop plants [30]. However, the improvement of NUE in maize cultivars is a great challenge due to the genetic complexity and strong interaction with the environment. Thus, information on the genetic control governing the inheritance of traits would be useful for crop researchers to choose the breeding method for obtaining NUE efficient cultivars [20] and to develop breeding program strategies for traits related to drought tolerance [92]. Therefore, assessment of combining ability and heterosis is of utmost importance for breeding hybrid maize [112], so that the genotypes could be successfully used to develop hybrids with superior NUE under diverse environmental conditions.

Increasing heterosis is the preferred choice for maximizing gains in crop plants and largely depends on the level of genetic diversity of the germplasm base [113]. For grain protein content, non-additive genetic action was important in the inheritance under well-watered conditions with nitrogen supply and under water stress with no-nitrogen fertilizer

(Table 6). However, under well-watered conditions with no-nitrogen fertilizer, the mean squares of variety heterosis were significant, which suggests that additive genetic effects are also important for this trait. The genetic regulation of protein content depends on the varieties studied, for example, Machida et al. [114] reported that there was a preponderance of GCA effects for protein content under well-watered conditions with nitrogen supply. Previous reports have shown that the partitioning of the sum of squares for general (GCA) and specific (SCA) combining ability indicated that both additive and non-additive effects were involved in the genetic control [115], and GCA (additive) variance was higher than SCA (non-additive) variance for grain protein content under water stress [116].

For grain NUtE, specific heterosis was significant under well-watered conditions with nitrogen supply, which suggested that non-additive gene action controlled this trait (Table 6). For PFF, under both water conditions, a variety and heterosis effects were significant, which suggested the importance of both additive and non-additive genetic effects (Table 7). Average heterosis was significant and positive for PFP indicating that the crosses had, on average, higher PFP than the populations per se for all traits (Table 5). For AE, there was no significant results about the type of inheritance in this study.

Absence of significant estimates of varietal effects or varietal heterosis for AE, indicates the lack of potential parents for increasing the frequency of favorable alleles for AE under both water regimes. BAH and MST showed positive significant additive effects for PFP, PC, and/or NUtE (Table 8), indicating that these populations are desirable parents for maize hybrid development and involvement in the maize breeding program, as they could be potential sources of favorable alleles for breeding programs. Identification of superior parents could be used by breeders to make and select better crosses for direct use or for further breeding. A successful recurrent selection program is expected to increase the mean performance of individuals and also maintain the genetic variability within the population to facilitate continuous improvement in advanced cycles of selection [117].

AOR × IZM, AOR × IGS, SHH × AOR, and AOR × BAH crosses were good specific combiners for developing hybrids with high values of AE, PFP, grain NutE, and/or grain protein content, which implied that it could be promising for developing drought-tolerant or/and low nitrogen hybrids through reciprocal recurrent selection to improve the previous characteristics.

As we hypothesized, differences among Algerian populations were significant for stress tolerance, and this genetic diversity affected the efficient use of nitrogen and the production of proteins, particularly under drought conditions. Furthermore, the genetic diversity for yield per unit of fertilizer applied has significant genotype × environment interaction and is affected by irrigation. Even though there is genotypic diversity for nutrient utilization and protein content, efficiency increases with irrigation, especially without N fertilization, while protein content increases with water stress and N fertilization as a low effect. There were significant differences among populations for the effects of fertilization on productivity, which were significantly affected by irrigation; furthermore, some Algerian populations were particularly promising as sources of stress tolerance. Finally, these results also show that heterosis and its components were more important than variety and environmental effects, indicating that dominance was more important than additive genetic effects. Some Algerian populations have promising varietal and heterosis effects for grain protein content and nutrient utilization efficiency, and some crosses were valuable for their specific heterosis effects, mainly with fertilization, and they varied with irrigation.

5. Conclusions

Our results revealed significant genetic variability in the populations per se and their crosses under stress. Reciprocal recurrent selection could be used to take advantage of additive and non-additive gene effects found based on estimations of genetic parameters. Additive genetic effects could be capitalized on using the population BAH under water stress with nitrogen supply for grain nitrogen utilization efficiency, and under well-watered conditions for partial fertilizer productivity, and MST under well-watered conditions with no-nitrogen supply for grain NUtE, and under water stress with nitrogen fertilizer for protein content. Dominance genetic effects could be exploited for protein content using BAH with significant heterotic effects under water stress with nitrogen supply, MST under well-watered conditions with no-nitrogen supply, and SHH under well-watered conditions. The most promising crosses were SHH × AOR with no-nitrogen supply under both water regimes for grain NUtE, AOR × IGS (under water stress for PFP and well-watered conditions with nitrogen supply for protein content), AOR × IZM for AE under water stress, and AOR × BAH for grain NUtE under well-watered conditions with nitrogen. These parents could be promising for developing drought-tolerant or/and low nitrogen hybrids to improve these traits.

The genetic effects of these genotypes will allow breeding programs to obtain high values of nitrogen efficiency indices (AE, PFP, and grain NUtE) and grain yield with more protein content. To conclude, maximum heterosis could be exploited using those populations and crosses after selection and classification into useful heterotic groups.

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References

1. United State Department of Agriculture (USDA). World Agricultural Production. Foreign Agricultural Service Circular Series. WAP 2-22. February 2022. Available online: https://apps.fas.usda.gov/PSDOnline/Circulars/2022/02/production.pdf (accessed on 11 April 2022).
2. Tanumihardjo, S.A.; Palacios, N.; Pixley, K.V. Provitamin A Carotenoid Bioavailability: What Really Matters? *Int. J. Vitam. Nutr. Res.* **2010**, *80*, 336–350. [CrossRef] [PubMed]
3. Masuka, B.; Atlin, G.N.; Olsen, M.; Magorokosho, C.; Labuschagne, M.; Crossa, J.; Bänziger, M.; Pixley, K.V.; Vivek, B.S.; Von Biljon, A.; et al. Gains in Maize Genetic Improvement in Eastern and Southern Africa: I. CIMMYT Hybrid Breeding Pipeline. *Crop Sci.* **2017**, *57*, 168–179. [CrossRef]
4. Dai, A. Erratum: Increasing Drought under Global Warming in Observations and Models. *Nat. Clim. Chang.* **2013**, *3*, 171. [CrossRef]
5. Mir, R.R.; Zaman-Allah, M.; Sreenivasulu, N.; Trethowan, R.; Varshney, R.K. Integrated Genomics, Physiology and Breeding Approaches for Improving Drought Tolerance in Crops. *Theor. Appl. Genet.* **2012**, *125*, 625–645. [CrossRef]
6. Alcadi, R.; Mathur, S.; Rémy, P. *Research and Innovation for Smallholder Farmers in the Context of Climate Change*; Discussion Paper for Round Table 3; IFAD: Rome, Italy, 2009.
7. Gracia-Romero, A.; Kefauver, S.C.; Fernandez-Gallego, J.A.; Vergara-Díaz, O.; Nieto-Taladriz, M.T.; Araus, J.L. UAV and Ground Image-Based Phenotyping: A Proof of Concept with Durum Wheat. *Remote Sens.* **2019**, *11*, 1244. [CrossRef]
8. Cline, W.R. Global Warming and Agriculture. *Financ. Dev.* **2008**, *45*, 23.
9. Parry, M. Effects of Climate Change on Potential Food Production and Risk of Hunger. In *Plant Genetic Resources and Climate Change*; Jackson, M., Ford-Lloyd, B., Parry, M., Eds.; CAB International: Wallingford, UK, 2013; Volume 4, pp. 61–77.
10. Parry, M.A.J.; Hawkesford, M.J. Food Security: Increasing Yield and Improving Resource Use Efficiency. *Proc. Nutr. Soc.* **2010**, *69*, 592–600. [CrossRef]

11. Tanger, P.; Klassen, S.; Mojica, J.P.; Lovell, J.T.; Moyers, B.T.; Baraoidan, M.; Naredo, M.E.B.; McNally, K.L.; Poland, J.; Bush, D.R.; et al. Field-Based High Throughput Phenotyping Rapidly Identifies Genomic Regions Controlling Yield Components in Rice. *Sci. Rep.* **2017**, *7*, 42839. [CrossRef]
12. Beddington, J. Food Security: Contributions from Science to a New and Greener Revolution. *Philos. Trans. R. Soc. B Biol. Sci.* **2010**, *365*, 61–71. [CrossRef]
13. Pandey, R.; Maranville, J.; Admou, A. Tropical Wheat Response to Irrigation and Nitrogen in a Sahelian Environment. I. Grain Yield, Yield Components and Water Use Efficiency. *Eur. J. Agron.* **2001**, *15*, 93–105. [CrossRef]
14. IPCC. Intergovernmental Panel on Climate Change. Africa. In *Climate Change 2014—Impacts, Adaptation and Vulnerability: Part B: Regional Aspects: Working Group II Contribution to the IPCC Fifth Assessment Report: Volume 2: Regional Aspects*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014; Volume 2, pp. 1199–1265; ISBN 9781107058163.
15. Abdoulaye, A.O.; Lu, H.; Zhu, Y.; Hamoud, Y.A.; Sheteiwy, M. The Global Trend of the Net Irrigation Water Requirement of Maize from 1960 to 2050. *Climate* **2019**, *7*, 124. [CrossRef]
16. World Meteorological Organization (WMO). *The Global Climate 2015–2019*; WMO Library: Geneva, Switzerland, 2019.
17. Kourat, T.; Smadhi, D.; Madani, A. Modeling the Impact of Future Climate Change Impacts on Rainfed Durum Wheat Production in Algeria. *Climate* **2022**, *10*, 50. [CrossRef]
18. Ex Ministère de l'Aménagement de Territoire et de l'Environnement (MATE). *Etude Diagnostique Sur La Biodiversité et Les Changements Climatiques En Algérie*; Cooperation Project between the Algerian Ministry of Land Planning and the Environment; United Nation: Algiers, Algeria, 2015.
19. Achite, M.; Bazrafshan, O.; Azhdari, Z.; Wałęga, A.; Krakauer, N.; Caloiero, T. Forecasting of SPI and SRI Using Multiplicative ARIMA under Climate Variability in a Mediterranean Region: Wadi Ouahrane Basin, Algeria. *Climate* **2022**, *10*, 36. [CrossRef]
20. dos Santos, A.; do Amaral Júnior, A.T.; Fritsche-Neto, R.; Kamphorst, S.H.; Ferreira, F.R.A.; do Amaral, J.F.T.; Vivas, J.M.S.; Santos, P.H.A.D.; de Lima, V.J.; Khan, S.; et al. Relative Importance of Gene Effects for Nitrogen-Use Efficiency in Popcorn. *PLoS ONE* **2019**, *14*, e0222726. [CrossRef]
21. Heinz, R.; Ribeiro, L.P.; Gonçalves, M.C.; Bhering, L.L.; Teodoro, P.E. Selection of Maize Top-Crosses for Different Nitrogen Levels through Specific Combining Ability. *Bragantia* **2019**, *78*, 208–214. [CrossRef]
22. Liu, J.; Li, J.; Chen, F.; Zhang, F.; Ren, T.; Zhuang, Z.; Mi, G. Mapping QTLs for Root Traits under Different Nitrate Levels at the Seedling Stage in Maize (*Zea mays* L.). *Plant Soil* **2008**, *305*, 253–265. [CrossRef]
23. Fu, W.; Wang, Y.; Ye, Y.; Zhen, S.; Zhou, B.; Wang, Y.; Hu, Y.; Zhao, Y.; Huang, Y. Grain Yields and Nitrogen Use Efficiencies in Different Types of Stay-Green Maize in Response to Nitrogen Fertilizer. *Plants* **2020**, *9*, 474. [CrossRef]
24. McAllister, C.H.; Beatty, P.H.; Good, A.G. Engineering Nitrogen Use Efficient Crop Plants: The Current Status. *Plant Biotechnol. J.* **2012**, *10*, 1011–1025. [CrossRef]
25. Rothstein, S.J. Returning to Our Roots: Making Plant Biology Research Relevant to Future Challenges in Agriculture. *Plant Cell* **2007**, *19*, 2695–2699. [CrossRef]
26. Guo, J.H.; Liu, X.J.; Zhang, Y.; Shen, J.L.; Han, W.X.; Zhang, W.F.; Christie, P.; Goulding, K.W.T.; Vitousek, P.M.; Zhang, F.S. Significant Acidification in Major Chinese Croplands. *Science* **2010**, *327*, 1008–1010. [CrossRef]
27. Liu, X.; Zhang, Y.; Han, W.; Tang, A.; Shen, J.; Cui, Z.; Vitousek, P.; Erisman, J.W.; Goulding, K.; Christie, P.; et al. Enhanced Nitrogen Deposition over China. *Nature* **2013**, *494*, 459–462. [CrossRef] [PubMed]
28. Kaur, G.; Asthir, B.; Bains, N.S.; Farooq, M. Nitrogen Nutrition, Its Assimilation and Remobilization in Diverse Wheat Genotypes. *Int. J. Agric. Biol.* **2015**, *17*, 531–538. [CrossRef]
29. Garnett, T.; Conn, V.; Kaiser, B.N. Root Based Approaches to Improving Nitrogen Use Efficiency in Plants. *Plant. Cell Environ.* **2009**, *32*, 1272–1283. [CrossRef] [PubMed]
30. Kant, S.; Bi, Y.-M.; Rothstein, S.J. Understanding Plant Response to Nitrogen Limitation for the Improvement of Crop Nitrogen Use Efficiency. *J. Exp. Bot.* **2011**, *62*, 1499–1509. [CrossRef]
31. Xu, G.; Fan, X.; Miller, A.J. Plant Nitrogen Assimilation and Use Efficiency. *Annu. Rev. Plant Biol.* **2012**, *63*, 153–182. [CrossRef]
32. Das, B.; Atlin, G.N.; Olsen, M.; Burgueño, J.; Tarekegne, A.; Babu, R.; Ndou, E.N.; Mashingaidze, K.; Moremoholo, L.; Ligeyo, D.; et al. Identification of Donors for Low-Nitrogen Stress with Maize Lethal Necrosis (MLN) Tolerance for Maize Breeding in Sub-Saharan Africa. *Euphytica* **2019**, *215*, 80. [CrossRef]
33. Ertiro, B.T.; Labuschagne, M.; Olsen, M.; Das, B.; Prasanna, B.M.; Gowda, M. Genetic Dissection of Nitrogen Use Efficiency in Tropical Maize through Genome-Wide Association and Genomic Prediction. *Front. Plant Sci.* **2020**, *11*, 474. [CrossRef]
34. Tadesse Ertiro, B.; Olsen, M.; Das, B.; Gowda, M.; Labuschagne, M. Genetic Dissection of Grain Yield and Agronomic Traits in Maize under Optimum and Low-Nitrogen Stressed Environments. *Int. J. Mol. Sci.* **2020**, *21*, 543. [CrossRef]
35. Ribeiro, P.F.; Badu-Apraku, B.; Gracen, V.E.; Danquah, E.Y.; Garcia-Oliveira, A.L.; Asante, M.D.; Afriyie-Debrah, C.; Gedil, M. Identification of Quantitative Trait Loci for Grain Yield and Other Traits in Tropical Maize Under High and Low Soil-Nitrogen Environments. *Crop Sci.* **2018**, *58*, 321–331. [CrossRef]
36. Masclaux-Daubresse, C.; Reisdorf-Cren, M.; Orsel, M. Leaf Nitrogen Remobilisation for Plant Development and Grain Filling. *Plant Biol.* **2008**, *10*, 23–36. [CrossRef]
37. Jansen, C.; Lübberstedt, T. Turning Maize Cobs into a Valuable Feedstock. *Bioenergy Res.* **2012**, *5*, 20–31. [CrossRef]
38. Zeigler, R.S.; Mohanty, S. Support for International Agricultural Research: Current Status and Future Challenges. *New Biotechnol.* **2010**, *27*, 565–572. [CrossRef] [PubMed]

39. Good, A.G.; Sharawat, A.K.; Muench, D.G. Can Less Yield More? Is Reducing Nutrient Input into the Environment Compatible with Maintaining Crop Production? *Trends Plant Sci.* **2004**, *9*, 597–605. [CrossRef] [PubMed]
40. Wu, Y.; Liu, W.; Li, X.; Li, M.; Zhang, D.; Hao, Z.; Weng, J.; Xu, Y.; Bai, L.; Zhang, S.; et al. Low-Nitrogen Stress Tolerance and Nitrogen Agronomic Efficiency among Maize Inbreds: Comparison of Multiple Indices and Evaluation of Genetic Variation. *Euphytica* **2011**, *180*, 281–290. [CrossRef]
41. Mi, G.; Chen, F.; Zhang, F. Physiological and Genetic Mechanisms for Nitrogen-Use Efficiency in Maize. *J. Crop Sci. Biotechnol.* **2005**, *10*, 57–63.
42. Edmeades, G.; Bänziger, M.; Campos, H.; Schussler, J. Improving Tolerance to Abiotic Stresses in Staple Crops: A Random or Planned Process? In *Plant Breeding: The Arnel R. Hallauer International Symposium*; Blackwell Publishing: Ames, IA, USA, 2006; pp. 293–309; ISBN 9780813828244.
43. Meseka, S.K.; Menkir, A.; Ibrahim, A.E.S. Yield Potential and Yield Stability of Maize Hybrids Selected for Drought Tolerance. *Science* **2008**, *3*, 82–90.
44. Dodig, D.; Božinović, S.; Nikolić, A.; Zorić, M.; Vančetović, J.; Ignjatović-Micić, D.; Delić, N.; Weigelt-Fischer, K.; Junker, A.; Altmann, T. Image-Derived Traits Related to Mid-Season Growth Performance of Maize under Nitrogen and Water Stress. *Front. Plant Sci.* **2019**, *10*, 814. [CrossRef]
45. Garoma, B.; Alamirew, S.; Chibsa, T. Review on Genetic and Breeding for Low -N Tolerance in Maize. *J. Nat. Sci. Res.* **2021**, *12*, 26–31. [CrossRef]
46. Molla, M.; Nakasathien, S.; Sarobol, E.; Vichukit, V. Effects of Nitrogen and Water on Maize Varieties under Short and Prolonged Drought. *J. Dev. Sustain. Agric.* **2014**, *9*, 97–110. [CrossRef]
47. Monneveux, P.; Zaidi, P.H.; Sanchez, C. Population Density and Low Nitrogen Affects Yield-Associated Traits in Tropical Maize. *Crop Sci.* **2005**, *45*, 535–545. [CrossRef]
48. Amegbor, I.K.; Badu-Apraku, B.; Annor, B. Combining Ability and Heterotic Patterns of Extra-Early Maturing White Maize Inbreds with Genes from Zea Diploperennis under Multiple Environments. *Euphytica* **2017**, *213*, 24. [CrossRef]
49. Gou, W.; Zheng, P.; Tian, L.; Gao, M.; Zhang, L.; Akram, N.A.; Ashraf, M. Exogenous Application of Urea and a Urease Inhibitor Improves Drought Stress Tolerance in Maize (*Zea mays* L.). *J. Plant Res.* **2017**, *130*, 599–609. [CrossRef] [PubMed]
50. Kamara, A.Y.; Ewansiha, S.U.; Menkir, A. Assessment of Nitrogen Uptake and Utilization in Drought Tolerant and Striga Resistant Tropical Maize Varieties. *Arch. Agron. Soil Sci.* **2014**, *60*, 195–207. [CrossRef]
51. Hallauer, A.R.; Carena, M.J.; Miranda Filho, J.B. *Quantitative Genetics in Maize Breeding*; Springer: New York, NY, USA, 2010; ISBN 978-1-4419-0765-3.
52. Congreves, K.A.; Otchere, O.; Ferland, D.; Farzadfar, S.; Williams, S.; Arcand, M.M. Nitrogen Use Efficiency Definitions of Today and Tomorrow. *Front. Plant Sci.* **2021**, *12*, 637108. [CrossRef] [PubMed]
53. Moll, R.H.; Kamprath, E.J.; Jackson, W.A. Analysis and Interpretation of Factors Which Contribute to Efficiency of Nitrogen Utilization. *Agron. J.* **1982**, *74*, 562–564. [CrossRef]
54. Dobermann, A. Nutrient Use Efficiency–Measurement and Management. In Proceedings of the International Fertilizer Industry Association (IFA) Workshop on Fertilizer Best Management Practices, Brussels, Belgium, 7–9 March 2007; pp. 1–28.
55. Masclaux-Daubresse, C.; Daniel-Vedele, F.; Dechorgnat, J.; Chardon, F.; Gaufichon, L.; Suzuki, A. Nitrogen Uptake, Assimilation and Remobilization in Plants: Challenges for Sustainable and Productive Agriculture. *Ann. Bot.* **2010**, *105*, 1141–1157. [CrossRef] [PubMed]
56. Dobermann, A.R. Nitrogen Use Efficiency—State of the Art. In Proceedings of the IFA International Workshop on Enhanced-Efficiency Fertilizers, Frankfurt, Germany, 28–30 June 2005; pp. 1–16.
57. IPNI Nitrogen Loss Pathways. International Plant Nutrition Institute. Available online: http://anz.ipni.net/article/ANZ-3002 (accessed on 11 April 2022).
58. Cañas, R.A.; Quilleré, I.; Gallais, A.; Hirel, B. Can Genetic Variability for Nitrogen Metabolism in the Developing Ear of Maize Be Exploited to Improve Yield? *New Phytol.* **2012**, *194*, 440–452. [CrossRef] [PubMed]
59. Silva, V.M.P.E.; Carneiro, P.C.S.; de Menezes Júnior, J.Â.N.; Carneiro, V.Q.; de Souza Carneiro, J.E.; Cruz, C.D.; Borém, A. Genetic Potential of Common Bean Parents for Plant Architecture Improvement. *Sci. Agric.* **2013**, *70*, 167–175. [CrossRef]
60. Badu-Apraku, B. Estimates of Genetic Variances in Striga Resistant Extra-Early-Maturing Maize Populations. *J. New Seeds* **2006**, *8*, 23–43. [CrossRef]
61. Badu-Apraku, B. Genetic Variances and Correlations in an Early Tropical White Maize Population after Three Cycles of Recurrent Selection for Striga Resistance. *Maydica* **2007**, *52*, 205–217.
62. Stephen, A.; Antonia, Y.T.; Patrick, T.; Kingsley, B.A.; Richard, A.A. Genetic Diversity in Lowland, Midaltitude and Highland African Maize Landraces by Morphological Trait Evaluation. *Afr. J. Plant Sci.* **2016**, *10*, 246–257. [CrossRef]
63. Djemel, A.; Revilla, P.; Hanifi-Mekliche, L.; Malvar, R.A.; Álvarez, A.; Khelifi, L. Maize (*Zea mays* L.) from the Saharan Oasis: Adaptation to Temperate Areas and Agronomic Performance. *Genet. Resour. Crop Evol.* **2012**, *59*, 1493–1504. [CrossRef]
64. Djemel, A.; Cherchali, F.Z.; Benchikh-Le-Hocine, M.; Malvar, R.A.; Revilla, P. Assessment of Drought Tolerance among Algerian Maize Populations from Oases of the Saharan. *Euphytica* **2018**, *214*, 149. [CrossRef]
65. Djemel, A.; Álvarez-Iglesias, L.; Santiago, R.; Malvar, R.A.; Pedrol, N.; Revilla, P. Algerian Maize Populations from the Sahara Desert as Potential Sources of Drought Tolerance. *Acta Physiol. Plant.* **2019**, *41*, 12. [CrossRef]

66. Maafi, O.; Revilla, P.; Álvarez-Iglesias, L.; Malvar, R.A.; Djemel, A. Adaptation Assessment of Drought Tolerance in Maize Populations from the Sahara in Both Shores of the Mediterranean Sea. *Euphytica* **2021**, *217*, 172. [CrossRef]
67. Aci, M.M.; Revilla, P.; Morsli, A.; Djemel, A.; Belalia, N.; Kadri, Y.; Khelifi-Saloui, M.; Ordás, B.; Khelifi, L. Genetic Diversity in Algerian Maize (*Zea mays* L.) Landraces Using SSR Markers. *Maydica* **2013**, *58*, 304–310.
68. Aci, M.M.; Lupini, A.; Mauceri, A.; Morsli, A.; Khelifi, L.; Sunseri, F. Genetic Variation and Structure of Maize Populations from Saoura and Gourara Oasis in Algerian Sahara. *BMC Genet.* **2018**, *19*, 51. [CrossRef]
69. Belalia, N.; Lupini, A.; Djemel, A.; Morsli, A.; Mauceri, A.; Lotti, C.; Khelifi-Slaoui, M.; Khelifi, L.; Sunseri, F. Analysis of Genetic Diversity and Population Structure in Saharan Maize (*Zea mays* L.) Populations Using Phenotypic Traits and SSR Markers. *Genet. Resour. Crop Evol.* **2019**, *66*, 243–257. [CrossRef]
70. Cherchali, F.Z.; Ordás, B.; Revilla, P.; Pedrol, N.; Djemel, A. Heterotic Patterns among Algerian, US Corn Belt, and European Flint Maize Populations under the Mediterranean Conditions of North Africa. *Crop Sci.* **2018**, *58*, 2422–2432. [CrossRef]
71. Riache, M.; Revilla, P.; Maafi, O.; Malvar, R.A.; Djemel, A. Combining Ability and Heterosis of Algerian Saharan Maize Populations (*Zea mays* L.) for Tolerance to No-Nitrogen Fertilization and Drought. *Agronomy* **2021**, *11*, 492. [CrossRef]
72. Infoclimat Climate Data. Available online: https://www.infoclimat.fr/climatologie-mensuelle/60390/avril/2019/dar-el-beida.html (accessed on 11 April 2022).
73. Kirk, P.L. Kjeldahl Method for Total Nitrogen. *Anal. Chem.* **1950**, *22*, 354–358. [CrossRef]
74. Fiez, T.E.; Pan, W.L.; Miller, B.C. Nitrogen Use Efficiency of Winter Wheat among Landscape Positions. *Soil Sci. Soc. Am. J.* **1995**, *59*, 1666–1671. [CrossRef]
75. Mosse, J. Nitrogen-to-Protein Conversion Factor for Ten Cereals and Six Legumes or Oilseeds. A Reappraisal of Its Definition and Determination. Variation According to Species and to Seed Protein Content. *J. Agric. Food Chem.* **1990**, *38*, 18–24. [CrossRef]
76. SAS Institute. *SAS Version 9.4*; SAS Institute: Cary, NC, USA, 2015.
77. Gardner, C.; Eberhart, S. Analysis and Interpretation of the Variety Cross Diallel and Related Populations. *Biometrics* **1966**, *22*, 439–452. [CrossRef]
78. Zhang, Y.; Kang, M.S.; Lamkey, K.R. DIALLEL-SAS05: A Comprehensive Program for Griffing's and Gardner-Eberhart Analyses. *Agron. J.* **2005**, *97*, 1097–1106. [CrossRef]
79. Edmeades, G.O.; Bänziger, M.; Mickelson, H.R.; Peña-Valdivia, C.B. Developing Drought- and Low N-Tolerant Maize. In Proceedings of the Symposium, El Batán, Mexico, 25–29 March 1996; pp. 485–489.
80. Osuman, A.S.; Badu-Apraku, B.; Ifie, B.E.; Tongoona, P.; Obeng-Bio, E.; Garcia-Oliveira, A.L. Genetic Diversity, Population Structure and Inter-Trait Relationships of Combined Heat and Drought Tolerant Early-Maturing Maize Inbred Lines from West and Central Africa. *Agronomy* **2020**, *10*, 1324. [CrossRef]
81. Naggar, A.M.M.A.; Shafik, M.M.; Musa, R.Y.M.; Younis, A.S.M.; Anany, A.H. Genetic Variability of Maize Hybrids and Populations and Interrelationships among Grain Yield and Its Related Traits under Drought and Low N Using Multivariate Analysis. *Asian J. Biochem. Genet. Mol. Biol.* **2020**, *4*, 26–44. [CrossRef]
82. Abu, P.; Badu-Apraku, B.; Ifie, B.E.; Tongoona, P.; Melomey, L.D.; Offei, S.K. Genetic Diversity and Inter-Trait Relationship of Tropical Extra-Early Maturing Quality Protein Maize Inbred Lines under Low Soil Nitrogen Stress. *PLoS ONE* **2021**, *16*, e0252506. [CrossRef]
83. Kondwakwenda, A.; Sibiya, J.; Amelework, A.B.; Zengeni, R. Diversity Analysis of Provitamin A Maize Inbred Lines Using Single Nucleotide Polymorphism Markers. *Acta Agric. Scand. Sect. B Soil Plant Sci.* **2020**, *70*, 265–271. [CrossRef]
84. Dao, A.; Sanou, J.; Mitchell, S.E.; Gracen, V.; Danquah, E.Y. Genetic Diversity among INERA Maize Inbred Lines with Single Nucleotide Polymorphism (SNP) Markers and Their Relationship with CIMMYT, IITA, and Temperate Lines. *BMC Genet.* **2014**, *15*, 127. [CrossRef]
85. Tefera, A. Pre-Breeding Concept and Role in Crop Improvement. *Int. J. Res. Appl. Sci. Biotechnol.* **2021**, *8*, 275–279. [CrossRef]
86. Ceccarelli, S.; Grando, S.; Baum, M. Participatory plant breeding in water-limited environments. *Exp. Agric.* **2007**, *43*, 411–435. [CrossRef]
87. Böhm, J.; Schipprack, W.; Mirdita, V.; Utz, H.F.; Melchinger, A.E. Breeding Potential of European Flint Maize Landraces Evaluated by Their Testcross Performance. *Crop Sci.* **2014**, *54*, 1665–1672. [CrossRef]
88. Popović, A.; Kravić, N.; Babić, M.; Prodanović, S.; Sečanski, M.; Babić, V. Breeding Potential of Maize Landraces Evaluated by Their Testcross Performance. *Zemdirbyste-Agriculture* **2020**, *107*, 153–160. [CrossRef]
89. Mikić, S.; Kondić-Špika, A.; Brbaklić, L.; Stanisavljević, D.; Ćeran, M.; Trkulja, D.; Mitrović, B. Molecular and Phenotypic Characterisation of Diverse Temperate Maize Inbred Lines in Southeast Europe. *Zemdirbyste-Agriculture* **2017**, *104*, 31–40. [CrossRef]
90. Gouesnard, B.; Zanetto, A.; Welcker, C. Identification of Adaptation Traits to Drought in Collections of Maize Landraces from Southern Europe and Temperate Regions. *Euphytica* **2016**, *209*, 565–584. [CrossRef]
91. Katna, G.; Sood, V.K. Plant Genetic Resources, Traditional Knowledge and Their Use in Crop Improvement. In *Plant Genetic Resources and Traditional Knowledge for Food Security*; Salgotra, R.K., Gupta, B.B., Eds.; Springer: Singapore, 2015; Volume 19, pp. 23–38.
92. Barbosa, P.A.M.; Fritsche-Neto, R.; Andrade, M.C.; Petroli, C.D.; Burgueño, J.; Galli, G.; Willcox, M.C.; Sonder, K.; Vidal-Martínez, V.A.; Sifuentes-Ibarra, E.; et al. Introgression of Maize Diversity for Drought Tolerance: Subtropical Maize Landraces as Source of New Positive Variants. *Front. Plant Sci.* **2021**, *12*, 691211. [CrossRef]

93. Hirel, B.; Le Gouis, J.; Ney, B.; Gallais, A. The Challenge of Improving Nitrogen Use Efficiency in Crop Plants: Towards a More Central Role for Genetic Variability and Quantitative Genetics within Integrated Approaches. *J. Exp. Bot.* **2007**, *58*, 2369–2387. [CrossRef]
94. Wang, Y.; Huang, Y.; Fu, W.; Guo, W.; Ren, N.; Zhao, Y.; Ye, Y. Efficient Physiological and Nutrient Use Efficiency Responses of Maize Leaves to Drought Stress under Different Field Nitrogen Conditions. *Agronomy* **2020**, *10*, 523. [CrossRef]
95. Qiu, S.J.; He, P.; Zhao, S.C.; Li, W.J.; Xie, J.G.; Hou, Y.P.; Grant, C.A.; Zhou, W.; Jin, J.Y. Impact of Nitrogen Rate on Maize Yield and Nitrogen Use Efficiencies in Northeast China. *Agron. J.* **2015**, *107*, 305–313. [CrossRef]
96. Wang, Y.; Zhang, X.; Chen, J.; Chen, A.; Wang, L.; Guo, X.; Niu, Y.; Liu, S.; Mi, G.; Gao, Q. Reducing Basal Nitrogen Rate to Improve Maize Seedling Growth, Water and Nitrogen Use Efficiencies under Drought Stress by Optimizing Root Morphology and Distribution. *Agric. Water Manag.* **2019**, *212*, 328–337. [CrossRef]
97. Boyer, C.D.; Hannah, L. Kernel Mutants of Corn. In *Specialty Corns*; CRC Press: Boca Raton, FL, USA, 2001; pp. 1–31.
98. Worku, M. Genetic and Crop-Physiological Basis of Nitrogen Efficiency in Tropical Maize: Field Studies. Ph.D. Thesis, Universität Hannover, Hannover, Germany, 2005.
99. Oktem, A.; Oktem, A.G.; Emeklier, H.Y. Effect of Nitrogen on Yield and Some Quality Parameters of Sweet Corn. *Commun. Soil Sci. Plant Anal.* **2010**, *41*, 832–847. [CrossRef]
100. Ochieng', I.O.; Gitari, H.I.; Mochoge, B.; Rezaei-Chiyaneh, E.; Gweyi-Onyango, J.P. Optimizing Maize Yield, Nitrogen Efficacy and Grain Protein Content under Different N Forms and Rates. *J. Soil Sci. Plant Nutr.* **2021**, *21*, 1867–1880. [CrossRef]
101. Machado, A.; Fernandes, M.S. Participatory Maize Breeding for Low Nitrogen Tolerance. *Euphytica* **2001**, *122*, 567–573. [CrossRef]
102. Worku, M.; Bänziger, M.; Schulte auf'm Erley, G.; Friesen, D.; Diallo, A.; Horst, W. Nitrogen Efficiency as Related to Dry Matter Partitioning and Root System Size in Tropical Mid-Altitude Maize Hybrids under Different Levels of Nitrogen Stress. *Field Crops Res.* **2012**, *130*, 57–67. [CrossRef]
103. Oikeh, S.O.; Kling, J.G.; Okoruwa, A.E. Nitrogen Fertilizer Management Effects on Maize Grain Quality in the West African Moist Savanna. *Crop Sci.* **1998**, *38*, 1056–1161. [CrossRef]
104. Ozturk, A.; Aydin, F. Effect of Water Stress at Various Growth Stages on Some Quality Characteristics of Winter Wheat. *J. Agron. Crop Sci.* **2004**, *190*, 93–99. [CrossRef]
105. Balla, K.; Rakszegi, M.; Li, Z.; Békés, F.; Bencze, S.; Veisz, O. Quality of Winter Wheat in Relation to Heat and Drought Shock after Anthesis. *Czech J. Food Sci.* **2011**, *29*, 117–128. [CrossRef]
106. Di Paolo, E.; Rinaldi, M. Yield Response of Corn to Irrigation and Nitrogen Fertilization in a Mediterranean Environment. *Field Crops Res.* **2008**, *105*, 202–210. [CrossRef]
107. Omoigui, L.O.; Alabi, S.O.; Kamara, A.Y. Response of Low-N Pool Maize Population to Nitrogen Uptake and Use Efficiency after Three Cycles of Full-Sib Recurrent Selection. *J. Agric. Sci.* **2007**, *145*, 481–490. [CrossRef]
108. Arisede, C.; Mainassara, Z.-A.; Jill, C.; Amsal, T.; Cosmos, M.; Bish, D.; Benhildah, M.; Mike, O.; Maruthi, P.B. Low-N Stress Tolerant Maize Hybrids Have Higher Fertilizer N Recovery Efficiency and Reduced N-Dilution in the Grain Compared to Susceptible Hybrids under Low N Conditions. *Plant Prod. Sci.* **2020**, *23*, 417–426. [CrossRef]
109. Dhugga, K.S.; Waines, J.G. Analysis of Nitrogen Accumulation and Use in Bread and Durum Wheat. *Crop Sci.* **1989**, *29*, 1232–1239. [CrossRef]
110. Ciampitti, I.A.; Vyn, T.J. A Comprehensive Study of Plant Density Consequences on Nitrogen Uptake Dynamics of Maize Plants from Vegetative to Reproductive Stages. *Field Crops Res.* **2011**, *121*, 2–18. [CrossRef]
111. Grohan, R.D. Breeding for Nutritional Characteristics in Cereals. In *Advances in Plant Nutrition*; Lauchli, A., Tinker, P.B., Eds.; Praeger Publishing: New York, NY, USA, 1984; pp. 57–102.
112. Yu, K.; Wang, H.; Liu, X.; Xu, C.; Li, Z.; Xu, X.; Liu, J.; Wang, Z.; Xu, Y. Large-Scale Analysis of Combining Ability and Heterosis for Development of Hybrid Maize Breeding Strategies Using Diverse Germplasm Resources. *Front. Plant Sci.* **2020**, *11*, 660. [CrossRef] [PubMed]
113. Badu-Apraku, B.; Garcia-Oliveira, A.L.; Petroli, C.D.; Hearne, S.; Adewale, S.A.; Gedil, M. Genetic Diversity and Population Structure of Early and Extra-Early Maturing Maize Germplasm Adapted to Sub-Saharan Africa. *BMC Plant Biol.* **2021**, *21*, 96. [CrossRef]
114. Machida, L.; Derera, J.; Tongoona, P.; MacRobert, J. Combining Ability and Reciprocal Cross Effects of Elite Quality Protein Maize Inbred Lines in Subtropical Environments. *Crop Sci.* **2010**, *50*, 1708–1717. [CrossRef]
115. Werle, A.J.K.; Ferreira, F.R.A.; Pinto, R.J.B.; Mangolin, C.A.; Scapim, C.A.; Gonçalves, L.S.A. Diallel Analysis of Maize Inbred Lines for Grain Yield, Oil and Protein Content. *Crop Breed. Appl. Biotechnol.* **2014**, *14*, 23–28. [CrossRef]
116. Al-Naggar, A.; Atta, M.; Ahmed, M.; Younis, A. Heterosis and Combining Ability of Maize (*Zea mays* L.) Grain Protein, Oil and Starch Content and Yield as Affected by Water Stress. *Arch. Curr. Res. Int.* **2016**, *4*, 1–15. [CrossRef]
117. Talabi, A.O.; Badu-Apraku, B.; Fakorede, M.A.B. Genetic Variances and Relationship among Traits of an Early Maturing Maize Population under Drought-Stress and Low Nitrogen Environments. *Crop Sci.* **2017**, *57*, 681–692. [CrossRef]