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Article

Screening the FIGS Set of Lentil (*Lens culinaris* Medikus) Germplasm for Tolerance to Terminal Heat and Combined Drought-Heat Stress

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Abstract: Lentil (*Lens culinaris* Medikus) is one of the most important cool season food legume crops grown in many countries. Seeds are typically rich in protein, fiber, prebiotic carbohydrates and minerals, such as iron and zinc. With changing climate and variability, the lentil crop faces frequent droughts and heat stress of varying intensity in its major production zones. In the present study, a set of 162 lentil accessions selected through the Focused Identification of Germplasm Strategy (FIGS) were screened for tolerance to heat stress and combined heat-drought stresses under field conditions at two contrasting locations, namely Marchouch and Tessaout in Morocco. The results showed a significant genotypic variation for heat tolerance and combined heat-drought tolerance among the accessions at both locations. Based on the heat tolerance index (HTI), accessions, namely ILL 7833, ILL 6338 and ILL 6104, were selected as potential sources of heat tolerance at Marchouch, and ILL 7814 and ILL 8029 at Tessaout. Using the stress tolerance index (STI), ILL 7835, ILL 6075 and ILL 6362 were identified as the most tolerant lines (STI > 1) at Marchouch, and ILL 7814, ILL 7835 and ILL 7804 (STI > 1) at Tessaout, under the combined heat-drought stress conditions. Accession ILL 7835 was identified as a good source of stable tolerance to heat stress and combined heat-drought stress at both locations.

Keywords: lentil; heat stress; combined heat-drought stress; heat tolerance index; stress tolerance index

1. Introduction

Lentil (*Lens culinaris* Medikus) is an annual, diploid (2n = 14) and self-pollinated crop. Its seeds are rich in protein (22–35%), fiber, prebiotic carbohydrates and minerals, such as iron and zinc [1]. It plays a major role in alleviating malnutrition and micronutrient deficiencies of people living in Central and West Asia and North Africa (CWANA), South Asia, East Africa, and North America [2]. Being a legume crop, it enhances nitrogen in the soil through symbiotic nitrogen fixation and, hence, plays a crucial role in the diversification and intensification of cereal-based cropping systems, worldwide [3]. In 2018, the total world area under lentil production was 6.1 million hectares, with a production of 6.3 million tons; in the African continent, Morocco ranked second in lentil production after Ethiopia. Nevertheless, the average productivity of lentil in Morocco was recorded as 798 kg/ha, which is still very low, compared to the world average of 1038 kg/ha [4].

Lentil has been mainly cultivated under rainfed conditions in the marginal areas where abiotic stresses, such as drought and heat, significantly reduced crop yield and productivity [5]. During 2007–2008 season, a severe drought struck the Mediterranean region, and caused huge yield reduction of lentil in Morocco, France, the Russian Republic, Spain, the Syrian Arab Republic and Turkey [4]. Next, there was a steep fall in lentil production and productivity in Morocco during 2016, which was declared as the warmest year of this century, and eventually the severe drought stress damaged the total cropped area of about 9581 ha [6]. It is predicted that the global mean surface temperature during mid and late 21st century will increase by 2 °C, leading to an extreme variation in precipitation events and creating more heat waves that menace crop cultivation [7].

In lentil, the reproductive phase is very sensitive to changes in the external environment, and exposure to heat and drought stress during this stage reduces crop productivity significantly [8,9]. Lentil performs well when its reproductive stage coincides with the average day/night temperatures of 15–25 °C/8–10 °C [10]. However, heat waves (temperatures >32 °C) during the flowering and pod-filling stages cause damage to reproductive organs, leading to flower drop, pollen sterility, pod abortion and reducing the total number of seeds in lentil [11–14]. On the other hand, the terminal drought stress caused by irregular and deficient precipitation during the reproductive phase shortens the duration of the seed filling phase, by accelerating the process of senescence and maturity and reducing the seed size in lentil [15]. As the combined stress reduces both total number of seeds and seed size, and cause more yield reductions than the individual stresses, the interaction between heat and drought stress is considered the most serious challenge, which has a more significant negative impact on crop yield and productivity than each stress individually [16–18]. Seed development is a crucial growth period under heat or drought stress in all grain crops; however, their combination affects adversely seed filling by suppressing the transfer of the assimilates needed, leading to low grain yields and poor grain quality [19]. The combined effects of heat and drought have been studied in some crops such as groundnut (*Arachis hypogaea L.*) [20], chickpea (*Cicer arietinum L.*) [21–23], barley (*Hordeum vulgare L.*) [24,25] and wheat (*Triticum aestivum L.*) [26,27], but only to a limited extent in lentil [18].

Commonly, traits including early flowering, early maturity and yield under stress conditions were employed as the key traits to identify heat and drought tolerant germplasm in many crops, such as lentil [28] and chickpea [29]. For instance, a heat tolerance index (HTI), based on the yield under heat stress, yield potential and flowering time, has been used effectively to evaluate the heat response in chickpea under heat conditions [30,31]. Likewise, several quantitative drought tolerance indices, such as the stress tolerance index (STI), geometric mean productivity (GMP), mean productivity (MP), harmonic mean (HARM) and stress tolerance (TOL) have been used widely to assess genotypes with better drought stress tolerance in many crops [32–34]. Siahsar et al. [35] reported that STI, GMP and HARM were the best indices for the selection of lentil lines under drought stress. Additionally, these tolerance indices have been used in selecting superior genotypes under heat stress conditions [36,37]. The adaptation of a genotype to terminal drought and heat stress is a sought-after strategy to minimize the economic impact of climate change on agriculture [38–40]. The development of new heat and drought tolerant lentil cultivars would improve yield stability and facilitate an increase in area under sustainable cropping systems [41]. Nevertheless, it requires extensive screening of the germplasm being conserved in gene banks which demands huge investment and time. To facilitate this process, the 'Focused Identification of Germplasm Strategy (FIGS) approach was developed by the International

Center for Agricultural Research in the Dry Areas (ICARDA). FIGS creates 'best-bet' trait-specific subsets of germplasm, by passing accession-level information, especially agro-climatic site information, through a series of filters, which increase the chances of finding the adaptive trait of interest [42]. This approach is based on the premise that the environment highly influences the natural selection process and consequently, the geographical distribution of crop species [43]. Previous studies confirm the effectiveness of the FIGS approach in the identification of desirable germplasm in wheat (*Triticum ssp.*) for major biotic stresses, such as Russian wheat aphid (*Diuraphis noxia*) [44], stem rust (*Puccinia graminis Pers.*) [45,46] and Sunn pest (*Eurygaster intergriceps Put.*) [47], as well for drought stress in faba bean (*Vicia faba L.*) [42]. The present study aimed to assess genetic variability for heat and drought tolerance in the ICARDA lentil germplasm, using the FIGS approach. The objectives of the study were: (i) to investigate the individual and combined effects of terminal heat and drought stress during the reproductive phase; and (ii) to use indices and identify promising accessions with tolerance to heat stress and combined heat-drought stress for future breeding.

2. Materials and Methods

2.1. Plant Material and Study Area

A FIGS set comprising 162 germplasm accessions of lentil developed by the ICARDA gene bank in 2013 was evaluated. These accessions were originated from Pakistan (66), Nepal (68), Ethiopia (13), India (4), Yemen (3), Russia (3), Sudan (2) and Iran (2). The FIGS set, along with the Moroccan cultivar, Bakria as a local check, was evaluated in an alpha lattice design, with two replicates at two locations: Tessaout (31.42° N, 6.47° W, 68 m altitude) in the 2013–2014 cropping season, and Marchouch (33.56° N, 6.63° W, 392 m altitude) in the 2014–2015 cropping season in Morocco. At both stations, each germplasm was grown in a 2-row plot of 1 m length, with a spacing of 30 cm between rows. In each row, seeds were sown by hand at a 2 cm depth maintaining a 10 cm space between plants, and the total plot size maintained was 0.6 m^2. In general, the Tessaout research station represents a typical Mediterranean semi-arid environment, characterized by a hot dry summer with an annual rainfall of 266 mm [48]. The Marchouch station also represents a Mediterranean semi-arid environment, but with higher annual precipitation (400 mm) [49]. The experimental site in Tessaout is silty-clay soil, whereas in Marchouch, it is vertisol.

2.2. Treatments

At each of the two locations, three experiments involving the same set of FIGS germplasm were conducted by manipulating the planting date and water supply, in order to impose heat and water stress at the reproductive phase of the plant growth. These three experiments were considered to represent three treatments, namely the normal date of planting (treatment A), late planting with irrigation at field capacity throughout the crop period (treatment B) and late planting without irrigation during the reproductive phase (treatment C), which were referred to as treatments. Treatment A resulted in optimal growing conditions (>150 mm well-distributed rainfall and below 27 °C temperature) without any heat and water stress to the plants. Treatment B (planted 50 days after normal planting date with irrigation at field capacity throughout the crop duration) imposed heat stress, as the plants were exposed under field conditions to a temperature above 32 °C during the reproductive phase (Table A1), while regular irrigation at field capacity avoided any water stress to the plants. Treatment C (planted 50 days after normal planting date without irrigation during the reproductive phase) imposed a combined heat and water stress. Treatment A was sown on 20 December, and no irrigation was applied during the crop period as the crop received well distributed enough rainfall at Tessaout (157.9 mm) and Marchouch (167.8 mm). Treatments B and C were planted on 8 February. Irrigation was applied to maintain water supply at field capacity using sprinkler system throughout the crop duration in treatment B, whereas irrigation was stopped from the flowering initiation stage onward in treatment C, to impose water stress in addition to the heat stress. All the three treatments were kept weed-free throughout the growing season. A wide temperature variation was recorded between normal and late planted treatments at the Tessaout and Marchouch research stations. During the reproductive stage, the averages of the maximum and minimum temperatures were 26.33 °C and 12.72 °C in Treatment A. However, the maximum temperatures during the flowering stage reached the threshold level of 42 °C in treatments B and C at Tessaout and 34 °C at Marchouch (Figure 1). Therefore, late planting with irrigation at field capacity was successful in imposing heat stress during the reproductive phase of test genotypes in treatment B, and late planting without irrigation in imposing drought and heat stress in treatment C.

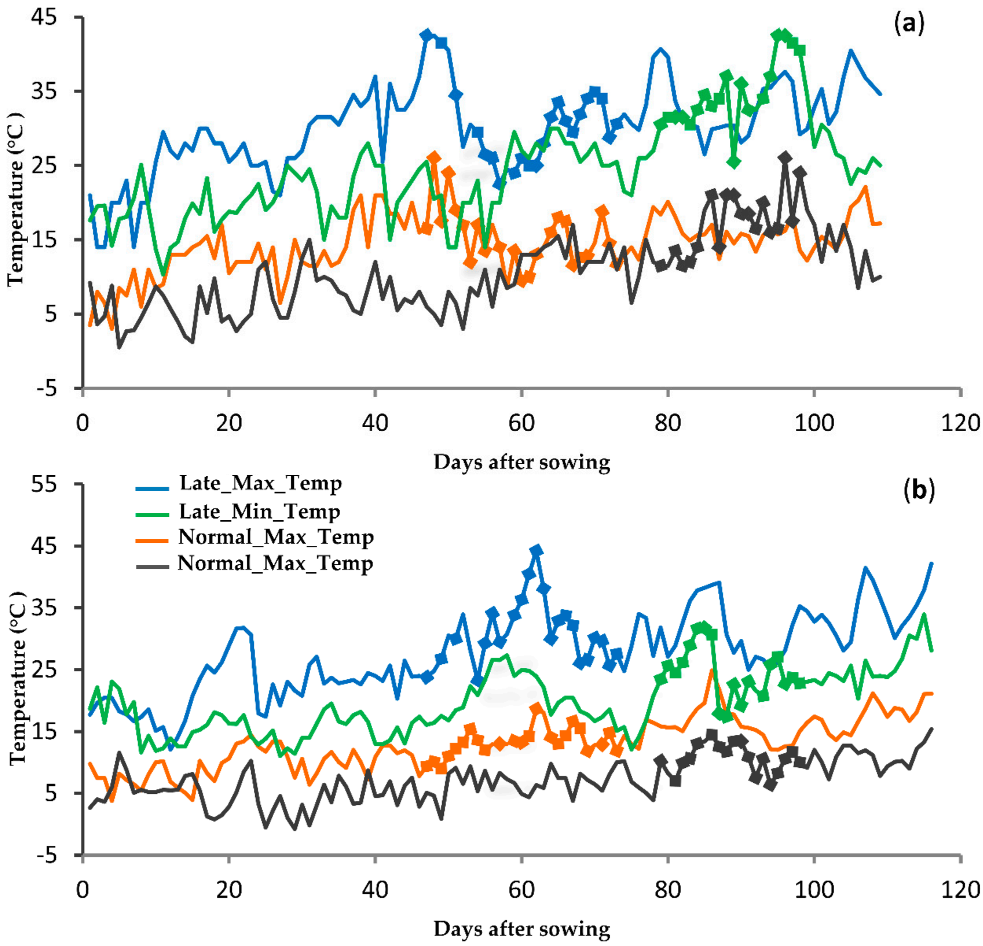

Figure 1. Averages of the maximum and minimum temperatures in normal and late planting at Tessaout (**a**) and Marchouch (**b**) during the crop season. The square icons indicate the flowering period for both normal and late sown crops.

2.3. Investigation and Calculation of Agronomic Traits

Data were recorded for the phenological traits (days to 50% flowering and maturity) on a plot basis, whereas five plants were selected randomly from each plot for the assessment of the morphological (numbers of primary, secondary and tertiary branches, and plant height) and yield (total numbers of filled and unfilled pods, biological yield, grain yield and 100-seed weight) traits, following the lentil ontology [50]. The heat tolerance index (HTI) was calculated for each genotype, following the multiple regression approach, as suggested by Bidinger et al. [51], and as used in chickpea [52]. Grain yield under stressed and non-stressed conditions was used to assess the tolerance of genotypes against the stress. This approach considers grain yield under heat stress conditions (Ys) to be a function of yield potential (Yp), days to 50% flowering (F) and heat tolerance index (HTI), such that the yield of a genotype can be expressed as Ysi = a + bYp + cFi + HTIi + E, where E is the random error with zero mean and variance σ, and a, b, c are regression parameters estimated by least square methods. The heat tolerance index (HTI) was calculated for each accession as the difference between the estimated late-season grain yield and the estimated optimal-season grain yield plus standardized residuals from regression.

On the basis of grain yield under stress (YS) and normal conditions (YP), the following quantitative tolerance indices were estimated to assess the combined effect of drought and heat stresses: stress tolerance index STI $= \frac{Y_{pi} * Y_{si}}{Y_p^2}$ [53]; tolerance index TOL $= Y_{pi} - Y_{si}$ [54]; geometric mean productivity GMP $= \sqrt{Y_{pi} * Y_{si}}$ [53]; mean productivity MP $= \frac{Y_{pi} + Y_{si}}{2}$ [54]; and harmonic mean HARM $= \frac{2(Y_{pi} * Y_{si})}{Y_{pi} + Y_{si}}$ [55] where, Ysi = yield of a genotype under stress condition, Ypi = yield of a genotype under normal sown condition, Ys = overall genotypic mean under stress condition, and Yp = overall genotypic mean under normal condition.

2.4. Statistical Analysis

Analysis of variance was performed using the general linear model (GLM) using IBM SPSS statistics 23. Treatment means were compared by least significant difference (LSD). Correlation coefficients (Pearson's) were calculated by multivariate analysis for heat stress condition, while Spearman's correlation coefficient was used for the combined heat-drought stress. Hierarchical cluster analysis using Ward's squared Euclidean distance method was performed for genotype grouping.

3. Results

3.1. Effects of Heat Stress on Morphological, Phenological, and Yield Contributing Traits

The analysis of variance (ANOVA) revealed significant differences among genotypes for all traits under stressed and non-stressed conditions at both the locations, Tessaout (Table 1) and Marchouch (Table 2). Furthermore, a highly significant variation ($p < 0.001\%$) was observed for all traits among treatments in Tessaout, as well as at Marchouch. The analysis also showed significant genotype x treatment interactions for all the traits at both locations, except for plant height, number of primary branches per plant, number of tertiary branches per plant and biomass yield per plant at Tessaout.

There existed a wide range of variability among lentil genotypes for phenological traits at both Tessaout (Table 1) and Marchouch (Table 2). Days to 50% flowering in normal planting conditions ranged from 61 to 78 days at Tessaout, and from 79 to 98 days at Marchouch. The range of days to 95% maturity varied from 100 to 119 days at Tessaout, and from 113 to 126 days at Marchouch under normal planting conditions. Heat stress decreased the crop duration by 23% at Tessaout, and 26% at Marchouch, while the combined heat-drought stress caused 28% reduction in crop duration at Tessaout and 27% at Marchouch. At each location, days to 50% of flowering was almost similar under both stress conditions: 46 days at Tessaout and 55 days at Marchouch (Table A1).

Under normal planting, plant height ranged from 17 to 37 cm, with the overall mean of 25 cm at Tessaout and from 14 to 52 cm, with a mean of 31.51 cm at Marchouch. Heat stress reduced plant height by 18% at Tessaout and by 31% at Marchouch. However, the combined heat-drought stress reduced plant height more than the heat stress: 29% at Tessaout and 35% at Marchouch (Table A1).

Heat stress and combined heat-drought stress reduced the number of primary, secondary and tertiary branches per plant significantly. The reduction was more pronounced under combined stress conditions at both locations, particularly at Marchouch. The number of primary branches per plant reduced by 24% at Tessaout and 30% at Marchouch. Likewise, the number of secondary and tertiary branches per plant were reduced by 38% and 63% at Tessaout, whereas in Marchouch, there was an 80% reduction in the number of secondary branches per plant, and a 91% reduction in the number of tertiary branches per plant (Table A1).

Under normal planting, the number of total pods per plant ranged from six to 160 at Tessaout, which decreased by 47% under heat stress and 62% under combined heat-drought stress conditions.

In contrast, the number of total pods per plant ranged from three to 230 at Marchouch but declined by 72% due to heat stress and 91% as a result of combined heat-drought stress. Likewise, heat stress and combined heat-drought stresses reduced number of filled pods by 58% and 65% at Tessaout, while it was 69% and 91% at Marchouch, compared to normal planting. The mean numbers of total pods and filled pods per plant were higher under stress conditions at Tessaout than at Marchouch (Table A1).

Biomass per plant ranged from 1.4 to 39.6 g at Tessaout and from 1.07 to 36.2 g at Marchouch under normal planting conditions. The heat stress reduced biomass by 69% at Tessaout and 77% at Marchouch. However, the reduction in biomass was higher under combined stress at both locations: it was recorded 71% at Tessaout and 85% at Marchouch. Similarly, the combined heat-drought stress decreased the seed yield by 76% at Tessaout and 90% at Marchouch, more than the heat stress alone (68% at Tessaout; 71% at Marchouch). The mean grain yields under heat stress and combined heat-drought stress were more at Tessaout than at Marchouch. Under the normal planting, the hundred-seed weight ranged from 0.50 to 3.70 g at Tessaout and 0.50 to 3.85 g at Marchouch. The combined heat-drought stress increased the hundred-seed weight by 21% at Tessaout and 10% at Marchouch. However, the increase was higher under heat stress by 38% at Tessaout and 27% at Marchouch (Table A1).

Table 1. Analysis of variance (ANOVA) expressed in mean square for different traits among 162 lentil accessions at Tessaout during 2013–2014.

Source	df	PH	DF	DM	PBPP	SBPP	TBPP	NTPP	NUPP	NFPP	BPP	GYP	HSW
Accession (A)	161	3179.93 **	9020.56 **	7926.79 **	85.73 *	2809.87 **	3116.53 **	134,681.09 **	17,979.63 **	97,275.47 **	6602.61 **	240.04 **	128.57 **
Treatment (T)	2	8801.50 **	81,401.01 **	194,468.02 **	87.07 **	4447.67 **	7474.59 **	221,759.77 **	6956.78 **	169,051.73 **	17,534.56 **	847.36 **	153.11 **
A × T	322	1373.34 ns	3564.90 **	9245.98 **	109.86 ns	2796.58 *	2834.41 ns	158,553.22 *	30,640.38 **	101,053.29 *	9055.03 ns	235.05 **	84.96 **
Error	486	2734.02	1675.88	4595.96	181.53	3506.01	3745.33	180,293.52	31,008.66	125,776.68	11,795.35	258.51	53.9
R^2		0.83 **	0.98 **	0.98 **	0.61 **	0.74 **	0.78 **	0.74 **	0.66 **	0.75 **	0.74 **	0.84 **	0.87 **

PH, plant height; DF, days to 50% flowering; DM, days to 95% maturity; PBPP, number of primary branches per plant; SBPP, number of secondary branches per plant; TBPP, number of tertiary branches per plant; NTPP, number of total pods per plant; NUPP, number of unfilled pods per plant; NFPP, number of filled pods per plant; BPP, biomass per plant; GYP, grain yield per plant; HSW, hundred-seed weight; df, degrees of freedom. Significant difference at: * $p < 0.01$, ** $p < 0.001$, ns denotes a non-significant difference.

Table 2. Analysis of variance (ANOVA) expressed in mean square for different traits among 162 lentil accessions at Marchouch during 2014–2015.

Source	df	PH	DF	DM	PBPP	SBPP	TBPP	NTPP	NUPP	NFPP	BPP	GYP	HSW
(A)	161	5998.87 **	12,577.23 **	8763.72 **	179.10 **	4794.79 **	2163.08 **	217,688.81 **	16,449.68 **	164,517.17 **	4042.86 **	297.13 **	168.53 **
(T)	2	23,422.11 **	235,449.92 **	223,732.48 **	103.03 **	46,726.49 **	33,818.93 **	638,843.72 **	45,673.66 **	344,672.12 **	18,250.69 **	976.43 **	67.07 **
A × T	322	6986.42 **	6242.97 **	5907.75 **	222.12 **	7827.42 **	4388.39 **	324,520.74 **	35,015.62 **	238,902.17 **	6559.96 **	382.04 **	86.57 **
Error	486	4714.99	503.09	952.59	122.45	4694.98	2275.94	160,769.5	14,911.52	121,599.93	2839.61	217.94	74.55
R^2		0.88 **	0.99 **	0.99 **	0.8 **	0.93 **	0.95 **	0.88 **	0.87 **	0.86 **	0.91 **	0.88 **	0.81 **

PH, plant height; DF, days to 50% flowering; DM, days to 95% maturity; PBPP, number of primary branches per plant; SBPP, number of secondary branches per plant; TBPP, number of tertiary branches per plant; NTPP, number of total pods per plant; NUPP, number of unfilled pods per plant; NFPP, number of filled pods per plant; BPP, biomass per plant; GYP, grain yield per plant; HSW, hundred-seed weight; df, degrees of freedom. Significant difference at: * $p < 0.01$, ** $p < 0.001$.

3.2. Correlations among the Traits under Heat Stress and Combined Heat-Drought Stress

The correlations between the variables under normal planting showed highly significant positive correlation at 0.01 level of grain yield with the number of the secondary and tertiary branches per plant and number of filled pods per plant at Tessaout and Marchouch (Tables A2 and A3). A highly positive correlation ($p < 0.01\%$) was also noticed between the grain yield and biomass at Marchouch. However, grain yield was negatively correlated with days to 50% flowering at Marchouch. Days to 50% flowering were positively correlated with plant height, days to 95% maturity, number of secondary and tertiary branches and hundred-seed weight at Tessaout (Table A2). Nevertheless, it was positively correlated only with plant height and days of 95% of maturity at Marchouch under normal planting (Table A3).

Under heat stress, grain yield was positively correlated ($p < 0.01\%$) with the number of the secondary and tertiary branches per plant, the number of total pods and biomass at both stations, Tessaout and Marchouch. Furthermore, grain yield had a positive correlation with days to 95% maturity at only Tessaout. A highly positive correlation of 0.01% was identified among plant height, days to 50% flowering, days to 95% maturity, biomass and hundred-seed weight in heat stress conditions at both stations. In combined heat-drought stress conditions, grain yield was positively correlated with all variables at both stations, except with days to 50% flowering at Marchouch. Additionally, positive associations ($p < 0.01\%$) existed among days to 50% flowering, days to 95% maturity and hundred-seed weight at Tessaout and Marchouch (Tables A2 and A3).

3.3. Classification of Genotypes Based on Heat Tolerance Index

Germplasm accessions were classified into representative groups based on the heat tolerance index (HTI). Hierarchical cluster analysis using Ward's incremental squared Euclidean distance method resulted in five clusters. These genotypic clusters differed significantly in HTI and defined as highly heat tolerant (HTI >1), heat tolerant (HTI means 0.68 in Marchouch and 0.66 in Tessaout), moderately heat tolerant (0.25 and 0.10), heat sensitive (−0.08 and −0.25) and highly heat sensitive (−0.37 and −0.55).

Based on the HTI, four accessions (ILL 7833, ILL 6338, ILL 7835 and ILL 6104) showed good performance under heat stress at Marchouch and three accessions (ILL 7835, ILL 7814 and ILL 8029) as highly heat tolerant at Tessaout. ILL 7835 emerged as heat tolerant at both the locations, showing its stable performance under heat stress. These accessions were characterized by a short phenological cycle with 53.5 days to achieve 50% flowering and about 86 days to 95% maturity at Marchouch, however, the duration was less at Tessaout with 45 days to 50% of flowering and 82 days to 95% maturity (Table 3). Additionally, 14 and 26 accessions were categorized as heat tolerant at Marchouch and Tessaout (Table A4), respectively. The moderately-heat tolerant group comprised of 26 accessions at Marchouch and 60 accessions at Tessaout. In this study, heat sensitive and highly heat-sensitive clusters were comprised of 76 and 42 accessions, respectively, at Marchouch. Whereas, it was 39 and 34 accessions at Tessaout (Table A5).

3.4. Response to Combined Heat-Drought Stress

Based on the stress tolerance index (STI) and the geometric mean productivity (GMP), genotype ILL 7835 was identified as tolerant to heat and drought at Marchouch and three accessions, ILL 7814, ILL 7835 and ILL 7804 at Tessaout. Genotype ILL 7835 showed tolerance to drought and heat stresses at both locations. The three highly tolerant genotypes at Tessaout achieved 50% flowering in around 43 days, while 50% flowering was achieved in about 60 days for the ILL 7835 at Marchouch. Furthermore, these genotypes reached 95% maturity in 83 days at Tessaout and in 90 days at Marchouch (Table 4). Using Spearman's correlation coefficient, the GMP was strongly correlated to STI ($r = 1$; $p < 0.01$) in Tessaout and Marchouch. Furthermore, highly positive correlation ($p < 0.01$) was recorded between yield potential (Yp) and yield under stress condition (Ys) ($p < 0.05$) at both stations. The Ys was positively correlated with the Yp, STI, GMP, MP and HARM indices, and negatively correlated with stress tolerance (TOL) at Tessaout and Marchouch (Table 5). Additionally, a non-significant correlation was observed between Ys and TOL under combined heat-drought stress in Marchouch (Table 5).

Table 3. Day to 50% flowering, days to 95% maturity, grain yield per plant and heat tolerant index of highly heat tolerant accessions of lentil at Marchouch and Tessaout.

		Marchouch				Tessaout			
Location	**Accession**	**DF**	**DM**	**GYP**	**HTI**	**DF**	**DM**	**GYP**	**HTI**
Marchouch	ILL 7833	53	85.00	4.33	1.97	45	80.00	0.23	−0.68
	ILL 6338	54	86.00	3.16	1.52	47	83.00	0.59	−0.12
	ILL 7835	54	86.00	3.02	1.39	43.5	81.00	3.52	1.95
	ILL 6104	53	85.00	2.52	1.11	44	82.20	0.43	−0.27
	Mean	53.5	85.5	3.26	1.49	44.87	81.55	1.19	0.22
	SD	0.5	0.5	0.66	0.31	1.34	1.14	1.34	1.02
Tessaout	ILL 7835	54	86.00	3.02	1.39	43.5	81.00	3.52	1.95
	ILL 7814	54	85.00	0.2	−0.38	43.5	82.50	3.26	1.83
	ILL 8029	55	85.00	1.43	0.44	47.5	83.50	2.65	1.36
	Mean	54.33	85.33	1.55	0.48	44.83	82.33	3.14	1.71
	SD	0.47	0.47	1.15	0.72	1.88	1.02	0.36	0.25

DF, days to 50% flowering; DM, days to 95% maturity; GYP, grain yield per plant; HTI, heat tolerance index.

Table 4. Days to 50% flowering, days to 95% maturity, grain yield and stress tolerance indices of the ten best tolerant accessions of lentil grown under normal planting and combined heat-drought stress at Marchouch and Tessaout.

Location	Accession	DF	DM	Ys	Yp	STI	GMP	MP	TOL	HARM
Marchouch	ILL 7835	59.50	89.50	1.88	3.98	1.12	2.73	2.93	2.10	2.55
	ILL 6075	58.00	87.00	1.99	2.15	0.64	2.07	2.07	0.16	2.07
	ILL 6362	59.00	87.50	0.77	5.30	0.61	2.02	3.04	4.53	1.34
	ILL 7819	55.00	87.50	1.54	2.43	0.56	1.93	1.98	0.89	1.88
	ILL 7266	56.00	88.00	1.20	2.20	0.40	1.62	1.70	1.00	1.55
	ILL 6361	59.00	89.00	0.60	4.21	0.38	1.59	2.40	3.61	1.05
	ILL 880	64.00	98.00	0.67	3.66	0.37	1.56	2.16	2.99	1.13
	ILL 4605	49.00	83.30	0.59	4.07	0.36	1.55	2.33	3.48	1.03
	ILL 6088	57.50	87.50	0.90	2.45	0.33	1.48	1.67	1.55	1.31
	ILL 7815	58.50	85.50	0.48	4.16	0.30	1.41	2.32	3.69	0.85
	Mean	57.55	88.28	1.062	3.461	0.507	1.796	2.26	2.4	1.476
	SD	3.64	3.64	0.53	1.02	0.23	0.38	0.43	1.38	0.51
Tessaout	ILL 7814	42.50	83.00	2.71	4.63	1.68	3.54	3.67	1.92	3.42
	ILL 7835	42.50	81.50	2.28	5.30	1.61	3.47	3.79	3.02	3.19
	ILL 7804	43.00	82.50	2.53	3.37	1.14	2.91	2.95	0.84	2.89
	ILL 6101	45.00	86.00	2.20	3.11	0.91	2.62	2.66	0.91	2.58
	ILL 6100	45.00	83.50	2.22	3.20	0.95	2.67	2.71	0.98	2.62
	ILL 7807	45.50	83.50	1.40	4.86	0.91	2.61	3.13	3.46	2.18
	ILL 6091	47.00	82.50	1.23	4.09	0.67	2.24	2.66	2.86	1.88
	ILL 8029	46.50	83.50	1.11	4.25	0.63	2.17	2.68	3.14	1.76
	ILL 4605	51.58	81.07	1.15	3.81	0.59	2.09	2.48	2.66	1.77
	ILL 8061	66.50	97.00	1.16	3.76	0.58	2.08	2.46	2.60	1.77
	Mean	47.51	84.41	1.79	4.04	0.97	2.64	2.92	2.24	2.41
	SD	6.82	4.39	0.61	0.69	0.38	0.51	0.45	0.95	0.59

DF, days to 50% flowering; DM, days to 95% maturity; Ys, seed yield in combined heat-drought condition; Yp, seed yield in normal condition; STI, stress tolerance index; GMP, geometric mean productivity; MP, mean productivity; TOL, tolerance index; and HARM, harmonic mean.

Table 5. Spearman's correlation coefficients between stress tolerance parameters in lentil under stressed and non-stressed environments at Tessaout and Marchouch.

Location	Stress Parameter	Ys	Yp	STI	GMP	MP	TOL	HARM
Tessaout	Yp	0.192 *	1					
	STI	0.862 **	0.613 **	1				
	GMP	0.862 **	0.613 **	1.00 **	1			
	MP	0.471 **	0.941 **	0.817 **	0.817 **	1		
	TOL	−0.157 *	0.905 **	0.293 **	0.293 **	0.726 **	1	
	HARM	0.979 **	0.334 **	0.936 **	0.230 **	0.595 **	0.051 ns	1
Marchouch	Yp	0.137 *	1					
	STI	0.544 **	0.831 **	1				
	GMP	0.544 **	0.831 **	1.00 **	1			
	MP	0.241 **	0.978 **	0.907 **	0.907 **	1		
	TOL	0.30 ns	0.977 **	0.728 **	0.728 **	0.916 **	1	
	HARM	0.950 **	0.373 **	0.728 **	0.728 **	0.468 **	0.265 **	1

* Correlation is significant at the 0.05 level, ** Correlation is significant at the 0.01 level, ns denotes non-significant difference. Ys, seed yield in combined heat-drought condition; Yp, seed yield in normal condition; STI, stress tolerance index; GMP, geometric mean productivity; MP, mean productivity; TOL, tolerance index; and HARM, harmonic mean.

4. Discussion

The present study demonstrated delayed sowing as an effective approach to screening lentil germplasm for heat tolerance. A similar methodology was used to assess heat tolerance responses in chickpea [30,31], lentil [19,56] and mung bean [57,58] successfully. High temperature and low vapor pressure deficits (VPD) decrease soil moisture and increase transpiration rate, resulting in combined heat and drought stress [59]. Hence, frequent irrigation must be provided to remove the confounding effects of drought stress, to assess the effect of heat stress. Even the photoperiod may change during late planting, and previous studies by Summerfield et al. [60] and Erskine et al. [61] reported that temperature had a much bigger effect on the flowering time than the photoperiod in lentil.

Our findings showed that heat stress adversely affected plant height, number of branches and pods, grain yield and biomass, which agrees with several investigations in chickpea [62,63], lentil [12] and faba bean [64]. However, the influence of the combined heat-drought stress was more severe when compared to heat stress only, due to the reduction in water use efficiency. Heat and combined heat-drought stresses shortened vegetative and reproductive periods by accelerating the rate of plant growth and development. Similar findings were reported in previous studies [65,66]. The combined heat-drought stress largely decreased the number of pods more than the individual heat stress, leading to severe yield losses and biomass. This is in agreement with the previous research of Sehgal et al. [18,19], which has also shown the impact of combined heat-drought stress in lentil.

The days to 50% flowering under stressed conditions have shown quite similar results in both locations: approximately 46 days at Tessaout and 54 days at Marchouch. Lentil responded in the same way to heat stress and combined heat-drought stress by forcing early flowering (Figure 1) in both locations. Awasthi et al. [22] reported a very similar response in days to 50% flowering eventually, accelerated markedly in chickpea genotypes under heat and combined heat-drought stresses environment.

Overall, grain yield decreased under stress conditions, with a more pronounced effect under the combined heat-drought stress condition. High temperature stress led to yield loss by altering pollen and stigma development, pollination and pod set, while drought directly influenced the seed filling stage [19,67,68]. Moreover, yield is always influenced by photosynthetic ability and the performance of reproductive organs under stressed conditions [69]. In this study, the number of primary, secondary and tertiary branches were significantly positively correlated with seed yield ($p < 0.01$) under stressed environments, at both stations, except heat stress of Tessaout, which was not correlated with seed yield (Tables A2 and A3). Previous studies agreed with our findings and demonstrated a positive direct effect of primary branches on seed yield in lentil [70,71]. Recently, Ahmadi et al. [72] suggested that if lentil genotypes have a greater number of branches—mainly secondary branches—the final potential would increase the plant yield under stress conditions. It appears that plant biomass was low, mostly due to combined heat-drought stress that demands high water use efficiency. Further, heat stress, in combination with drought, increases leaf temperature and decreased net photosynthetic rate and stomatal conductance, resulting in a more damaging impact under the combined stress condition [73]. Overall, biomass reduction largely affected the number of total pods and seed yield per plant [74]. It was also positively correlated with number of total pods per plant, the numbers of primary, secondary and tertiary branches, and seed yield under heat stress and combined heat-drought stress at Tessaout and Marchouch (Table 5). The present study showed increased 100-seed weight under heat stress and the combined heat-drought stress condition, due to the reduction of seed numbers per plant. Similar results were reported by Chakherchaman et al. [75] in lentil under drought stress.

In the present study, three accessions, namely, ILL7833, ILL6338 and ILL6104, were selected as potential sources of heat tolerance at Marchouch and two accessions (ILL7814 an ILL8029) at Tessaout. Tolerant accessions produced significantly more pods under heat stress, as compared to heat sensitive genotypes. Under the combined stress of heat and drought, the most tolerant lines were ILL 7835, ILL 6075 and ILL6362 (STI >1) at Marchouch and ILL7814, ILL7835 and 7804 (STI >1) at Tessaout. Altogether, ILL7835 was identified as a good source of tolerance under heat stress and combined heat-drought stress at Tessaout, as well as at Marchouch, while ILL7814 was identified as promising accession under both stresses at Tessaout. These selected lines are characterized by early flowering, which helped them to escape from heat and drought stress and shorter crop cycles (Tables 3 and 4). Usually, early flowering and maturity are the stress escape mechanism that can help lentil to perform well under stress conditions, and the development of genotypes with short duration is one of the major strategies used in breeding programs [76]. Although, early duration is considered to be the best adapted trait for chickpea genotypes to Mediterranean (spring sown) and south Indian environments [77,78]. Furthermore, the identified lines had a greater number of filled pods per plant, representing an excellent source for the lentil breeding program, and can be directly used in the crossing program to transfer heat and drought tolerance in a high yielding genetic background.

The selection of superior germplasm against combined stress was carried out by using a stress tolerance index (STI) and geometric mean productivity (GMP). STI and GMP have been used earlier for screening genotypes of chickpea [37,79,80], lentil [81,82], bread wheat [83], barley [84,85], fenugreek [86], oat [87] and maize [88,89] against abiotic stresses. Higher GMP and STI values indicate more tolerance to drought stress [90]. The stress tolerance index (STI) showed a highly positive correlation with both yield under stress conditions (Ys) and yield potential (Yp), GMP, MP and HARM at both locations. These results are in conformity with those of Ganjali et al. [91] in chickpea under stress and non-stress conditions. However, stress tolerance (TOL) was negatively correlated with Ys at Tessaout and non-significantly correlated at Marchouch, while it was positively correlated with potential yield at both locations. Similar results were reported also by Chakherchaman et al. [75] and Rad et al. [81] for lentil under drought stress conditions. Majidi et al. [92] also reported non-significant correlation between TOL and Ys, and a highly significant correlation between TOL and Yp, confirming that selection based on TOL should decrease yield in the moisture stress environment and increase grain yield under normal conditions. The limitations of using the TOL index have been described previously in several studies [35,93]. In general, our findings confirmed the effectiveness of using STI and GMP as reliable selection criteria for terminal heat or drought tolerance, as reported earlier by Fernandez [53], Farshadfar et al. [94] and Talebi et al. [95].

5. Conclusions

The present study shows that heat, as well as combined heat-drought stress, severely affects flower production and pod set, leading to a substantial loss in grain yield in lentil. The field screening technique has been demonstrated as an effective way for evaluating and selecting promising lines under heat or drought stress. The adaptation by selecting the robust genotypes can be a strong approach to mitigating the impact of climate change. Our study suggests that the FIGS approach in identifying heat tolerant germplasm in lentil is a successful approach under heat and combined heat-drought stress. This research identified a group of highly heat tolerant genotypes using HTI based on flowering time, and grain yield under stress and non-stress conditions. Our findings confirmed that STI, GMP and MP are the most suitable criteria, not only for selecting the high yielding genotypes under individual heat and drought stresses, but also in combined heat-drought stress. These lines would be an excellent source of stress tolerance to increase the adaptation of lentil under climate change, a major issue that currently affects agriculture.

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Appendix A

Table A1. Minimum, maximum and mean (±SD) values of traits of 162 lentil accessions under normal planting, heat stress and combined heat-drought stress in the field experiments at Tessaout during 2013–2014 and Marchouch during 2014–2015.

Trait	Heat Stress Conditions				Heat-Drought Conditions				Normal Conditions			
	Tessaout		Marchouch		Tessaout		Marchouch		Tessaout		Marchouch	
	Min–Max	Mean ± SD	Min–Max	Mean ± SD	Min–Max	Mean ± SD	Min–Max	Mean ± SD	Min–Max	Mean ± SD	Min–Max	Mean ± SD
PH	15.00–28.0	20.32 ± 2.40	15.00–34.0	21.79 ± 3.13	12.75–28.90	17.67 ± 2.91	15.00–30.0	20.52 ± 2.83	17.00–37.0	24.95 ± 2.87	14.00–52	31.51 ± 6.09
DF	41.00–67.0	45.98 ± 4.28	47.00–73.0	54.58 ± 4.15	40.00–67.0	45.92 ± 4.70	48.50–73.0	54.62 ± 4.11	61.00–78.0	65.37 ± 1.90	79.00–98	87.62 ± 5.07
DM	80.00–103	88.21 ± 4.70	81.00–109	87.09 ± 4.82	77.00–101.0	82.97 ± 4.26	72.00–109.0	86.22 ± 4.39	100.00–119.0	115.63 ± 2.66	113.00–126	118.83 ± 2.48
PBPP	1.00–3.67	2.53 ± 0.58	1.00–4.67	2.35 ± 0.71	1.00–3.67	2.29 ± 0.59	1.00–5.00	1.81 ± 0.69	2.00–4.00	3.01 ± 0.68	1.00–5.00	2.59 ± 0.80
SBPP	2.00–17.10	9.42 ± 3.30	1.00–20.00	6.30 ± 3.31	2.00–16.50	8.02 ± 3.39	1.00–17.00	3.82 ± 2.62	4.00–25.00	13.10 ± 0.68	5.33–34.70	19.61 ± 5.98
TBPP	0.15–16.50	6.22 ± 3.43	0.20–8.90	2.54 ± 1.45	0.10–12.30	3.88 ± 3.22	0.00–9.00	1.22 ± 0.94	3.00–21.00	10.57 ± 2.79	1.00–30.70	14.34 ± 4.95
NTPP	2.29–126.0	29.88 ± 19.94	2.00–140.0	18.50 ± 15.89	1.00–70.75	21.22 ± 14.08	1.00–36.00	6.09 ± 3.79	6.00–160.45	56.68 ± 24.08	3.00–230.00	65.60 ± 40.69
NUPP	0.00–83.50	10.83 ± 9.13	0.00–38.0	3.44 ± 2.63	0.00–33.50	5.55 ± 3.47	0.00–14.00	1.82 ± 1.63	0.00–57.20	11.54 ± 7.65	0.00–82.67	17.11 ± 11.31
NFPP	0.50–96.20	19.06 ± 15.19	1.00–102.0	15.06 ± 12.11	0.00–62.75	15.66 ± 11.03	1.00–30.50	4.26 ± 2.13	2.00–129.45	45.14 ± 20.61	1.00–195.33	48.50 ± 35.15
BPP	0.25–15.80	3.99 ± 1.59	0.45–11.89	2.55 ± 1.92	0.50–32.21	3.72 ± 2.34	0.50–11.30	1.63 ± 1.03	1.40–39.60	12.86 ± 6.19	1.07–36.20	11.25 ± 4.08
GYP	0.13–3.94	0.88 ± 0.69	0.16–4.89	0.74 ± 0.68	0.12–2.78	0.66 ± 0.55	0.13–2.49	0.27 ± 0.20	0.15–7.71	2.74 ± 1.22	0.39–7.33	2.59 ± 1.49
HSW	0.90–5.00	2.50 ± 0.58	1.10–5.00	2.36 ± 0.59	0.70–4.20	1.94 ± 0.46	0.90–4.30	1.93 ± 0.52	0.50–3.70	1.54 ± 0.51	0.53–3.85	1.73 ± 0.62

PH, Plant height; DF, Days to 50% flowering; DM, Days to 95% maturity; PBPP, Number of primary branches per plant; SBPP, Number of secondary branches per plant; TBPP, Number of tertiary branches per plant; NTPP, Number of total pods per plant; NUPP, Number of unfilled pods per plant; NFPP, Number of filled pods per plant; BPP, biomass per plant; GYP, grain yield per plant; HSW, hundred-seed weight.

Table A2. Pearson's correlation coefficients among various traits based on162 accessions of lentil under normal planting (A), heat stress (B) and combined heat-drought stress (C) at Tessaout.

Trait	PH	DF	DM	PBPP	SBPP	TBPP	NTPP	NUPP	NFPP	BPP	GYP
					A. Under normal planting						
DF	0.156 **										
DM	0.020ns	0.141 *									
PBPP	−0.070ns	−0.067ns	−0.050ns								
SBPP	0.242 **	0.152 **	0.015ns	−0.058ns							
TBPP	0.164 **	0.148 **	0.020ns	−0.060ns	0.570 **						
NTPP	0.080ns	−0.010ns	−0.055ns	0.062ns	0.428 **	0.372 **					
NUPP	0.090ns	−0.050ns	−0.132 *	0.070ns	0.199 **	0.163 **	0.521 **				
NFPP	0.058ns	0.010ns	−0.010ns	0.040ns	0.409 **	0.360 **	0.931 **	0.174 **			
BPP	−0.008ns	0.103ns	0.079ns	−0.089ns	0.086ns	0.095ns	0.131 *	0.144 **	0.090ns		
GYP	0.056ns	0.058ns	0.011ns	0.033ns	0.400 **	0.396 **	0.873 **	0.148 **	0.944 **	0.112 *	
HSW	0.119 *	0.123 *	−0.120ns	−0.027ns	0.084ns	0.043ns	0.061ns	0.026ns	0.059ns	−0.057ns	0.070ns

Table A2. *Cont.*

Trait	PH	DF	DM	PBPP	SBPP	TBPP	NTPP	NUPP	NFPP	BPP	GYP
B. Under heat stress condition											
DF	0.234 **										
DM	0.146 **	0.363 **									
PBPP	0.070ns	0.110ns	0.090ns								
SBPP	0.050ns	0.05ns	0.124 *	0.147 **							
TBPP	0.115 *	0.030ns	0.110ns	0.226 **	0.657 **						
NTPP	0.020ns	0.010ns	0.110ns	0.129 *	0.515 **	0.520 **					
NUPP	0.040ns	0.040ns	0.122 *	0.127 *	0.295 **	0.281 **	0.694 **				
NFPP	0.03ns	−0.020ns	0.050ns	0.090ns	0.496 **	0.512 **	0.885 **	0.278 **			
BPP	0.179 **	0.216 **	0.249 **	0.208 **	0.438 **	0.374 **	0.468 **	0.344 **	0.402 **		
GYP	0.070ns	0.020ns	0.116 *	0.110ns	0.491 **	0.522 **	0.854 **	0.372 **	0.898 **	0.476 **	
HSW	0.182 **	0.139 *	0.090ns	−0.010ns	−0.110ns	−0.030ns	−0.020ns	−0.060ns	0.010ns	0.040ns	0.020ns
Trait	**PH**	**DF**	**DM**	**PBPP**	**SBPP**	**TBPP**	**NTPP**	**NUPP**	**NFPP**	**BPP**	**GYP**
C. Under heat-drought conditions											
DF	0.121 *										
DM	0.191 **	0.432 **									
PBPP	0.080ns	0.010ns	0.148 **								
SBPP	0.311 **	0.090ns	0.203 **	0.135 *							
TBPP	0.210 **	−0.080ns	0.110ns	0.060ns	0.694 **						
NTPP	0.272 **	0.145 **	0.224 **	0.174 **	0.665 **	0.645 **					
NUPP	0.184 **	0.230 **	0.145 **	0.040ns	0.337 **	0.238 **	0.522 **				
NFPP	0.241 **	0.080ns	0.200 **	0.185 **	0.631 **	0.647 **	0.943 **	0.209 **			
BPP	0.356 **	0.391 **	0.344 **	0.182 **	0.460 **	0.294 **	0.435 **	0.378 **	0.352 **		
GYP	0.278 **	0.121 *	0.238 **	0.186 **	0.598 **	0.589 **	0.902 **	0.223 **	0.948 **	0.391 **	
HSW	0.086ns	0.159 **	0.144 **	0.019ns	−0.154 **	−0.135 *	0.020ns	0.111 *	−0.023ns	0.073ns	0.014ns

*. Correlation is significant at the 0.05 level, **. Correlation is significant at the 0.01 level, ns denotes non significant difference. PH, Plant height; DF, Days to 50% flowering; DM, Days to 95% maturity; PBPP, Number of primary branches per plant; SBPP, Number of secondary branches per plant; TBPP, Number of tertiary branches per plant; NTPP, Number of total pods per plant; NUPP, Number of unfilled pods per plant; NFPP, Number of filled pods per plant; BPP, biomass per plant; GYP, grain yield per plant; HSW, hundred-seed weight.

Table A3. Pearson's correlation coefficients among various traits based on 162 accessions of lentil under normal planting (A), heat stress (B) and combined heat-drought stress (C) at Marchouch.

	PH	DF	DM	PBPP	SBPP	TBPP	NTPP	NUPP	NFPP	BPP	GYP
A. Under normal planting											
DF	0.205 **										
DM	0.321 **	0.462 **									
PBPP	0.043ns	−0.010ns	−0.008ns								
SBPP	0.053ns	0.022ns	0.034ns	0.032ns							
TBPP	0.142 *	−0.015ns	0.057ns	0.034ns	0.670 **						
NTPP	−0.012ns	−0.086ns	0.068ns	0.073ns	0.272 **	0.222 **					
NUPP	−0.087ns	−0.064ns	−0.005ns	−0.052ns	0.295 **	0.287 **	0.545 **				
NFPP	0.018ns	−0.076ns	0.080ns	0.110ns	0.207 **	0.152 **	0.954 **	0.268 **			
BPP	0.143 *	0.001ns	0.074ns	0.114 *	0.517 **	0.472 **	0.406 **	0.348 **	0.342 **		
GYP	0.017ns	−0.126 *	0.060ns	0.090ns	0.177 **	0.110ns	0.861 **	0.228 **	0.908 **	0.302 **	
HSW	0.221 **	−0.050ns	0.030ns	0.144 **	0.020ns	0.050ns	−0.110ns	−0.129 *	−0.078ns	0.146 **	−0.060ns
B. Under heat stress condition											
DF	0.163 **										
DM	0.358 **	0.619 **									
PBPP	0.030ns	0.040ns	0.150 **								
SBPP	0.148 **	0.054ns	0.148 **	0.405 **							
TBPP	0.069ns	0.071ns	0.073ns	0.277 **	0.674 **						
NTPP	0.223 **	0.030ns	0.115 *	0.357 **	0.531 **	0.431 **					
NUPP	0.118 *	0.139 *	0.257 **	0.287 **	0.407 **	0.307 **	0.684 **				
NFPP	0.228 **	−0.010ns	0.060ns	0.335 **	0.504 **	0.417 **	0.975 **	0.504 **			
BPP	0.293 **	0.251 **	0.341 **	0.360 **	0.535 **	0.445 **	0.648 **	0.616 **	0.579 **		
GYP	0.248 **	−0.023ns	0.040ns	0.314 **	0.511 **	0.422 **	0.931 **	0.511 **	0.946 **	0.584 **	
HSW	0.208 **	0.190 **	0.269 **	0.227 **	0.114 *	0.103ns	0.092ns	0.145 **	0.065ns	0.284 **	0.110ns

Table A3. *Cont*.

Trait	PH	DF	DM	PBPP	SBPP	TBPP	NTPP	NUPP	NFPP	BPP	GYP
C. Under heat-drought condition											
DF	0.092ns										
DM	0.125 *	0.561 **									
PBPP	0.224 **	−0.044ns	0.118*								
SBPP	0.180 **	0.041ns	0.198 **	0.586 **							
TBPP	0.115*	−0.010ns	0.115*	0.357 **	0.537 **						
NTPP	0.188 **	−0.010ns	0.153 **	0.535 **	0.463 **	0.419 **					
NUPP	0.139*	−0.042ns	0.060ns	0.489 **	0.426 **	0.441 **	0.769 **				
NFPP	0.175 **	0.013ns	0.177 **	0.439 **	0.379 **	0.307 **	0.913 **	0.443 **			
BPP	0.237 **	0.070ns	0.223 **	0.335 **	0.424 **	0.464 **	0.436 **	0.350 **	0.389 **		
GYP	0.190 **	0.020ns	0.168 **	0.417 **	0.402 **	0.371 **	0.890 **	0.482 **	0.942 **	0.408 **	
HSW	0.194 **	0.152 **	0.169 **	0.158 **	0.204 **	0.179 **	0.139 *	0.139 *	0.107ns	0.228 **	0.123 *

*. Correlation is significant at the 0.05 level, **. Correlation is significant at the 0.01 level, ns denotes non significant difference. PH, Plant height; DF, Days to 50% flowering; DM, Days to 95% maturity; PBPP, Number of primary branches per plant; SBPP, Number of secondary branches per plant; TBPP, Number of tertiary branches per plant; NTPP, Number of total pods per plant; NUPP, Number of unfilled pods per plant; NFPP, Number of filled pods per plant; BPP, biomass per plant; GYP, grain yield per plant; HSW, hundred-seed weight.

Table A4. Day to 50% flowering (DF), days to 95% maturity (DM), seed yield under stress condition (Yp), seed yield under normal condition (Yp) and heat tolerant index (HTI) of heat tolerant accessions of lentil.

Accession	DF	DM	Ys	Yp	HTI	Accession	DF	DM	Ys	Yp	HTI
	Tessoaut Location						**Marchouch Location**				
ILL 6359	47.00	89.00	1.96	2.96	0.94	ILL 6363	54.00	85.00	2.38	3.91	0.97
ILL 7295	46.00	88.50	1.91	2.71	0.94	ILL 8025	54.50	86.50	1.91	1.70	0.87
ILL 2524	43.00	87.00	1.95	2.91	0.94	ILL 7819	51.50	84.50	2.00	2.43	0.85
ILL 6053	42.50	88.50	1.68	1.66	0.90	ILL 7223	51.50	88.00	2.05	3.80	0.75
ILL 7389	46.00	88.00	2.00	3.57	0.88	ILL 6361	53.00	85.50	2.10	4.21	0.74
ILL 8019	43.00	83.50	1.93	3.14	0.88	ILL 6053	52.50	85.00	1.91	3.13	0.72
ILL 8018	45.50	88.50	1.80	2.60	0.86	ILL 6075	55.00	86.00	1.71	2.15	0.69
ILL 6094	45.00	95.00	1.93	3.41	0.84	ILL 4902	68.00	90.00	1.78	3.70	0.64
ILL 8025	44.50	87.00	1.88	3.16	0.84	ILL 8061	61.50	93.00	1.42	1.25	0.61

Table A4. *Cont.*

Accession	DF	DM	Ys	Yp	HTI	Accession	DF	DM	Ys	Yp	HTI
Tessoaut Location						**Marchouch Location**					
ILL 6095	45.00	90.00	1.46	1.02	0.82	ILL 6362	57.00	88.00	2.01	5.30	0.59
ILL 4605	50.84	84.59	1.95	3.81	0.81	ILL 7806	55.50	88.00	1.59	2.65	0.57
ILL 7932	44.00	84.50	1.21	0.76	0.64	ILL 6359	51.00	86.50	1.27	0.90	0.51
ILL 6364	44.50	86.50	1.74	3.64	0.62	ILL 880	70.50	100.00	1.53	3.66	0.48
ILL 5919	50.00	81.00	1.32	1.77	0.59	ILL 504	67.00	106.00	1.38	2.80	0.45
ILL 7250	44.00	90.00	1.39	2.16	0.56						
ILL 7796	48.50	88.00	1.64	3.65	0.55						
ILL 7817	43.00	85.00	1.75	4.12	0.55						
ILL 6055	47.00	86.50	1.42	2.65	0.51						
ILL 8437	46.50	97.00	1.27	1.93	0.50						
ILL 6080	45.50	84.00	1.08	0.99	0.48						
ILL 8023	44.50	91.00	1.35	2.46	0.47						
ILL 7795	44.00	88.00	1.27	2.16	0.45						
ILL 6107	44.50	89.50	1.46	3.26	0.43						
ILL 7808	44.00	85.00	1.35	2.82	0.41						
ILL 7301	46.00	85.00	1.25	2.32	0.41						
ILL 7327	44.50	90.00	0.96	1.00	0.37						

Table A5. Day to 50% flowering (DF), days to 95% maturity (DM), seed yield in stress condition (Yp), seed yield in normal condition (Yp) and heat tolerant index (HTI) of moderately heat tolerant, heat sensitive and highly heat sensitive accessions cluster of lentil at Tessaout and at Marchouch.

Accession	DF	DM	Ys	Yp	HTI	Accession	DF	DM	Ys	Yp	HTI
Marchouch Station						**Tessaout Station**					
Moderately heat tolerant						Moderately heat tolerant					
ILL 7308	53.00	86.00	1.52	2.82	0.49	ILL 206	44.50	92.00	1.21	3.68	0.14
ILL 8029	55.00	85.00	1.43	2.76	0.45	ILL 221	62.50	98.00	1.31	4.68	0.12
ILL 3635	54.00	85.50	1.31	2.12	0.43	ILL 1734	50.50	96.50	0.93	1.59	0.26
ILL 7807	52.50	92.00	1.36	2.99	0.37	ILL 1861	42.00	95.00	0.85	2.15	0.06
ILL 7301	54.00	85.00	1.25	2.47	0.35	ILL 3484	46.50	94.50	1.10	2.11	0.31
ILL 7798	53.50	86.00	0.99	0.91	0.33	ILL 3635	45.00	83.50	1.30	3.64	0.23
ILL 7295	53.00	86.00	1.15	2.13	0.32	ILL 4743	46.50	86.00	0.77	2.71	−0.09
ILL 6325	50.50	90.00	1.16	2.28	0.30	ILL 4772	43.50	89.50	0.70	2.01	−0.04

Table A5. *Cont.*

Accession	DF	DM	Ys	Yp	HTI	Accession	DF	DM	Ys	Yp	HTI
		Marchouch Station						**Tessaout Station**			
ILL 6095	53.50	84.50	0.87	0.55	0.28	ILL 4902	65.00	101.00	0.99	2.76	0.17
ILL 729	66.50	106.00	1.24	3.78	0.26	ILL 5918	46.50	81.50	0.68	1.72	0.00
ILL 6086	53.00	87.00	1.07	2.22	0.25	ILL 5929	51.00	90.00	1.04	2.77	0.16
ILL 6364	51.00	81.00	1.20	3.16	0.24	ILL 5958	45.00	89.50	0.69	1.53	0.04
ILL 7286	53.50	85.50	0.85	0.90	0.24	ILL 6059	51.00	88.50	0.81	2.48	0.00
ILL 6337	51.00	87.00	1.30	3.89	0.24	ILL 6074	46.00	88.00	0.61	1.13	0.04
ILL 6094	53.50	85.00	1.01	2.03	0.23	ILL 6075	43.00	89.00	1.22	4.40	0.02
ILL 7830	54.50	85.50	0.90	1.38	0.23	ILL 6077	48.50	88.50	0.79	1.21	0.19
ILL 5958	53.50	84.50	0.92	1.75	0.20	ILL 6079	45.00	84.50	0.78	2.41	−0.03
ILL 8019	53.00	85.50	1.08	2.87	0.20	ILL 6088	43.50	85.00	0.93	1.94	0.18
ILL 7344	54.00	87.00	1.12	3.33	0.18	ILL 6092	46.00	86.50	0.81	1.03	0.23
ILL 7309	52.00	85.00	0.71	0.70	0.16	ILL 6096	44.50	90.50	1.09	3.11	0.13
ILL 8017	54.50	87.00	1.20	4.14	0.16	ILL 6101	45.50	88.50	1.23	3.11	0.25
ILL 7250	53.00	87.50	0.87	2.05	0.14	ILL 6102	45.00	90.50	1.05	2.96	0.11
ILL 7238	53.50	86.00	0.80	1.60	0.14	ILL 6325	44.50	94.00	0.74	1.83	0.03
ILL 7300	57.50	88.00	0.82	2.00	0.13	ILL 6337	43.50	88.00	0.75	1.71	0.05
ILL 1861	52.50	100.00	0.56	0.50	0.08	ILL 6346	46.00	90.50	0.90	2.38	0.09
ILL 7380	53.00	86.00	0.75	2.15	0.05	ILL 6356	45.50	87.50	1.17	3.26	0.17
	Heat sensitive					ILL 6361	45.00	86.50	1.01	2.25	0.20
ILL 7290	51.00	83.50	0.71	1.14	0.11	ILL 6363	47.00	85.00	0.80	2.56	−0.03
ILL 8056	62.00	93.00	0.68	1.43	0.10	ILL 6385	60.50	91.00	0.94	2.24	0.20
ILL 7264	53.00	87.00	0.60	0.67	0.09	ILL 7223	45.00	89.00	1.16	2.40	0.31
ILL 7312	51.00	85.50	0.70	1.35	0.09	ILL 7290	45.50	88.50	0.87	2.96	−0.05
ILL 6057	52.00	88.00	0.63	0.95	0.08	ILL 7303	54.00	98.00	0.88	3.22	−0.05
ILL 7305	52.00	87.00	0.78	2.00	0.08	ILL 7304	44.50	86.50	0.70	2.12	−0.06
ILL 7824	53.50	85.50	1.10	4.24	0.08	ILL 7306	43.50	92.00	1.10	2.10	0.31
ILL 6091	55.00	86.00	0.68	1.46	0.08	ILL 7308	44.50	83.50	0.74	1.91	0.02
ILL 4743	49.50	86.00	0.71	1.47	0.08	ILL 7309	46.50	84.00	0.92	2.00	0.17
ILL 7310	54.00	85.00	0.60	0.90	0.07	ILL 7312	44.00	84.50	0.68	2.06	−0.07

Table A5. *Cont.*

Accession	DF	DM	Ys	Yp	HTI	Accession	DF	DM	Ys	Yp	HTI
		Marchouch Station						**Tessaout Station**			
ILL 6088	51.50	85.00	0.80	2.45	0.05	ILL 7313	44.50	87.00	0.80	1.72	0.10
ILL 7831	53.00	86.00	0.82	2.62	0.05	ILL 7316	44.50	85.00	1.31	4.55	0.08
ILL 8016	53.00	85.00	0.62	1.30	0.04	ILL 7326	44.50	87.00	0.93	2.45	0.09
ILL 8012	54.00	85.00	0.75	2.24	0.04	ILL 7380	44.50	91.50	0.76	2.51	−0.07
ILL 6322	50.00	84.00	0.94	3.50	0.03	ILL 7383	46.50	87.00	1.04	3.31	0.05
ILL 7316	53.00	87.00	0.72	2.10	0.03	ILL 7798	45.50	91.50	1.05	2.81	0.14
ILL 6087	51.00	85.00	0.65	1.63	0.02	ILL 7799	43.00	88.00	1.43	4.00	0.27
ILL 8022	53.50	86.00	0.62	1.55	0.02	ILL 7801	45.00	85.50	0.43	0.86	−0.09
ILL 206	54.00	86.00	0.69	2.11	0.02	ILL 7806	44.50	90.50	0.90	0.93	0.33
ILL 6077	54.50	85.00	0.79	2.99	0.00	ILL 7807	45.00	86.50	1.20	4.86	−0.07
ILL 7826	58.00	90.00	0.56	1.59	−0.01	ILL 7818	43.50	87.00	1.08	2.95	0.14
ILL 6079	58.00	87.00	0.49	1.25	−0.02	ILL 7826	49.50	87.50	0.81	1.87	0.10
ILL 7796	54.00	88.00	0.44	0.77	−0.02	ILL 7827	43.50	88.50	0.93	2.73	0.05
ILL 8021	54.50	85.00	0.40	0.67	−0.04	ILL 7831	45.00	85.50	0.85	2.84	−0.04
ILL 8026	52.50	85.00	0.85	3.69	−0.04	ILL 8013	46.50	90.00	1.30	4.18	0.14
ILL 7303	58.50	104.50	0.92	4.40	−0.04	ILL 8014	48.00	93.50	0.96	1.90	0.23
ILL 4758	47.50	83.00	0.78	3.10	−0.05	ILL 8016	44.00	83.50	1.04	2.13	0.24
ILL 7795	55.00	86.00	0.37	0.60	−0.05	ILL 8020	45.00	82.00	0.95	2.16	0.17
ILL 221	55.00	88.00	0.65	2.52	−0.05	ILL 8024	44.50	85.00	1.06	2.83	0.15
ILL 7339	54.00	87.50	0.52	1.73	−0.06	ILL 8026	45.00	85.50	0.97	3.43	−0.04
ILL 8015	53.50	85.00	0.46	1.34	−0.06	ILL 8028	43.50	87.00	1.11	3.51	0.07
ILL 7836	52.00	84.00	0.70	2.95	−0.07	ILL 8056	47.50	95.00	0.94	3.01	0.02
ILL 7389	54.50	84.50	0.92	4.55	−0.07	ILL 8061	60.50	93.00	1.34	3.76	0.30
ILL 6074	53.00	86.00	0.40	1.00	−0.07			Heat sensitive			
ILL 7306	54.00	86.00	0.70	3.13	−0.08	ILL 247	43.00	88.50	0.58	2.01	−0.15
ILL 1734	54.50	94.50	0.56	2.23	−0.08	ILL 5505	49.50	85.00	0.64	2.46	−0.15
ILL 5918	51.00	83.00	0.38	0.95	−0.09	ILL 5957	47.00	80.00	0.28	0.58	−0.17
ILL 7827	53.00	85.00	0.66	2.96	−0.09	ILL 5964	43.50	85.00	0.32	0.94	−0.20
ILL 7325	51.00	81.00	0.38	1.10	−0.10	ILL 6057	44.00	88.50	0.13	1.01	−0.39
ILL 6059	65.00	98.00	0.32	1.35	−0.12	ILL 6058	42.50	86.50	0.16	1.05	−0.37

Table A5. *Cont.*

Accession	DF	DM	Ys	Yp	HTI	Accession	DF	DM	Ys	Yp	HTI
		Marchouch Station						**Tessaout Station**			
ILL 6099	66.50	95.00	0.17	0.39	−0.12	ILL 6060	46.00	87.00	0.50	2.23	−0.25
ILL 5940	54.00	87.00	0.37	1.30	−0.12	ILL 6086	45.00	87.00	0.59	2.97	−0.30
ILL 8437	52.00	102.50	0.76	3.93	−0.12	ILL 6087	45.00	83.50	0.55	2.76	−0.30
ILL 6058	65.00	98.00	0.23	0.80	−0.12	ILL 6099	46.00	89.00	0.42	1.58	−0.22
ILL 6319	50.00	82.50	0.80	4.23	−0.13	ILL 6104	44.00	87.50	0.43	1.92	−0.27
ILL 7818	54.50	86.00	0.49	2.31	−0.14	ILL 6105	45.50	85.00	0.84	3.41	−0.15
ILL 6096	55.00	84.00	0.35	1.38	−0.14	ILL 6320	43.00	85.50	0.75	3.26	−0.22
ILL 5957	48.00	81.00	0.51	2.24	−0.14	ILL 6332	51.00	92.00	0.37	2.31	−0.37
ILL 4605	49.34	82.65	0.77	4.07	−0.14	ILL 6338	47.00	91.00	0.59	1.96	−0.12
ILL 3484	51.50	85.00	0.57	2.82	−0.14	ILL 6360	44.50	87.50	0.71	3.37	−0.27
ILL 7289	56.00	89.00	0.33	1.40	−0.15	ILL 7238	46.00	96.50	0.96	4.91	−0.30
ILL 7817	55.00	85.00	0.21	0.59	−0.15	ILL 7264	45.00	87.00	0.84	3.56	−0.18
ILL 6100	52.00	84.00	0.50	2.45	−0.15	ILL 7286	44.00	88.00	0.69	3.16	−0.25
ILL 7304	53.50	85.00	0.37	1.70	−0.16	ILL 7310	43.00	86.50	0.40	2.49	−0.40
ILL 7327	53.00	85.00	0.45	2.25	−0.17	ILL 7311	50.00	89.50	0.40	2.00	−0.29
ILL 7307	54.00	85.00	0.41	2.07	−0.17	ILL 7314	44.00	85.00	0.47	2.03	−0.26
ILL 247	54.50	88.00	0.26	1.10	−0.17	ILL 7317	45.50	90.00	0.66	2.94	−0.23
ILL 7812	53.00	85.00	0.50	2.68	−0.17	ILL 7325	44.50	90.00	0.53	1.66	−0.13
ILL 8013	54.00	95.50	0.81	4.85	−0.17	ILL 7328	54.50	95.00	1.08	4.69	−0.12
ILL 6356	51.50	84.50	0.86	5.10	−0.17	ILL 7344	44.00	87.00	0.63	3.17	−0.31
ILL 6332	73.00	98.00	0.19	1.31	−0.17	ILL 7813	49.50	84.50	0.55	2.81	−0.29
ILL 5955	56.00	87.00	0.20	0.80	−0.18	ILL 7815	48.00	93.00	0.61	2.43	−0.18
ILL 7838	50.50	83.50	0.32	1.39	−0.18	ILL 7816	44.00	92.50	0.75	3.03	−0.17
ILL 8028	58.00	90.00	0.52	3.08	−0.18	ILL 7819	43.50	86.00	0.41	1.19	−0.16
ILL 7328	65.00	90.00	0.24	1.42	−0.18	ILL 7820	44.50	87.50	0.80	3.03	−0.12
ILL 6055	50.50	84.00	0.56	3.10	−0.18	ILL 7830	44.50	86.00	0.67	3.78	−0.37
ILL 6092	58.00	89.00	0.41	2.38	−0.18	ILL 7836	45.50	84.50	0.26	0.54	−0.19
ILL 6360	51.00	83.00	0.42	2.20	−0.18	ILL 7837	42.50	82.50	0.66	2.71	−0.20

Table A5. *Cont.*

Accession	DF	DM	Ys	Yp	HTI	Accession	DF	DM	Ys	Yp	HTI
		Marchouch Station						**Tessaout Station**			
ILL 8018	52.00	82.00	0.44	2.55	−0.20	ILL 8015	48.00	84.50	0.68	4.01	−0.39
ILL 7311	57.00	86.00	0.25	1.48	−0.21	ILL 8017	45.00	84.00	0.55	2.71	−0.30
ILL 6102	54.00	88.00	0.22	1.17	−0.21	ILL 8021	45.00	87.00	0.60	2.97	−0.30
ILL 7313	53.00	87.00	0.30	1.70	−0.21	ILL 8054	44.50	88.00	0.61	3.49	−0.38
ILL 8023	51.50	85.00	0.61	3.85	−0.22	ILL 8280	50.00	91.00	0.22	1.66	−0.40
ILL 8054	52.50	82.50	0.24	1.41	−0.22		Highly heat sensitive				
ILL 6385	70.00	89.00	0.21	1.94	−0.23	ILL 504	66.50	93.50	0.18	2.22	−0.47
ILL 6080	54.00	84.00	0.35	2.36	−0.24	ILL 729	63.50	98.50	0.66	4.83	−0.49
	Highly heat sensitive					ILL 880	45.50	86.50	0.23	3.11	−0.65
ILL 5919	51.50	83.00	0.52	3.61	−0.26	ILL 4758	42.00	89.00	0.31	2.91	−0.56
ILL 5929	55.00	88.00	0.18	1.60	−0.27	ILL 4910	43.50	95.00	0.29	3.36	−0.65
ILL 8014	61.00	88.50	0.30	2.70	−0.28	ILL 5940	47.00	93.00	0.42	3.56	−0.55
ILL 5964	55.00	85.00	0.27	2.28	−0.28	ILL 5943	46.00	88.50	0.31	2.96	−0.55
ILL 7837	54.50	86.50	0.61	4.58	−0.28	ILL 5955	43.50	85.50	0.19	1.81	−0.47
ILL 7317	55.50	89.00	0.17	1.71	−0.29	ILL 6054	44.50	86.50	0.22	2.48	−0.56
ILL 7266	56.50	89.00	0.23	2.20	−0.29	ILL 6072	46.00	88.00	0.33	3.68	−0.66
ILL 8020	54.00	86.00	0.40	3.27	−0.29	ILL 6081	43.50	86.50	0.23	1.87	−0.45
ILL 7808	52.50	84.00	0.27	2.30	−0.29	ILL 6089	45.00	88.50	0.27	2.40	−0.50
ILL 7832	51.00	84.00	0.38	3.05	−0.29	ILL 6091	45.50	85.50	0.55	4.09	−0.53
ILL 6105	57.00	89.00	0.26	2.50	−0.30	ILL 6100	44.50	96.50	0.28	3.20	−0.62
ILL 7314	54.00	86.00	0.29	2.62	−0.30	ILL 6319	45.00	90.50	0.32	2.56	−0.48
ILL 6101	55.00	84.00	0.21	2.25	−0.31	ILL 6322	44.00	91.00	0.26	2.41	−0.51
ILL 7326	54.00	86.00	0.46	3.95	−0.32	ILL 6362	43.50	90.50	0.55	3.85	−0.50
ILL 7813	50.00	84.00	0.55	4.45	−0.32	ILL 7232	43.50	89.50	0.53	3.43	−0.44
ILL 7800	52.50	87.00	0.41	3.75	−0.34	ILL 7266	44.50	87.50	0.36	3.41	−0.59
ILL 7232	57.00	88.00	0.25	2.85	−0.34	ILL 7289	44.50	83.00	0.20	3.48	−0.75
ILL 7797	55.00	87.00	0.31	3.20	−0.34	ILL 7300	43.50	87.00	0.49	3.61	−0.51
ILL 7815	51.00	84.00	0.47	4.16	−0.35	ILL 7305	44.50	85.00	0.13	2.10	−0.57
ILL 7801	55.00	83.00	0.21	2.60	−0.35	ILL 7307	45.00	87.00	0.32	2.51	−0.47
ILL 7820	54.50	84.00	0.29	3.16	−0.35	ILL 7339	44.00	86.50	0.35	4.07	−0.71

Table A5. *Cont.*

Accession	DF	DM	Ys	Yp	HTI	Accession	DF	DM	Ys	Yp	HTI
		Marchouch Station						**Tessaout Station**			
ILL 6346	54.00	86.00	0.37	3.65	−0.35	ILL 7797	47.50	92.00	0.24	3.52	−0.71
ILL 7383	55.00	83.50	0.46	4.30	−0.35	ILL 7800	44.50	84.50	0.26	2.41	−0.51
ILL 4910	55.00	86.00	0.21	2.70	−0.36	ILL 7804	43.00	83.50	0.53	3.37	−0.44
ILL 6089	55.50	86.00	0.22	2.80	−0.36	ILL 7812	43.50	85.00	0.53	3.54	−0.46
ILL 8024	53.00	88.00	0.23	2.83	−0.37	ILL 7824	45.50	85.00	0.74	4.74	−0.47
ILL 6060	53.00	88.00	0.20	2.69	−0.37	ILL 7829	44.00	84.00	0.43	3.61	−0.57
ILL 6072	54.00	88.00	0.48	4.67	−0.38	ILL 7833	45.00	85.00	0.23	3.28	−0.68
ILL 7814	54.00	85.00	0.20	2.78	−0.38	ILL 7838	44.00	83.00	0.43	2.95	−0.45
ILL 6107	53.00	87.00	0.50	4.80	−0.38	ILL 8012	43.00	84.50	0.41	2.84	−0.45
ILL 8280	55.00	85.00	0.20	2.85	−0.38	ILL 8022	47.50	93.00	0.46	4.21	−0.62
ILL 2524	54.00	83.00	0.21	2.97	−0.39						
ILL 5943	53.00	85.00	0.19	3.09	−0.42						
ILL 7804	58.00	88.00	0.20	3.35	−0.42						
ILL 7829	55.00	84.00	0.28	3.80	−0.42						
ILL 4772	53.00	84.00	0.24	3.54	−0.43						
ILL 6081	54.00	86.00	0.30	4.17	−0.45						
ILL 7799	55.00	82.00	0.22	3.80	−0.46						
ILL 7816	61.50	89.50	0.21	4.95	−0.56						
ILL 6054	52.00	86.00	0.25	4.85	−0.56						
ILL 5505	58.50	109.00	0.17	5.08	−0.61						
ILL 6320	54.00	88.50	0.17	7.20	−0.83						

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