Genet Resour Crop Evol (2023) 70:235–250
https://doi.org/10.1007/s10722-022-01429-z

RESEARCH ARTICLE

Variation of morphological traits among wheat (*Triticum aestivum* L.) landraces from two regions of the Algerian Sahara. Potential interest for wheat breeding

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Received: 27 January 2022 / Accepted: 11 June 2022 / Published online: 3 July 2022

Abstract In the Saharan regions of Algeria wheat is cultivated by farmers in small areas of the oases. Saharan wheat landraces that are the result of natural and human selection in hostile environments for several centuries could represent an interesting material to improve abiotic stress tolerance in breeding programs. Indeed, a high level of drought, heat and salt tolerance has been reported in this germplasm. Very little information is however available on the morphological characteristics of these landraces. In the present study, a total of 58 bread wheat landraces originating from ten oases of the Adrar and Tamanrasset regions were characterised, together with two commercial varieties, for 21 quantitative traits related to plant, spike, grain, glume and lemma. A wide morphological variation was noted among landraces, as well as differences related to their environments of origin. Altitude was a determining factor of variation, landraces originating from low altitude exhibiting shorter stems and less fertile tillers and producing more grain, compared to landraces originating from high altitude. The landraces of Adrar with very dense spike of normal type were opposed to the varieties with spikes of speltoid type originating from Tamanrasset. High heritability was recorded for thousand grain weight, number of grains per spike, number of fertile tillers per plant, spike length and spike width, suggesting the possibility of using these traits in wheat breeding programs.

Keywords Algerian Sahara · Altitude · Breeding · Heritability · Morphological traits · Oasis wheat

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10722-022-01429-z.

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Introduction

Wheat cultivation in Algeria is concentrated in semi-arid regions, characterized by irregular and insufficient rainfall and high temperature amplitudes. Drought, heat and frost are the main constraints limiting production (Benbelkacem 1996). Moreover, Schilling et al. (2020) and Mrabet et al. (2020) described a negative impact of climate change in North Africa. Algeria's geographical situation and climatic specificities make it very vulnerable to climate change (Sahnoune et al. 2013; Chourghal et al. 2016) reported that wheat yields would tend to decrease in the following years.

Saharan wheat landraces, resulting from natural and human selection for several centuries in hostile environments, could represent an interesting genetic material to meet these current and future agricultural concerns. In the Saharan oases, wheat is frequently facing drought problems because of the high evaporative demand (Sekkoum et al. 2012) and the limitation of water resources (Touitou and Abul Quasem 2018). High temperatures represents another stress as temperature can reach 45ºC during the day. Finally, oases soils are frequently saline (Chevalier 1932). The wheat landraces of the Saharan oases, probably introduced long time ago and submitted during centuries to strong selection pressures related to these physical constraints, are expected to exhibit a high level of abiotic stresses tolerance (Zaharieva et al. 2014). A high level of tolerance to drought (Ducellier 1920; Toutain 1977), heat (Ducellier 1920; Rodriguez 1932; De Arana 1934) and salinity (Erroux 1952; Toutain 1977) was effectively reported in this germplasm. *In-situ* conservation and management of genetic resources carried out by farmers allowed maintaining varieties that could represent a valuable source of abiotic stress tolerance. The further use of this germplasm in breeding programs however requires morphological characterization. Ducellier (1929), Erroux (1962) and Oumata et al. (2020) reported huge differences among landraces for plant, spike and grain chracteristics, but the quantative variation of these traits has never been analyzed.

The objective of this study was consequently to (i) describe the variation for plants, spike, grains, glumes and lemmas traits, (ii) estimate their genetic variance and heritability, (iii) evaluate the distribution of this variation at different geographical scales (region, oasis) and (iv) analyze its relationship with agro-climatic conditions.

Materials and methods

Plant material

A total of 58 Saharan bread wheat landraces was assessed in this study. Their morphological traits were compared to those of Anza and HD 1220, two commercial varieties widely cultivated in Algeria. Anza was selected by the Technical Institute of Field Crops (Institut Technique des Grandes Cultures, ITGC) of Sétif (Algeria) in 1998 from a variety from the United States. HD 1220 (or Hiddab) was selected by the same Institute in 1997 from material created at the International Wheat and Maize Improvement Center (Centro Internacional de Maiz y Trigo, CIMMYT) in Mexico. The Saharan wheat landraces were collected from farmers' fields in six oases of the Adrar region (Adrar, Bouda, Timmi, Tamantit, Tsabit and Timimoun), at altitudes comprised between 220 and 283 m, and in four oases of the Tamanrasset region (Abalessa, Ideles, In Amguel and Tamanrasset), at altitudes comprised between 889 and 1478 m (Table 1). These two regions are classified among the warmest of the Algerian Sahara. Low annual rainfall (74.0 mm) and high annual minimal and maximal temperatures (17.1 and 33.3°C, respectively) characterize the Adrar region. Negative temperatures are exceptionally registered in this location. The Tamanrasset region, located in the Hoggar Mountains, is characterized by slightly higher rainfall (139.7 mm) and lower minimal and maximal temperatures (15.2°C and 29.1°C, respectively), compared to the Adrar region. Absolute minimal temperatures over the 1980–2020 period were comprised between 1.7 and − 19.5°C. Temperatures below 0°C are common in March and can occur in April and May.

Field experiment

The bread wheat landraces and commercial varieties were sown in November 2012 at the Adrar experimental station of the National Institute for Agricultural Research of Algeria (INRAA), located in South-West Algeria (27° 49' N, 00° 11' W, 278 m a.s.l.). The experimental site is located in a desert climate. Annual rainfall is less than 50 mm year^{-1} and average temperature is around 25.4° C. The soil texture is sandy (92% sand). Irrigation was performed by submersion once a week. Fertilization was applied at the doses recommended by ITGC. Harvest was carried out at the end of April 2013.

The experimental design was a complete randomized block design with three replications. For each landrace collected, 15 spikes were randomly selected.

Table 1 List of the Saharan bread wheat landraces with their code and origin (region, oasis and altitude)

	Local name	Code	Region	Oasis	Altitude (m)
1	Bahmoud	A08	Adrar	Timimoun	240
2	Bahmoud	TI01	Adrar	Timimoun	240
3	Bel Mabrouk	A18	Adrar	Tamantit	246
4	Chater	A23	Adrar	Timmi	235
5	El-Farh	A27	Adrar	Timmi	258
6	Moumna	A30	Adrar	Adrar	250
7	Guemh Lahmar	TI02	Adrar	Timimoun	240
8	Mekkaouiya	A43	Adrar	Timimoun	220
9	Mekkaouiya	A44	Adrar	Bouda	241
10	Oum M'rakba	A47	Adrar	Tsabit	255
11	Oum M' rakba	A48	Adrar	Adrar	250
12	Oum M'rakba	TI03	Adrar	Adrar	250
13	Sebaga	A53	Adrar	Adrar	258
14	Touatia	A62	Adrar	Timimoun	240
15	Zeghloul	A63	Adrar	Timimoun	220
16	Baida	T01	Tamanrasset	In Amguel	970
17	Baida	T02	Tamanrasset	Ideles	1427
18	Baida	T03	Tamanrasset	In Amguel	1042
19	Baida	T04	Tamanrasset	In Amguel	990
20	Baida	T05	Tamanrasset	Ideles	1478
21	Baida	T06	Tamanrasset	Ideles	1280
22	Baida	T07A	Tamanrasset	Ideles	1280
23	Baida	T07B	Tamanrasset	Ideles	1280
24	Baida	T08	Tamanrasset	Ideles	1427
25	Baida	T09	Tamanrasset	In Amguel	1042
26	Bent el Hamra	T11	Tamanrasset	Tamanrasset	1379
27	Bent el Hamra	T12	Tamanrasset	Tamanrasset	1379
28	Bent M'Barek	T13	Tamanrasset	Tamanrasset	1283
29	Chouitar	T16	Tamanrasset	Tamanrasset	1205
30	H'bircha	T18	Tamanrasset	In Amguel	990
31	Hamra	T19	Tamanrasset	Ideles	1280
32	Hamra	T21	Tamanrasset	Abalessa	994
33	Hamra	T23	Tamanrasset	Abalessa	1059
34	Hamra	T24	Tamanrasset	Tamanrasset	1283
35	Hamra	T25	Tamanrasset	In Amguel	1042
36	Hamra	T26	Tamanrasset	In Amguel	1042
37	Hamra	T27	Tamanrasset	Ideles	1280
38	Hamra	T58	Tamanrasset	Ideles	1478
39	Hamra Lakhfifa	T28	Tamanrasset	Abalessa	918
40	Hanafi	T29	Tamanrasset	InAmguel	1042
41	Houiya	T30	Tamanrasset	Ideles	1418
42	Manga	T22	Tamanrasset	Abalessa	918
43	Manga	T31	Tamanrasset	Ideles	1418
44	Manga	T32	Tamanrasset	Tamanrasset	1379
45	Manga	T33	Tamanrasset	Abalessa	1059
46	Manga	T34	Tamanrasset	Tamanrasset	1379
47	Manga	T37	Tamanrasset	In Amguel	1042

Table 1 (continued)

	Local name	Code	Region	Oasis	Altitude (m)
48	Manga	T38	Tamanrasset	In Amguel	990
49	Manga	T39	Tamanrasset	In Amguel	1042
50	Manga	T41	Tamanrasset	Ideles	1478
51	Manga	T42	Tamanrasset	Abalessa	1059
52	Manga	T43	Tamanrasset	Tamanrasset	1283
53	Manga	T51	Tamanrasset	Abalessa	1059
54	Ras el Mouch	T50	Tamanrasset	Ideles	1418
55	Guemh	T54	Tamanrasset	Tamanrassset	1283
56	Skandria	T55	Tamanrasset	Abalessa	994
57	Skandria	T56	Tamanrasset	Abalessa	1059
58	Terouzi	T57	Tamanrasset	Ideles	1478

Table 2 Mean square value, mean value of regions, oases and Saharan bread wheat landraces

Traits	Mean Square Region (df = 1)	Mean value		Mean Square Oasis (df = 9)	Mean Square Landrace	
		Adrar	Tamanrasset			df
Plant height	2864.40 ***	89.20	98.70	549.50 **	306.4***	56
Stem length	1830.70 ***	79.80	87.40	362.80 *	248.4 *	56
Number of fertile tillers per plant	1781.45 ***	10.51	18.06	348.12 ***	94.22***	56
Number of internodes	3.92 ***	4.34	4.69	0.55 ***	0.21***	56
Internodes length	65.76 ns	36.42	37.87	52.87 ns	48.07 **	56
Last internode length	2.21 ns	16.57	16.30	39.40 ns	33.3***	56
Spike length	3934.90 ***	87.30	100.60	1125.00 ***	532.14***	57
Face spike width	109.91 ***	14.79	12.56	29.82 ***	8.94***	57
Profile spike width	129.42 ***	13.97	11.54	32.38 ***	7.99***	57
Spike weight	41.13 ***	4.16	2.76	7.04 ***	1.65***	56
Number of spikelets per spike	21.50 *	20.80	2.76	6.21 *	5.65***	58
Number of grain per spike	4017.20 ***	74.00	60.20	937.80 ***	314.26***	56
Thousand grain weight	2066.64 ***	46.40	36.45	304.28 ***	67.77***	56
Grain length	5.95 ***	6.72	6.20	0.70 ***	0.17***	57
Grain width	3.27 ***	3.44	3.06	0.58 ***	0.27***	57
Grain thickness	2.66 ***	3.15	2.81	0.48 ***	0.10***	57
Glume length	1.14 ns	9.16	8.93	0.65 ns	0.78***	58
Glume width	0.40 *	4.87	4.73	0.23 ***	0.12***	58
Glume beak length	0.84 ns	1.85	2.04	0.40 ns	1.61***	58
Lemma length	1.18 *	10.47	10.24	0.36 ns	0.48***	58
Lemma width	0.14 ns	4.94	4.86	0.12 *	0.10***	58

MS : mean square, df : degree of freedom, significance level ns : non significant ; * : $p \leq 0,05$; ** : $p \leq 0,01$; *** : $p \leq 0,001$

Five spikes were used in each replication. The grains of each spike were sown on a 1.5 m row with grain spacing of 15 and 20 cm between rows.

Morphological characterization

At maturity, plants were harvested and twenty-one morphological traits were measured (Table 2).

Measurements were performed on 5 plants per row.

Data analysis

An analysis of variance (ANOVA) was carried out on all the studied traits in order to analyse the distribution of the variation between regions, and among oases and landraces. The comparison of means was performed using the Fisher's PLSD (protected least significant difference) test at 5% ($P \leq 0.05$). Pearson correlations were calculated to determine the existence and level of correlations ($p \leq 0.05$) between the different traits studied. The data was analyzed using GenStat 15th edition. A Principal Component Analysis (PCA) was also performed on 55 Saharan landraces and 15 morphological traits of the plant (stem length, number of fertile tillers per plant, internodes length, number of internodes, and last internode length), spike (length, profile and face width, weight, number of spikelets and number of grains) and grain (length, width, thickness and weight) as well as a supplementary variable (altitude). The PCA was computed using the FactoMineR (Lê et al. 2008) and Factoshiny (Vaissie et al. 2017) packages in R software.

Genotypic variance, phenotypic variance and environmental variance were estimated respectively as $\sigma^2_g = [(MSG) - (MSE)] / r$, $\sigma^2_p = [\sigma^2_g + (\sigma^2_e / r)]$ and σ^2_e = error mean square, with MSG = mean square of landrace; MSE = error mean square; r = number of replications (blocks) (Singh and Chaudhary 1985). The genotypic and phenotypic coefficients of variation were calculated respectively as $GCV = [(\sqrt{\sigma^2_g} / \bar{X})] \times 100$ and $PCV = [(\sqrt{\sigma^2_p} / \bar{X})] \times 100$, with $\bar{X}$ = grand mean of a trait. The coefficients of variation was classified, according to Singh and Chaudhary (1985) as low (0–10%), moderate (10–20%) and high (> 20%). Broad sense heritability (h^2_{bs}) was calculated as $h^2_{bs} = [(\sigma^2_g) / (\sigma^2_P)] \times 100$, with h^2_{bs} = heritability in broad sense, σ^2_g = genotypic variance and σ^2_P = phenotypic variance. Broad sense heritability was classified, according to Allard (1960) as low (0–30%), moderate (30–60%) and high (> 60%).

Genetic advance as percentage of the mean (GAM) and genetic advance (GA) were calculated according to Johnson et al. (1955) as $GAM (\%) = (GA / \bar{X}) \times 100$ where $GA = K (\sigma_P) h^2$, with K = constant 2.06 at 5% selection pressure, σ_P = phenotypic standard deviation and $\bar{X}$ = grand mean of a trait. Genetic advance as percentage of mean (GAM) was classified as low ($0 \leq GAM \leq 10$); moderate ($10 \leq GAM \leq 20$) and high ($GAM \geq 20\%$).

Results

Effects of regions, oases and landraces on plant, spike and grain characteristics

Significant region and oasis effects were noted for the majority of the traits (Table 2). The coefficient of variation varied from low to high depending on the trait. The region effect was highly significant for plant height, stem length, number of fertile tillers per plant, number of internodes, spike length, spike width, spike weight, number of grains per spike, thousand grain weight, grain length, width and thickness. It was significant for the number of spikelets per spike, glume width and lemma length. No significant region effect was noted for the length of the internode, last internode length, glume length, lemma width and glume beak length. The oasis effect was highly significant for the number of fertile tillers per plant, number of internodes, length of the spike, spike width (face and profile), spike weight, number of grains per spike, thousand grain weight, grain length, width and thickness, and glume width. It was significant for plant height, stem length, number of spikelets per spike and lemma width. Significant differences were noted among landraces for all quantitative traits (Table 2).

Distribution of the variation for plant traits between regions and among oases and landraces

A significant variation in plant height was noted in the collected material and significant differences were recorded for this trait between the two prospected regions. Landraces from the Tamanrasset region were taller. The highest plants (115.45 cm) were observed in Manga T51 from the Abalessa oasis of the Tamanrasset region while the shortest plants (77.51 cm) were noted in Moumna A30 from the Adrar oasis. The longest stems were also observed in landraces collected in the Tamanrasset region. Manga T43 from the Tamanrasset oasis was characterized by the longest stem (101.57 cm). Among landraces, the shortest stems were recorded in those from the Tsabit oasis of the Adrar region. The commercial varieties Anza and HD 1220 showed the shortest stems (65.03 cm).

The number of fertile tillers per plant ranged from 5.81 for Moumna A30 from the Adrar oasis to 26.77 for Hamra T25 from the In Amguel oasis (Tamanrasset region) and Bent el Hamra T12 from the Tamanrasset oasis. Three groups of oases were distinguished, based on this trait. The first group, composed by the oases of In Amguel, Tamanrasset and Ideles (Tamanrasset region) included landraces with the highest number of fertile tillers per plant, followed by the group composed by landraces from the oases of Timimoun (Adrar region) and Abalessa (Tamanrasset region) with average values (Table 3). The lowest number fertile tillers per plant was observed in landraces from the Adrar region. Commercial varieties were characterized by low values (9.61 for HD 1220 and 14.09 for Anza).

Landraces originating from Tamanrasset region had the highest number of internodes per plant (4.69), while those originating from Tsabit (Adrar region) had the lowest ones. Among of the landraces from Tamanrasset region, Bent el Hamra T11 and Manga T41 had the highest number of internodes (4.99). The commercial variety HD 1220 has the lowest number of internodes per plant (3.93).

No significant differences were noted between the two regions and among oases for the length of the internodes. However, highly significant differences existed among landraces. The length of the internodes varied from 28.57 cm for Sebaga A53 from the Adrar oasis to 45.52 cm for Manga T42 and T31 from the Abalessa and Ideles oases, recpectively, both located in the Tamanrasset region.

Similarly, regions and oases did not differ significantly for last internode length, while highly significant differences were noted among landraces, even within a same oasis. Manga T42 had the longest last internode (23.58 cm) and Skandria T56 had the shortest (9.25 cm) while both landraces were collected in the Abalessa oasis of the Tamanrasset region. The commercial varieties showed values equal to or lower than the general mean (16.33 cm).

Distribution of the variation for spike traits between regions and among oases and landraces

The longest spikes were observed in landraces from the Tamanrasset region (100.60 mm) and, among them, in landraces from the Abalessa oasis (111.78 mm). Conversely, the shortest spikes (72.48 mm) were found in landraces from Tsabit (Adrar region). The length of the spike varied from 68.86 mm for Chater A23 from the Timmi oasis (Adrar region) to 139.65 mm for Manga T33 from the Abalessa oasis (Tamanrasset region). The commercial varieties HD 1220 and Anza showed average values of 112.41 mm and 102.87 mm, respectively (Table S1).

Landraces originating from the oases of the Adrar region, with the exception of those from the oasis of Timimoun, were characterized by the widest spike face. Moumna A30 from the oasis of Adrar has the widest spike face (18.19 mm). The narrowest spikes face (9.02 mm) was recorded in the oasis of Tamanrasset and in Bent el Hamra T12. The commercial varieties Anza and HD 1220 had a wide spike face (15.2 mm). Landraces originating from the oases of the Adrar region, with the exception of those from the oasis of Timimoun, were also characterized by the widest spike profile. The profile width of the spikes varied considerably among landraces, ranging from 8.98 mm for Bent el Hamra T12 originating from the Tamanrasset oasis to 17.91 mm for Mekkaouiya A44 from the Bouda oasis (Adrar region). The commercial varieties had narrow spike profile (less than the average of 12.11 mm).

Landraces from the Adrar region had the highest spike weight (4.16 g) and those from the Ideles, In Amguel and Tamanrasset oases in the Tamanrasset region had the lowest one. A wide variation for this trait was noted among landraces. Spike weight varied from 1.64 g for Bent el Hamra T12 to 5.60 g for Mekkaouiya A44. The commercial varieties Anza and HD 1220 had average weights (2.91 and 2.93 g, respectively).

Higher number of spikelets per spike (22.5) was observed in landraces from the Bouda oasis, compared to landraces from other locations. The highest number of spikelets per spike (25.0) was noted in Bent M'Barek T13 from the Tamanrasset oasis. The varieties HD 1220 and Anza were characterized by the lowest number of spikelets per spike (17.1 and 18.9, respectively).

The number of grains per spike varied considerably. Mekkaouiya A44 had the highest number of grains per spike (94.7) and Bent el Hamra T12 the lowest (41.3). Landraces from the Adrar region were among those with the highest number of grains per spike (74.0). Among them, those from the Bouda

Table 3 Mean value and group mean of morphological traits among oasis for Saharan bread wheat landraces

	Tamanrasset					Adrar				
	Abalessa	Tamanrasset	Timimoun	In Amguel	Ideles	Adrar	Tamantit	Timmi	Bouda	Tsabit
Plant height	101.24 a	99.09 ab	97.39 abc	96.6 abc	98.78 ab	88.07 cd	82.95 bcd	83.91 d	82.87 bcd	79.68 d
Stem length	86.79 abc	89.24 a	86.71 abc	86.05 abc	87.77 ab	78.82 bcd	73.22 bcd	75.56 d	74.74 abcd	71.93 cd
Last internode length	17.61	16.98	19.37	15.16	16.07	16.92	14.54	13.14	14.15	16.25
Internodes length	38.87	38.3	39.51	36.69	37.97	37.25	34.69	32.33	33.81	35.06
Number of internodes	4.6 bc	4.76 a	4.37 de	4.72 ab	4.68 ab	4.24 de	4.56 abcd	4.45 cd	4.22 de	4.04 e
Number of fertile tillers per plant	13.04 b	19.38 a	15.52 b	19.6 a	18.95 a	7.8 c	7.13 c	8.3 c	6.62 c	7.5 c
Spike length	111.78 a	106.86 ab	95.97 bc	95.67 c	94.61 c	88.34 cd	79.78 cd	79.33 d	77.73 d	72.48 d
Face spike width	12.95 b	11.39 c	12.28 bc	12.7 b	12.89 b	16.31 a	16.11 a	16.49 a	17.75 a	15.96 a
Profile spike width	11.33 cd	10.41 d	11.6 c	11.91 c	12.02 c	14.67 b	15.75 ab	15.18 b	17.91 a	16.73 ab
Number of spikelets per spike	21.57 abc	21.56 abc	19.86 bd	22.35 abc	21.62 abc	21.53 abcd	22.44 ab	20.77 abcd	22.5 a	21.06 abcd
Number of grain per spike	66.95 bde	54.71 f	61.08 def	60.98 def	58.77 df	81.73 abc	82.61 ab	78.17 abc	94.72 a	74.12 abcd
Spike weight	3.34 c	2.54 d	3.24 c	2.62 d	2.66 d	4.63 ab	4.66 ab	4.56 ab	5.6 a	4.24 bc
Grain length	6.12 bc	6.22 bc	6.78 a	6.16 c	6.23 bc	6.74 a	6.47 ab	6.62 a	6.88 a	6.67 a
Grain width	3.21 bd	2.96 e	3.2 bde	3.13 bde	2.97 e	3.57 abc	3.58 ab	3.66 a	3.58 ab	3.56 abcd
Grain thickness	2.88 c	2.74 d	2.89 c	2.78 d	2.82 cd	3.22 b	3.33 ab	3.4 a	3.35 ab	3.38 ab
Thousand grain weight	38.85 bc	35.35 d	40.65 b	35.23 d	36.68 cd	48.79 a	49.74 a	50.67 a	49.31 a	48.95 a
Glume length	8.79	8.72	9.07	8.84	9.22	9.27	8.83	9.07	9.5	9.6
Glume width	4.87 abcd	4.54 e	4.74 abcdefg	4.84 abcdef	4.69 aceg	4.93 abcd	5.00 a	4.98 ab	4.85 abcde	4.95 abc
Glume beak length	1.92	1.88	1.63	2.04	2.21	1.92	2	2.07	2.23	1.7
Lemma length	10.32	10.26	10.47	10.06	10.33	10.65	9.83	10.5	10.5	10.5
Lemma width	4,98 abc	4,69 bdf	4,87 abcde	4,9 abc	4,87 abcde	5,03 a	5 ab	5 abc	4,85 abcdef	4,9 abcd

a,b,c,d,e,f,g homogenous groups following the Fisher's PLSD test oasis exhibited the highest values (94.7). The commercial varieties showed mean values of 58.2 for Anza and 54.9 for HD 1220.

Distribution of the variation for grain traits between regions and among oases and landraces

Landraces with the highest thousand-grain weight originated from the Adrar region (46.40 g). Among them, those from Timmi, Tamantit, Bouda, Tsabit and Adrar had heavier grains. Landraces from the oases of Tamanrasset and In Amguel had the lowest thousand-grain weight (35.23 g). Thousand grain weight ranged from 26.97 g for Hanafi T29 from the In Amguel oasis (Tamanrasset region) to 55.26 g for Chater A23 from the Adrar oasis. Anza and HD 1220 presented respectively average values of 39.05 and 41.16 g.

The longest grains were observed in landraces from the oases of the Adrar region (6.72 mm) and the shortest grains in landraces from the In Amguel oasis of the Tamanrasset region (6.16 mm). Zeghloul A63 from the Timimoun oasis (Adrar region) had the longest grains (7.35 mm) and Bent el Hamra T13 from the Tamanrasset oasis the shortest ones (5.94 mm). Anza and HD 1220 had fairly long grains (6.31 and 6.43 mm).

The landraces from the Timmi oasis (Adrar region) had the largest grains (3.66 mm) and those from the oases of Ideles and Tamanrasset (Tamanrasset region) the narrowest (2.96 mm). The widest grains (3.82 mm) were observed in Chater A23 from the Timmi oasis (Adrar region). Anza, T50, T57 and T54 have the narrowest grains (2.34 mm) (Table S1).

The landraces from the oases of the Adrar region had, in average, thickest grains (3.15 mm) than those from the oases of the Tamanrasset region (2.81 mm). Chater A23 and El-Farh A 27 from the Timmi oasis had the thickest grains (3.51 mm) and Hanafi T29 from In Amguel the thinnest ones (2.53 mm). Grain thickness of the commercial varieties HD 1220 and Anza was 2.66 and 2.69 mm, respectively.

Distribution of the variation for glume and lemma traits between regions and among oases and landraces

Regions and oases did not significantly differ for the length of the glume. However, highly significant differences existed among landraces. The length of the glume varied from 7.95 mm for Baida T09 from In Amguel (Tamanrasset region) to 11.06 mm for Zeghloul A63 from Timminoun (Adrar region).

Significant variations between regions and oases were noted for the width of the glume. Landraces from the Tamantit oasis (Adrar region) had, in average, the widest glumes (5 mm). Manga T22 from the Abalessa oasis (Tamanrasset region) however presented the highest value for this trait (5.10 mm). The narrowest glumes were recorded in the Tamanrasset oasis landraces (4.54 mm). Hanafi T29 from In Amguel oasis had the narrowest glumes (3.95 mm). The varieties Anza and HD 1220, with a width of 4.80 mm, were grouped together.

No significant differences were found between the two regions and among the oases for the beak length trait. Nevertheless, significant differences among landraces were recorded. The longest glume beak (7.4 mm) was observed in the commercial variety HD 1220. Among Saharan wheat landraces, the highest value (3.4 mm) was found in Ras el Mouch T50 from the Ideles oasis of the Tamanrasset region. The shortest beak (1.05 mm) was observed in Mekkaouiya A43 from the Timimoun oasis of the Adrar region.

No significant differences were noted between oases for the length of the lemma. However, significant differences ($P \leq 0.001$) among landraces were observed. The commercial variety HD 1220 as well as Zeghloul A63 from the Timimoun oasis (Adrar) were characterized by the longest lemma length (11.50 mm). The shortest lemma (7.95 mm) was noted in Baida T09 from In Amguel oasis (Tamanrasset).

The widest lemmas were observed in landraces from the Adrar oasis (4.94 mm). The narrowest (4.69 mm) were found in the Tamanrasset oasis. The commercial variety HD 1220 presented the widest lemmas (5.65 mm) while the narrowest (4.20 mm) were noted in Bent el Hamra T12 from the Tamanrasset oasis.

Correlations among traits

The phenotypic correlations among the different traits are presented in Table 4. Thousand grain weight was highly positively correlated with weight spike, number of grains per spike, spike widths (face and profile), grain length, grain width and thickness, glume width and width lemma and highly negatively associated with number of fertile tillers per plant and

Table 4 Pearson correlation between different morphological traits of 55 Saharan bread wheat landraces

	SW	NGP	TGW	NTP	STL	IL	LIL	NI	SL	SWP	SWF	NSS	GRL	GRW	GRT	GL	GW	BLG	LL	LW	ALT
SW	1,000																				
NGP	0.912***	1.000																			
TGW	0.881***	0.672***	1.000																		
NTP	− 0.933***	− 0.875***	− 0.786***	1.000																	
STL	− 0.388**	− 0.475***	− 0.323*	0.408**	1.000																
IL	− 0.134	− 0.308*	− 0.083	0.131	0.849***	1.000															
LIL	− 0.025	− 0.275*	0.088	0.032	0.735***	0.942***	1.000														
NI	− 0.551***	− 0.407**	− 0.667***	0.508***	0.274*	0.001	-0.178	1.000													
SL	− 0.083	− 0.130	− 0.253	0.001	0.489***	0.617***	0.554***	0.199	1.000												
SWP	0.678***	0.664***	0.718***	− 0.570***	− 0.543***	− 0.491***	− 0.404**	− 0.475***	− 0.737***	1.000											
SWF	0.829***	0.847***	0.738***	− 0.782***	− 0.545***	− 0.385**	− 0.348**	− 0.496***	− 0.386**	0.806***	1.000										
NSS	0.135	0.407**	− 0.087	− 0.108	− 0.141	− 0.370**	− 0.479***	0.318*	− 0.201	0.285*	0.124	1.000									
GRL	0.578***	0.423**	0.642***	− 0.492***	− 0.412**	− 0.205	-0.081	− 0.613***	− 0.284*	0.511***	0.566***	− 0.268*	1.000								
GRW	0.781***	0.727***	0.740***	− 0.738***	− 0.290*	− 0.100	0.038	− 0.482***	− 0.031	0.503***	0.617***	0.096	0.298*	1.000							
GRT	0.846***	0.677***	0.926***	− 0.763***	− 0.355**	− 0.156	-0.025	-0.563***	− 0.322*	0.775***	0.782***	− 0.027	0.543***	0.680***	1.000						
GL	0.151	0.108	0.125	− 0.123	− 0.097	0.074	-0.008	− 0.207	− 0.026	0.174	0.413**	− 0.407**	0.397**	-0.049	0.206	1.000					
GW	0.540***	0.404**	0.621***	− 0.462***	− 0.031	0.125	0.208	− 0.331*	− 0.029	0.432**	0.438***	− 0.008	0.177	0.594***	0.596***	0.098	1.000				
BLG	− 0.115	− 0.073	-0.167	0.098	− 0.013	− 0.064	− 0.194	0.054	− 0.032	0.011	0.155	− 0.180	0.118	− 0.398**	− 0.009	0.536***	− 0.070	1.000			
LL	0.229	0.121	0.229*	− 0.225	− 0.056	0.147	0.141	− 0.380*	0.214	0.007	0.301*	− 0.491***	0.527***	0.064	0.161	0.692***	0.001	0.275*	1.000		
LW	0.530***	0.498***	0.545***	− 0.485***	− 0.084	0.042	0.050	− 0.268*	− 0.105	0.465***	0.534***	0.223	0.118	0.511***	0.530***	0.166	0.807***	− 0.036	0.017	1.000	
ALT	− 0.672***	− 0.519***	− 0.759***	0.595***	0.380**	0.159	-0.040	0.602***	0.326*	-0.569***	− 0.559***	0.160	− 0.686***	− 0.593***	− 0.679***	− 0.005	− 0.361**	0.207	− 0.136	− 0.193	1.000

Degree of freedom = 53. α 0.05 = 0.2663. α 0.01 = 0.3454. α 0.001 = 0.4326

SW: spike weight; NGP: number of grains per spike; TGW: thousand grains weight; NTP: number of fertile tillers per plant; STL: stem length; IL: internodes length; LIL: last internode length ; NI: number of internodes; SL: spike length; SWP: spike width (profile); SWF: spike width (face); NSS: number of spikelets per spike; GRL: grains length; GRW: grain width; GRT: grain thickness; GL: glume length; GW: glume width; BLG: beak length of the glume; LL: lemma length; LW: lemma width; ALT: altitude number of internodes. Stem length, internodes length and last internode length were closely associated. However, Manga T22 and Manga T42 from the Abalessa and Ideles oases, respectively, showed a slightly higher last internode to stem height ratio (data not shown). The number of grains per spike showed a highly significant positive association with spike width, grain width, grain thickness, lemma width and highly significant negative association with number of fertile tillers per plant and stem length. Highly significant negative correlations were noted between the number of fertile tillers per plant and spike width, grain length, grain width, grain thickness, glume width, lemma width. The number of fertile tillers per plant and the number of internodes were highly significantly positively associated.

Relationship between the morphology of landraces and altitude of their origin

Altitude was highly significantly and negatively correlated with spike weight, number of grains per spike, thousand weight grains, spike width, grain length, grain width and thickness grain, and significantly positively associated with stem length, number of fertile tillers per plant, number of internodes and spike length (Table 4).

The first two principal components of the Principal Component Analysis explained 72.3% of the total variation (Table 5). The first component (PC1) explained 51.17% and the second component (PC2) 21.14% of this variation. The first axis was positively correlated with spike weight, number of grains per spike, thousand grain weight, spike profile width, spike face width, grain length, grain width, grain thickness, and negatively with the number of fertile tillers per plant, stem height, number of internodes, and altitude (Fig. 1). PC1 mainly opposed landraces from the Adrar region (low altitudes) which more grains per spike, and higher spike weight and thousand grains weight, compared to the landraces from the Tamanrasset region (high altitudes) (Fig. 2). The landraces from low altitudes were also characterized by wider spikes (face and profile), very long, wide and thick grains, short stems and a low number of fertile tillers per plant and internodes. Landraces from Adrar (low altitudes) Bel Mabrouk A18, Chater A23, El-Farh A27, El Moumna A30, Mekkaouiya A44, Oum Mrakba A47, Sebaga A53 and Oum Mrakba Ti03 were opposed to Bent-Hamra T11, Bent el Hamra T12 and Manga T43 from the oasis of Tamanrasset. The second axis was positively correlated to internodes, last internode and spike lengths, and negatively correlated to the number of spikelets per spike. It opposed landraces from Tamanrasset with long spikes, a reduced number of spikelets and long internodes and last internode as Manga T22, T31, T32, T42 and T51, to the landraces Bent M'Barek T13, Skandria T56, Houiya T30 and Baida T09 also originating from Tamanrasset.

Table 5 Principal Component analysis for morphological traits in Saharan bread wheat landraces

	PC1	PC2	PC3	PC4	PC5
Eigen value	7.68	3.17	1.55	0.87	0.49
% of variance	51.17	21.14	10.37	5.82	3.26
Cumulative %	51.17	72.32	82.68	88.50	91.76
Traits					
PEP	0.92	0.28	0.22	– 0.06	0.09
NGE	0.87	0.02	0.42	– 0.10	0.12
PMG	0.88	0.35	– 0.10	0.13	– 0.06
NTP	– 0.86	– 0.28	– 0.27	0.19	– 0.05
HTG	– 0.62	0.58	0.17	0.41	0.15
LEN	– 0.42	0.85	0.09	0.21	0.12
LCE	– 0.30	0.92	-0.04	0.17	– 0.02
NEN	– 0.62	– 0.37	0.43	0.04	0.11
LGE	– 0.42	0.60	0.42	– 0.49	0.06
LAE	0.86	– 0.25	– 0.11	0.39	0.03
EPE	0.92	– 0.05	0.04	– 0.01	0.10
NEP	0.15	– 0.52	0.70	0.29	0.18
LGG	0.65	0.14	– 0.50	– 0.19	0.43
LAG	0.74	0.30	0.29	– 0.04	-0.41
EPG	0.88	0.23	– 0.06	0.21	-0.08
ALT	– 0.72	– 0.22	0.26	– 0.01	0.03

Traits heritability

Genetic parameters and variance for the 21 traits are presented in Table 6. Genotypic variance ranged from 0.04 (width lemma) to 250.14 (spike length) and phenotypic variance ranged from 0.05 (thickness grain, width lemma) to 266.07 (spike length). Both

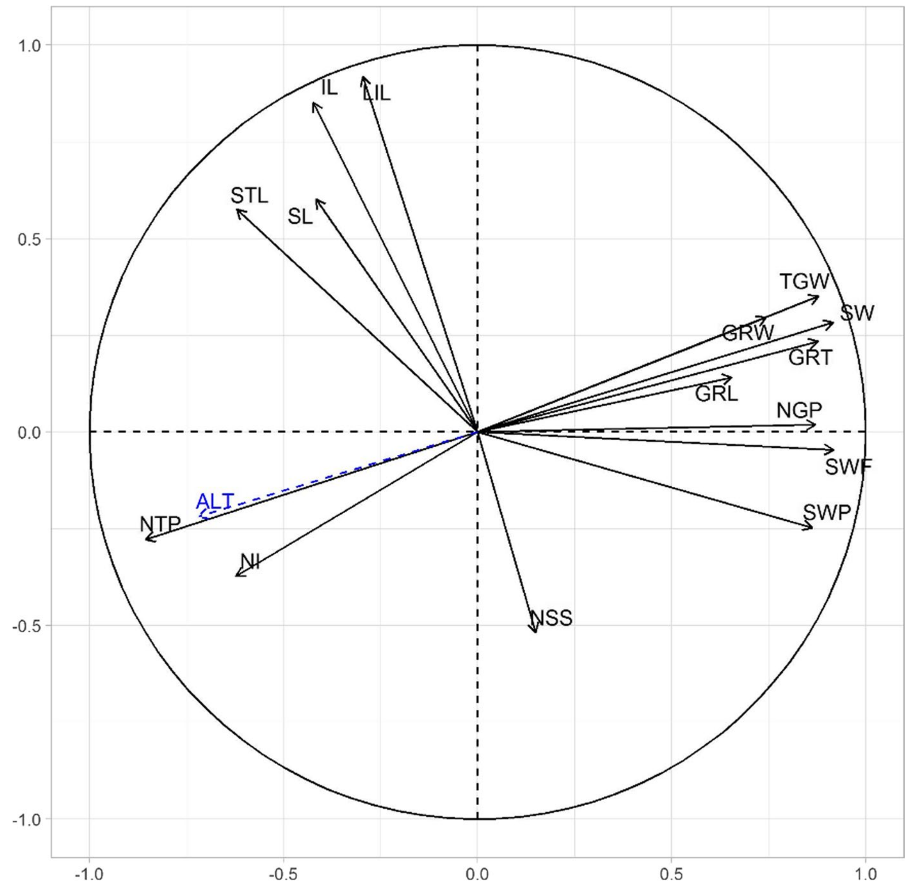

Fig. 1 Graphical representation of the correlations between the quantitative variables of Saharan bread wheat landraces and the first two axes of the principal component analysis. SW: spike weight; NGP: number of grains per spike; TGW: thousand grains weight; NTP: number of fertile tillers per plant; STL: stem length; IL: internodes length; LIL: last internode length ; NI: number of internodes; SL: spike length; SWP: spike width (profile); SWF: spike width (face); NSS: number of spikelets per spike; GRL: grains length; GRW: grain width; GRT: grain thickness; ALT: altitude

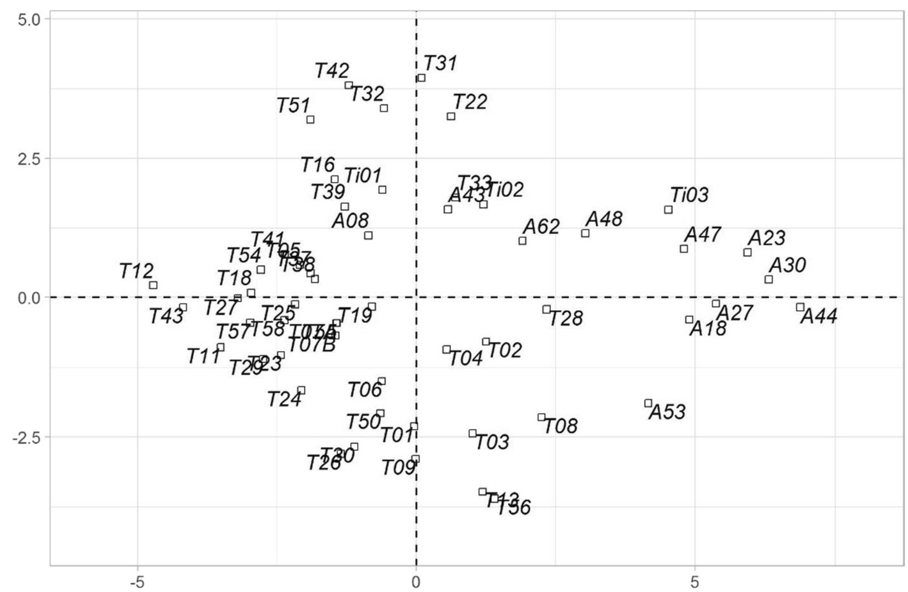

Fig. 2 factor coordinate for PC1 and PC2 for 15 morphological traits of 55 Saharan bread wheat landraces originating from oases of the Adrar and Tamanrasset regions

the phenotypic and genotypic coefficients of variance were low to high. Broad sense heritability ranged from 38.8% (stem length) to 94.0% (spike length). It was high (> 60%) for number of internodes, number

Table 6 Genetic parameters and variance for 21 traits of Saharan bread wheat landraces

Trait	Range	Mean	σ^2g	σ^2p	h^2_{bs} (%)	GCV (%)	PCV (%)	GA	GAM (%)
Plant height	77.51–115.45	95.78	50.00	102.13	48.96	7.38	10.55	10.19	10.64
Stem length	65.03–101.57	84.8	32.13	82.90	38.76	6.68	10.74	7.27	8.57
Internodes length	28.57–45.52	37.35	7.23	16.02	45.14	7.20	10.72	3.72	9.96
Number of internodes	3.89–4.99	4.59	0.05	0.07	71.43	4.87	5.76	0.39	8.50
Last internode length	9.25–23.58	16.33	5.86	11.10	52.76	14.82	20.40	3.62	22.17
Number of fertile tillers per plant	5.81–26.77	15.99	28.58	31.41	91.00	33.43	35.05	10.51	65.73
Spike length	68.86–139.65	97.24	250.14	266.07	94.01	16.26	16.77	31.59	32.49
Spike width (face)	9.02–18.19	13.27	3.95	4.47	88.26	14.98	15.93	3.84	28.94
Spike width (profile)	8.98–17.91	12.11	3.68	4.00	91.99	15.84	16.52	3.79	31.30
Number of spikelets per spike	17.14–24.98	21.41	2.08	2.85	73.11	6.74	7.89	2.54	11.86
Spike weight	1.64–5.60	31.1	0.69	0.83	83.64	2.67	2.93	1.57	5.05
Number of grains per spike	41.34–94.72	63.45	120.18	157.13	76.48	17.28	19.76	19.75	31.10
Thousand grains weight	26.97–55.26	39.03	28.14	33.89	83.03	13.59	14.92	9.96	25.52
Length grain	5.94–7.35	6.34	0.08	0.09	88.24	4.46	4.73	0.55	8.68
Width grain	2.34–3.82	3.14	0.08	0.14	59.26	9.01	11.92	0.46	14.65
Thickness grain	2.53–3.55	2.89	0.05	0.05	90.00	7.74	7.74	0.41	14.19
Length glume	7.95–11.06	9.03	0.32	0.39	80.77	6.26	6.92	1.04	11.52
Width glume	3.95–5.10	4.77	0.05	0.06	75.00	4.69	5.14	0.38	7.97
Beak length of the glume	1.05–7.40	2.08	0.73	0.81	90.06	41.08	43.27	1.67	80.29
Length lemma	9.50–11.50	10.32	0.15	0.24	62.50	3.75	4.75	0.63	6.10
Width lemma	4.20–5.65	4.89	0.04	0.05	70.00	4.09	4.57	0.32	6.54

σ^2_g genotypic variance, σ^2_p phenotypic variance, h^2_{bs} (%) broad sense heritability, GCV (%) genotypic coefficients of variation, PCV (%) phenotypic coefficients of variation, GA genetic advance, GAM genetic advance as percentage of the mean

of fertile tillers per plant, spike length, width and weight, number of spikelets per spike, number of grains per spike, thousand grain weight, grain length and thickness, glume length and width and glume beak length. Genetic advance as percentage of mean ranged from low (5.05) for spike weight to high (80.3%) for glume beak length. Genetic advance as percentage of mean was high (> 20) for last internode length, number of fertile tillers per plant, spike length, spike width, number of grains per spike, thousand grains weight and beak length of the glume.

Discussion

A huge variation was observed among landraces for all the studied traits. These results confirmed previous studies from Ducellier (1920, 1929) and Erroux (1952, 1958, 1962 and 1991) which emphasized the high number of forms grown in the Saharan oases. A high number of botanical forms associated to different morphological characteristics has also been reported by Zaharieva et al. (2014) and Oumata et al. (2020). This morphological variation is likely to be due to the high diversity of wheats introduced in the oasis as well as from interspecific crosses (Zaharieva et al. 2015). Compactoid wheat is expected to derive from crosses between bread wheat and compact wheat (*T. aeastivum* ssp. *compactum* (Host) MacKey). The oldest remains of compact wheat were found in the site of Tell Ramad in Syria (7,000 BCE) (Renfrew 1969). The presence of this sub-species was reported in Egypt from the 5th Millenium BCE (site of Merimdah Beni Salame) (Renfrew 1969) and was cultivated in this country probably until 2,500 BCE (site of Afyeh) (Chowdhury and Buth 1971). Saharan speltoid forms have many traits in common with spelt wheat (*Triticum spelta* L.). The speltoid wheat landraces present in the Saharan oasis could consequently have originated from intermediate forms, with semi-adherent glumes and spikes difficult to thresh, already reported in Turkestan, Iran and Afghanistan by Vavilov (1987).

Internode, glume and glume beak length did not vary between regions and among oases. Conversely, a high genetic variance was observed for plant height, stem length, number of fertile tillers per plant, spike length, number of grain per spike and thousand grains weight, suggesting a broad variation for these traits. Biomass and grain yield related traits like plant height, number of fertile tillers per plant, spike weight, spike length, number of grains per spike and thousand grain weight highly differed between regions and among oases. The distribution of this variation between the two considered regions and among oases is likely to be due to the selection made by farmers among these introductions, according to the specific climatic conditions of the environment (Pecetti and Damania 1996).

Saharan wheat landraces are generally tall. Farmers in the oases are highly interested by long stems, as straw is generally used for livestock feeding (Erroux 1962). Some few short statured forms were found, in agreement to Zhukovsky (1964). Some Saharan landraces have heavy grains, compared to commercial varieties. Erroux (1962) already reported high thousand grain weight in the Saharan landraces Fartass and El Hamra. In the present study, high thousand grain weight was mainly noted in landraces from the Adrar region, as already reported by Merdas (2012). The number of grains per spike was high, in good agreement with observations of Ducellier (1920), Erroux (1962) and Merdas (2012) in Algeria and Ciferri and Garavini (1941) in Libya. Interestingly, among the landraces, number of grains per spike and thousand-grain weight were positively associated.

Several associations between the traits related to the yield components were noted, some of them having been reported in other conditions. Stem length was significantly and negatively correlated with thousand grain weight as reported by Mahmood and Shahid (1993). The number of spikelets per spike was positively correlated with the number of grains per spike, in accordance with Akram et al. (2008) and Baye et al. (2020). However, spike length was not correlated with yield components in contrast to what was reported by Ali et al. (2008), Uddin et al. (2015) and Xhulaj et al. (2019). This is likely to be due to the presence, among Saharan wheat, of two differents forms, with different spike compacity and fertility.

Principal component analysis revealed that the morphological variation was influenced by altitude. Landraces originating from the Adrar region (low altitudes) are opposed to landraces originating from the Tamanrasset region (high altitudes). Climatic factors of these regions could have contributed in a non-negligible proportion in the arrangement of this intra and inter-regional variability (Oumata et al. 2020). Interestingly, Saharan landraces from low altitudes oases of Adrar had short stems and less fertile tillering but very wide, short and heavy spikes with more grains per spike and higher thousand-grain weight. These landraces included the compactoid landrace Bel Mabrouk previously mentioned by Erroux (1962) for its high yield. Acccording to Sattar et al. (2010) and Altuhaish et al. (2014) reduced plant height and number of tillers in low altitude areas could be due to higher temperatures. Conversely, landraces from the high altitude Tamanrasset oases were tall, with fertile and had long lax spikes. They included the speltoid landraces El Hamra and Manga. Erroux (1962) already distinguished within the Saharan landraces, “speltoid” and “compactoid” forms differing for their spike characteristics.

The phenotypic coefficient of variance (PCV) was higher than the genotypic coefficient variance (GCV) for plant height, stem length, internodes length, last internode length, number of grains per spike and thousand grain weight, suggesting that environmental factors strongly influenced the expression of these agronomical traits. Sareen et al. (2018) found similar results for thousand grain weight. Spike weight, grain length and thickness, glume length and lemma width were much less affected by environmental conditions. Moderate heritability was observed for plant height, stem length and internodes length. High heritability coupled with high genetic advance as percentage of mean were recorded for number of fertile tillers per plant, spike length and width, number of grains per spike, thousand grain weight and beak length of the glume. This indicated that the genotypic component was highly responsible for the total variation and suggested that these traits could be easily transmitted by selection from parents to the progeny. High heritability coupled with high genetic advance was also reported for both traits by number of grains per spike and thousand grain by Meena et al. (2014), Balkan (2018), Farooq et al. (2019) and Yacoubi et al. (2020). It was also noted for number of grains per spike by Balkan (2018) and for thousand grain weight by Singh et al. (2018).

Oumata et al. (2020) reported that the maintenance of highly diverse landraces by oases farmers meets social, economic, cultural and environmental needs. These landraces also represent a tremendous source of germplasm for breeding programs. In addition to their earliness (Erroux 1962) and tolerance to abiotic stresses (Zaharieva et al. 2014), the oases wheats exhibit a serie of useful morphological traits.

Landraces from the Adrar region could represent a particularly valuable source of germplasm to improve number of grains per spike and thousand grain weight in breeding programs. Mekkaouiya A44 from the Bouda oasis and Chater A23 from the Adrar oasis appear to be promising progenitors to increase number of grains per spike and thousand grain weight, respectively. Both traits are of interest to improve yield in modern varieties (Munir et al. 2007; Khan and Hassan 2017). Moreover, the use of these traits in breeding programs should be facilitated by their high heritability coupled with high genetic advance.

Genetic advance as percentage of mean was also high for last internode length, a trait that was reported to be closely associated to yield under drought stress conditions (Modarresi et al. 2010; Schnyder 1993; Wang et al. 2001) considered that last internode has an important role in CO^2 assimilation. Ehdaie et al. (2006) and Merah et al. (2018) mentioned that remobilization of photosynthates stored in last internode has an important participation in grain filling under terminal drought conditions. Mursalova et al. (2015) and Farooq et al. (2018) suggested the use of this trait as an indirect selection criterion for improving drought tolerance.

Manga T22 and Manga T42 from the Abalessa and Ideles oases, respectively, which had a high last internode to stem height ratio could be used for manipulating this trait in breeding programs. The Manga landraces were reported to have a good lodging resistance (Erroux 1962, 1991) and to be resistant to wind and birds attacks (Oumata et al. 2020).

Conclusions

The study confirmed the high variation of morphological traits in wheat landraces from the Saharan oases, a consequence of crosses that occurred over time between different forms (an even different species) introduced in these environments. High heritability and genetic advance were recorded among Saharan oases landraces for yield components like spike fertility and thousand grain weight, suggesting a possible use of this germplasm to improve those traits in breeding programs. It also emphasizes the key role of Saharan farmers in the maintenance and conservation of wheat adapted to the harsh conditions of the oases and the importance of improving our knowledge of this germplasm that could help to mitigate the effects of climate change on the wheat production.

Funding The authors declare that no funds, grants, or other supports were received during the preparation of this manuscript.

Declarations

Conflict of interest The authors declare no conflict of interest.

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