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 m². 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 $Y_{si} = a + bY_p + cF_i + HTI_i + E$, where $E$ is the random error with
zero mean and variance $\sigma$, 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 $\text{STI} = \frac{Y_{pi} \times Y_{si}}{Y_{si}}$ [53]; tolerance index $\text{TOL} = Y_{pi} - Y_{si}$ [54]; geometric mean productivity $\text{GMP} = \sqrt{Y_{pi} \times Y_{si}}$ [53]; mean productivity $\text{MP} = \frac{Y_{pi} + Y_{si}}{2}$ [54]; and harmonic mean $\text{HARM} = 2\frac{Y_{pi} \times Y_{si}}{Y_{pi} + Y_{si}}$ [55] where, $Y_{si} =$ yield of a genotype under stress condition, $Y_{pi} =$ yield of a genotype under normal sown condition, $Y_{s} =$ overall genotypic mean under stress condition, and $Y_{p} =$ 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 ** | 221,799.77 ** | 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 * | 3745.33 ** | 180,293.52 | 31,008.66 | 125,776.68 | 11,795.35 | 258.51    | 53.9      |
| Error               | 486 | 2734.02    | 1675.88  | 4595.96  | 181.53    | 3506.01   | 3745.33 ** | 158,053.29 ** | 45,673.66 ** | 238,002.17 ** | 18,250.69 ** | 976.43 ** | 67.07 **  |

| R²      | 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 ** | 164,517.12 ** | 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 ** | 238,002.17 ** | 6559.96 ** | 382.04 ** | 86.57 **  |
| Error    | 486 | 4714.99    | 503.09   | 952.59   | 122.45    | 4694.98   | 2775.94   | 140,769.5 | 14,911.52 | 121,599.93 | 2839.61   | 217.94    | 74.55     |

| R²      | 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.

| 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 tolerant 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 | 0.37 | 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     |
|-----------|------------------|----|-----|---------|-------|------|--------|----------|
|           | Yp               | 0.192 * | 1   |         |       |      |        |          |
|           | STI              | 0.862 ** | 0.613 ** | 1.00 ** | 1.00 ** | 1    |        |          |
|           | GMP              | 0.862 ** | 0.941 ** | 0.941 ** | 0.941 ** | 1    |        |          |
|           | MP               | 0.471 ** | 0.726 ** | 0.726 ** | 0.726 ** | 1    |        |          |
|           | TOL              | −0.157 * | 0.293 ** | 0.293 ** | 0.293 ** | 1    |        |          |
|           | HARM             | 0.979 ** | 0.936 ** | 0.936 ** | 0.936 ** | 1    |        |          |

| Location  | Stress Parameter | Ys | Yp  | STI     | GMP   | MP   | TOL    | HARM     |
|-----------|------------------|----|-----|---------|-------|------|--------|----------|
|           | Yp               | 0.137 * | 1   |         |       |      |        |          |
|           | STI              | 0.544 ** | 0.831 ** | 1.00 ** | 1.00 ** | 1    |        |          |
|           | GMP              | 0.544 ** | 0.831 ** | 0.978 ** | 0.978 ** | 1    |        |          |
|           | MP               | 0.241 ** | 0.977 ** | 0.977 ** | 0.977 ** | 1    |        |          |
|           | TOL              | 0.30 ns | 0.728 ** | 0.728 ** | 0.728 ** | 1    |        |          |
|           | HARM             | 0.950 ** | 0.373 ** | 0.373 ** | 0.373 ** | 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 | Tessaout | Marchouch |
| PH    | Mean ± SD  | Min–Max  | Mean ± SD  | Min–Max  | Mean ± SD  | Min–Max  | Mean ± SD  | Min–Max  |
| DF    | 20.32 ± 2.40 | 15.00–34.0 | 21.79 ± 3.13 | 17.75–28.90 | 20.52 ± 2.83 | 17.00–37.0 | 24.95 ± 2.87 | 14.00–52.00 |
| DM    | 45.98 ± 4.28 | 40.00–67.0 | 45.92 ± 4.70 | 48.50–73.0 | 54.62 ± 4.11 | 61.00–78.0 | 65.37 ± 1.90 | 79.00–98.00 |
| PBPP  | 0.58 ± 0.38 | 0.10–2.00 | 0.35 ± 0.71 | 1.00–3.67 | 2.29 ± 0.59 | 1.00–5.00 | 1.81 ± 0.69 | 2.00–4.00 |
| SBPP  | 9.42 ± 3.30 | 6.30–3.31 | 8.02 ± 3.39 | 1.00–17.00 | 3.82 ± 2.62 | 4.00–25.00 | 13.10 ± 0.68 | 5.33–34.70 |
| TBPP  | 6.22 ± 3.43 | 0.10–8.10 | 3.88 ± 3.22 | 0.00–9.00 | 1.22 ± 0.94 | 3.00–21.00 | 10.57 ± 2.79 | 1.00–30.70 |
| NTPP  | 29.88 ± 19.94 | 18.50–15.89 | 21.22 ± 14.08 | 1.00–36.00 | 6.09 ± 3.79 | 6.00–160.45 | 56.68 ± 24.08 | 3.00–230.00 |
| NUPP  | 10.83 ± 9.13 | 0.00–33.50 | 5.55 ± 3.47 | 0.00–14.00 | 1.81 ± 1.63 | 0.00–57.20 | 11.54 ± 7.65 | 0.00–82.67 |
| NFPP  | 19.06 ± 15.19 | 1.00–102.0 | 15.06 ± 12.11 | 0.00–62.75 | 5.16 ± 11.03 | 0.00–30.50 | 4.26 ± 2.13 | 2.00–129.45 |
| BPP   | 3.99 ± 1.59 | 0.45–11.99 | 2.55 ± 1.92 | 0.50–32.21 | 3.72 ± 2.34 | 0.50–11.30 | 1.63 ± 1.03 | 1.40–39.60 |
| GYP   | 0.13–3.94 | 0.88–0.69 | 0.16–4.89 | 0.12–2.78 | 0.66 ± 0.55 | 0.13–2.49 | 0.27 ± 0.20 | 0.15–7.71 |
| HSW   | 2.50 ± 0.58 | 1.10–5.08 | 2.36 ± 0.59 | 0.70–4.20 | 1.94 ± 0.46 | 0.90–4.30 | 1.93 ± 0.52 | 0.50–3.70 |

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.

PH. 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 |
|-------|----|----|----|------|------|------|------|------|------|-----|-----|
| DF    | 0.156 ** | 0.020ns | 0.141 * |
| DM    | 0.242 ** | 0.070ns | 0.067ns | 0.050ns |
| PBPP  | 0.164 ** | 0.020ns | 0.060ns | 0.570 ** |
| SBPP  | 0.080ns | 0.010ns | 0.055ns | 0.428 ** | 0.372 ** |
| TBPP  | 0.090ns | 0.050ns | 0.132 * | 0.199 ** | 0.163 ** | 0.521 ** |
| NTPP  | 0.058ns | 0.010ns | 0.010ns | 0.409 ** | 0.360 ** | 0.931 ** | 0.174 ** |
| NFPP  | 0.089ns | 0.103ns | 0.079ns | 0.089ns | 0.869ns | 0.095ns | 0.131 * | 0.144 ** | 0.090ns |
| BPP   | 0.056ns | 0.058ns | 0.011ns | 0.033ns | 0.400 ** | 0.396 ** | 0.873 ** | 0.148 ** | 0.944 ** | 0.112 * |
| GYP   | 0.119 * | 0.123 * | 0.120ns | 0.084ns | 0.043ns | 0.061ns | 0.026ns | 0.059ns | 0.057ns | 0.070ns |

A. Under normal planting
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 | 0.050ns | 0.124 * | 0.147 ** |      |      |      |      |      |     |     |
| TBPP  | 0.115 *  | 0.030ns | 0.110ns | 0.226 ** | 0.657 ** |      |      |      |      |     |     |
| NTTP  | 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  | 0.030ns | −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 |
| **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 ** |      |      |      |      |     |     |
| NTTP  | 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 | NTTP | NUPT | NFPT | 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 ** |     |      |      |      |      |      |
| NTTP  | −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 ** |     |      |      |      |      |      |
| NTTP  | 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**|    |      |      |      |     |     |
| NTTP  | 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**| 0.355**| 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 (Ys), 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 |
|-----------|------|------|------|------|-----|-----------|------|------|------|------|-----|
| Tessaout 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 9250  | 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 6880  | 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 7288  | 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 |      |      |      |      |     |
| 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 |
|-----------|----|----|----|----|-----|-----------|----|----|----|----|-----|
| 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 5938  | 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 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 |
| Accession | DF  | DM  | Ys  | Yp  | HTI | Accession | DF  | DM  | Ys  | Yp  | HTI |
|-----------|-----|-----|-----|-----|-----|-----------|-----|-----|-----|-----|-----|
| 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 8012  | 53.50 | 86.00 | 0.62 | 1.55 | 0.02 | ILL 7801  | 45.00 | 85.50 | 0.43 | 0.86 | −0.09 |
| ILL 7303  | 58.50 | 104.50 | 0.92 | 4.40 | −0.04 | ILL 7806  | 44.50 | 90.50 | 0.90 | 0.93 | 0.33 |
| ILL 4758  | 47.50 | 83.00 | 0.78 | 3.10 | −0.05 | ILL 7807  | 45.00 | 86.50 | 1.20 | 4.86 | −0.07 |
| ILL 7795  | 55.00 | 86.00 | 0.37 | 0.60 | −0.05 | ILL 7818  | 43.50 | 87.00 | 1.08 | 2.95 | 0.14 |
| ILL 221   | 55.00 | 88.00 | 0.65 | 2.52 | −0.05 | ILL 7826  | 49.50 | 87.50 | 0.81 | 1.87 | 0.10 |
| ILL 7339  | 54.00 | 87.50 | 0.52 | 1.73 | −0.06 | ILL 7827  | 43.50 | 88.50 | 0.93 | 2.73 | 0.05 |
| 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 8036  | 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 8437  | 52.00 | 87.00 | 0.35 | 1.84 | −0.14 | ILL 6105  | 43.00 | 85.50 | 0.75 | 3.26 | −0.22 |
| ILL 5940  | 54.00 | 87.00 | 0.37 | 1.30 | −0.12 | ILL 6106  | 51.00 | 92.00 | 0.37 | 2.31 | −0.37 |
| ILL 6096  | 55.00 | 84.00 | 0.35 | 1.38 | −0.14 | ILL 6107  | 49.00 | 86.00 | 0.71 | 3.37 | −0.27 |
| ILL 5957  | 48.00 | 81.00 | 0.51 | 2.24 | −0.14 | ILL 6108  | 47.00 | 91.00 | 0.59 | 1.96 | −0.12 |
| ILL 6058  | 65.00 | 98.00 | 0.23 | 0.80 | −0.12 | ILL 6109  | 46.00 | 89.00 | 0.42 | 1.58 | −0.22 |
| ILL 6319  | 50.00 | 82.50 | 0.80 | 4.23 | −0.13 | ILL 6110  | 44.00 | 87.50 | 0.43 | 1.92 | −0.27 |
| ILL 8437  | 52.00 | 87.00 | 0.35 | 1.84 | −0.14 | ILL 6111  | 43.00 | 85.50 | 0.75 | 3.26 | −0.22 |
| ILL 5940  | 54.00 | 87.00 | 0.37 | 1.30 | −0.12 | ILL 6112  | 51.00 | 92.00 | 0.37 | 2.31 | −0.37 |
| ILL 6096  | 55.00 | 84.00 | 0.35 | 1.38 | −0.14 | ILL 6113  | 49.00 | 86.00 | 0.71 | 3.37 | −0.27 |
| ILL 5957  | 48.00 | 81.00 | 0.51 | 2.24 | −0.14 | ILL 6114  | 47.00 | 91.00 | 0.59 | 1.96 | −0.12 |
| ILL 6058  | 65.00 | 98.00 | 0.23 | 0.80 | −0.12 | ILL 6115  | 46.00 | 89.00 | 0.42 | 1.58 | −0.22 |
| ILL 6319  | 50.00 | 82.50 | 0.80 | 4.23 | −0.13 | ILL 6116  | 44.00 | 87.50 | 0.43 | 1.92 | −0.27 |
| ILL 8437  | 52.00 | 87.00 | 0.35 | 1.84 | −0.14 | ILL 6117  | 43.00 | 85.50 | 0.75 | 3.26 | −0.22 |
| ILL 5940  | 54.00 | 87.00 | 0.37 | 1.30 | −0.12 | ILL 6118  | 51.00 | 92.00 | 0.37 | 2.31 | −0.37 |
| ILL 6096  | 55.00 | 84.00 | 0.35 | 1.38 | −0.14 | ILL 6119  | 49.00 | 86.00 | 0.71 | 3.37 | −0.27 |
| ILL 5957  | 48.00 | 81.00 | 0.51 | 2.24 | −0.14 | ILL 6120  | 47.00 | 91.00 | 0.59 | 1.96 | −0.12 |
| ILL 6058  | 65.00 | 98.00 | 0.23 | 0.80 | −0.12 | ILL 6121  | 46.00 | 89.00 | 0.42 | 1.58 | −0.22 |
| ILL 6319  | 50.00 | 82.50 | 0.80 | 4.23 | −0.13 | ILL 6122  | 44.00 | 87.50 | 0.43 | 1.92 | −0.27 |
| ILL 8437  | 52.00 | 87.00 | 0.35 | 1.84 | −0.14 | ILL 6123  | 43.00 | 85.50 | 0.75 | 3.26 | −0.22 |
| ILL 5940  | 54.00 | 87.00 | 0.37 | 1.30 | −0.12 | ILL 6124  | 51.00 | 92.00 | 0.37 | 2.31 | −0.37 |
| ILL 6096  | 55.00 | 84.00 | 0.35 | 1.38 | −0.14 | ILL 6125  | 49.00 | 86.00 | 0.71 | 3.37 | −0.27 |
| ILL 5957  | 48.00 | 81.00 | 0.51 | 2.24 | −0.14 | ILL 6126  | 47.00 | 91.00 | 0.59 | 1.96 | −0.12 |
| ILL 6058  | 65.00 | 98.00 | 0.23 | 0.80 | −0.12 | ILL 6127  | 46.00 | 89.00 | 0.42 | 1.58 | −0.22 |
| ILL 6319  | 50.00 | 82.50 | 0.80 | 4.23 | −0.13 | ILL 6128  | 44.00 | 87.50 | 0.43 | 1.92 | −0.27 |
| ILL 8437  | 52.00 | 87.00 | 0.35 | 1.84 | −0.14 | ILL 6129  | 43.00 | 85.50 | 0.75 | 3.26 | −0.22 |
| ILL 5940  | 54.00 | 87.00 | 0.37 | 1.30 | −0.12 | ILL 6130  | 51.00 | 92.00 | 0.37 | 2.31 | −0.37 |
| ILL 6096  | 55.00 | 84.00 | 0.35 | 1.38 | −0.14 | ILL 6131  | 49.00 | 86.00 | 0.71 | 3.37 | −0.27 |
| 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 | ILL 8054 | 52.50 | 82.50 | 0.24 | 1.41 | −0.22 |
| ILL 7311 | 57.00 | 86.00 | 0.25 | 1.48 | −0.21 | ILL 8054 | 52.50 | 82.50 | 0.24 | 1.41 | −0.22 |
| ILL 6102 | 54.00 | 88.00 | 0.22 | 1.17 | −0.21 | ILL 8054 | 52.50 | 82.50 | 0.24 | 1.41 | −0.22 |
| ILL 7313 | 53.00 | 87.00 | 0.30 | 1.70 | −0.21 | ILL 8054 | 52.50 | 82.50 | 0.24 | 1.41 | −0.22 |
| 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 | ILL 8054 | 52.50 | 82.50 | 0.24 | 1.41 | −0.22 |
| Highly heat sensitive |     |     |     |     |     | Highly heat sensitive |     |     |     |     |     |
| 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.**

| Accession | DF   | DM    | Ys | Yp  | HTI | Accession | DF   | DM    | Ys   | Yp  | HTI |
|-----------|------|-------|----|-----|-----|-----------|------|-------|------|-----|-----|
| 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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