agriculture

MDPI

Article

Traits Related to Heat Stress in *Phaseolus* Species

Thierry Michel Tene *, Hatice Sari, Huseyin Canci, Amar Maaruf, Tuba Eker and Cengiz Toker

Department of Field Crops, Faculty of Agriculture, Akdeniz University, TR 07070 Antalya, Turkiye; haticesari@akdeniz.edu.tr (H.S.); toker@akdeniz.edu.tr (C.T.)

* Correspondence: 20175142002@ogr.akdeniz.edu.tr; Tel.: +90-242-310-24-21

Abstract: Traits related to heat stress in bean species (*Phaseolus* spp.) have been insufficiently explored to date, yet studies of these traits are needed given that heat stress is predicted to become more frequent and severe in many parts of the world because of climate change. In order to detect agro-morphological and physiological traits related to heat stress and selection for resistance to heat stress, a total of 196 bean genotypes including eight genotypes of tepary bean (*P. acutifolius* L.), five genotypes of scarlet runner bean (*P. coccineus* A. Gray), two genotypes of year bean (*P. dumosus* Macfady), five genotypes of lima bean (*P. lunatus* L.), and 176 genotypes of common bean (*P. vulgaris* L.) were evaluated in 2019 and 2020 under moderate (field) and extreme heat stress (greenhouse) conditions. Although most genotypes of *P. acutifolius*, *P. lunatus*, and *P. coccineus* were found to be more resistant to heat stress than most genotypes of common bean, some genotypes of common bean were shown to perform as well as *P. acutifolius*, *P. lunatus*, and *P. coccineus*. Biomass among agronomical traits had the highest significant direct effects on the resistance to heat stress score. The maximum quantum efficiency of PSII and SPAD values among physiological traits showed significant direct effects on the resistance to heat stress score. Biomass, leaflet size, the SPAD value and maximum quantum efficiency of PSII can be considered as heat stress-related traits, and, *P. acutifolius*, *P. lunatus*, *P. coccineus*, and some genotypes of *P. vulgaris* can be considered for exploitation in a heat stress tolerance breeding program.

Keywords: *Phaseolus* spp.; heat stress; SPAD value; maximum quantum efficiency of PSII; biomass; physiological traits

check for updates

Citation: Tene, T.M.; Sari, H.; Canci, H.; Maaruf, A.; Eker, T.; Toker, C. Traits Related to Heat Stress in *Phaseolus* Species. *Agriculture* **2023**, *13*, 953. https://doi.org/10.3390/agriculture13050953

Academic Editor: Urs Feller

Received: 23 March 2023
Revised: 16 April 2023
Accepted: 18 April 2023
Published: 26 April 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Although the bean genus (*Phaseolus* spp.) consists of 81 species, only five species including tepary bean (*P. acutifolius* A. Gray), runner bean (*P. coccineus* L.), lima bean (*P. lunatus* L.), year bean (*P. dumosus* Macfady), and common bean (*P. vulgaris* L.) have been domesticated since pre-Colombian times for their dry or fresh beans and green pods [1–3]. Among the domesticated species, the common bean was reported to be dominant based on sowing area and production quantity in the world [4]. Beans are the most widely consumed grain legume in the world, providing an essential source of dietary fiber, starch, protein, and minerals such as potassium, thiamine, vitamin B6, and folic acid for human nutrition [5–7]. According to the Food and Agriculture Organization Statistical Database (FAOSTAT), the production quantities for dry and fresh beans in 2020 were 27.6 and 23.3 million tons in the world, respectively [8]. This crop is highly consumed because of its high protein content which is a substitute for animal protein difficult to access by low-income households [9–11]. In developing countries, which are generally characterized by limited inputs and resources, bean production faces biotic and abiotic stresses such as diseases, pests, drought, low soil fertility, and heat stress. In developed countries, however, these stresses are removed through the use of expensive inputs such as pesticides, fertilizers, and irrigation [9]. Unfortunately, the use of such inputs seriously affects profitability and sometimes has negative effects on the environment. Abiotic and biotic constraints are

therefore a serious limiting factor affecting bean production worldwide and constitute a major risk to food insecurity.

Among the abiotic constraints likely to impact plant production in general and beans in particular, heat stress is revealed as a serious factor that should provoke concern [10,12–14]. It affects a range of processes, including physiological, growth, developmental, yield, and quality. Our review highlights the need for more information on the interactive effects of these stresses, particularly when they occur in combination [15]. Heat stress occurs when organisms are exposed to temperatures above their normal optimum for a prolonged period. This disrupts cellular homeostasis and can lead to delayed growth, development, or even death. Plants are particularly vulnerable to heat stress as they are sessile and exposed to high temperatures for extended periods [16,17].

At 35–42 °C, heat stress reduces photosynthesis below enzyme kinetics expectations by disrupting the complex biochemical reactions in photosynthesis, including the functioning of chloroplasts and enzymes. The mechanism is unclear but is believed to involve damage to the photosynthetic apparatus, changes in membrane fluidity, and alterations in enzyme activity [18]. At high temperatures above 45 °C, photosynthesis is severely impaired, and irreversible damage occurs to the plant's cellular machinery. However, some plants are more tolerant of high temperatures than others, and these species have evolved various adaptive mechanisms to cope with heat stress [19]. These include the production of heat-shock proteins, which protect cellular components from damage caused by high temperatures, and changes in membrane lipid composition, which help maintain membrane fluidity and stability at high temperatures [20–23]. In addition to photosynthesis, heat stress can also affect other biochemical processes in plants, including respiration, protein synthesis, and lipid metabolism. These effects can lead to changes in the plant's metabolism, growth, and development, and can ultimately impact the plant's ability to survive and reproduce under high-temperature conditions. [22,24,25].

Bean production constraints and predicted future temperature increases due to climate change are discouraging for producers [10,11,20,26,27]. Studies show global temperatures have risen by 0.8 °C since the 1880s, with an estimated increase of 0.15 to 0.20 °C per decade, which will limit bean production in most countries [26]. Additionally, for every 1 °C increase in atmospheric temperature, crop species experience yield losses of around 9% [28].

To cope with these constraints, effective measures must be taken now, and among these measures we advocate the development of new varieties of beans resistant to heat stress and with high nutritive and productive potential [10]. According to the Intergovernmental Panel on Climate Change (IPCC) report, the heat stress effect differs from region-to-region in the world, and the effect of heat stress will be felt in the near future [29]. Different countries and regions will require different measures and breeding approaches to develop heat-resistant/tolerant beans. Traits related to heat tolerance are crucial for selecting new beans under heat stress conditions. As global warming continues, about two-thirds of bean production areas are expected to be affected in the next 30 years. Developing heat-tolerant varieties could then increase the areas suitable for bean production by up to 54%. [14,24]. However, most studies are carried out under laboratory conditions and do not consider the variability of the environment, which is an important factor in the process of plant selection [14,21]. At the same time, direct and indirect associations between yield and agro-morphological traits in beans were studied several times especially in the common bean [30–33] using path analysis [34]. The path coefficient is a useful multivariate analysis in detecting not only the direct contribution of yield criteria on seed yield, but also the indirect contribution of other traits. However, the elucidation of direct and indirect relationships between resistance to heat stress and agro-morphological traits and physiological traits, as well, is an original topic to study [35]. Due to all of these reasons, this study was conducted under both greenhouse and field conditions. The aims of this study were therefore (i) to determine the agro-morphological, and physiological traits in relation to heat stress, (ii) to elucidate the direct and indirect effects of these agro-morphological and physiological traits

on resistance to heat stress using path analysis, and (iii) to compare *Phaseolus* species and genotypes using the agglomerative hierarchical clustering analysis under moderate (field) and extreme heat stress (greenhouse) conditions.

2. Materials and Methods

2.1. Plant Materials

In 2019, a total of 170 genotypes of common bean (*P. vulgaris* L.) were sown, while in 2020, 196 genotypes of *Phaseolus* were sown, comprising of eight genotypes of tepary bean (*P. acutifolius* L.), five genotypes of scarlet runner bean (*P. coccineus* A. Gray), two genotypes of year bean (*P. dumosus* Macfady), five genotypes of lima bean (*P. lunatus* L.), and 176 genotypes of common bean (*P. vulgaris* L.). Plant materials were mainly obtained from the Biodiversity and Genetic Resources of the Aegean Agricultural Research Institute (Turkiye), introduced plants from the National Plant Germplasm System (NPGS) of the United States Department of Agriculture (USDA), and advanced breeding lines (Table S1). Additional *Phaseolus* species in the second year were used to compare genotypes for resistance to heat stresses. The assessment of different numbers of *Phaseolus* beans depends on the available bean species and genotypes as studied by Blair, Soler [36] and Buitrago-Bitar, Cortés [37].

2.2. Study Sites and Experimental Designs

The experiments were carried out in April 2019 and May 2020, which corresponds to a period of two years, at the campus of Akdeniz University, Antalya, Turkey (30°38′ E, 36°53′ N, 51 m above sea level). Four experiments were conducted between May and September of 2019 and 2020, respectively. The selection of these dates was based on the summer season when the plants were exposed to the highest peaks in annual temperature.

The experimental design used was a randomized complete block design (RCBD) with three replications in both the greenhouse and rainfed field. The spacing between plants in a row and between rows in a plot was 20 cm and 100 cm, respectively. In the greenhouse, each plot consisted of three plants, while in the field, each plot consisted of a row of 6 plants. To minimize side effects, three plants in the middle of the plot were evaluated to collect data in the field experiments. The seeds of *P. acutifolius*, *P. coccineus*, *P. dumosus*, and *P. lunatus* were pre-germinated in the laboratory and then sown in the field and the greenhouse. Regular watering was carried out to reduce the effects of drought stress, using a drip irrigation system with a flow rate of 2 L per hour and 20 cm emitter spacing for each plant row. No chemical treatment was applied during the study, and weeds were removed manually on a regular basis.

The temperatures and relative humidity of the greenhouse and field were recorded daily using the computer-assisted device MITHRA Clima Pro, manufactured by Nutricontrol, Spain. The growing conditions for the plants in the greenhouse were 85.87% mean relative humidity and 12 h natural photoperiod.

2.3. Screening for Resistance to Heat Stress

For the screening of bean genotypes, we adapted the visual scale from the 1 to 9 scale proposed by Canci and Toker [38] for the screening of chickpea resistance against heat and drought stresses. Scores associated with this scale were assigned to genotypes according to the following modalities: 1 = very highly resistant (free from high temperature effects, very good plant vigor, early flowering and 100% pod set); 2 = highly resistant (good plant vigor, early flowering and 90–99% pod set); 3 = resistant (good plant vigor, early flowering and 75–89% pod set); 4 = moderately resistant (moderate plant vigor, early flowering and 60–74% pod set); 5 = tolerant (lack of plant vigor, medium flowering, poor plant flowering and 45–59% pod set); 6 = moderately susceptible (lack of plant vigor, medium flowering and 30–44% pod set), 7 = susceptible (lack of plant vigor, late flowering and 15–29% pod set); 8 = highly susceptible (lack of plant vigor, late flowering and 1–14% pod set); and 9 = very

highly susceptible (no flowering, no pod set and 100% plant death). Genotypes were assessed after the susceptible genotypes had scores of 7 or more than 7 on the visual scale.

2.4. Phenological Traits

Throughout the duration of the study, the bean genotypes were evaluated for phenological traits including days to flowering (DF) and days to pod setting (DP). DF was recorded as the time from germination to flowering, whereas DP was recorded as the time from germination to first pod formation.

2.5. Morphological Traits

Plant height (PH) was measured as cm from ground to the top of the plant. The number of stems per plant (NS) was counted as the number of main stems per plant. The length of the middle leaflet in the third leaf (LL) from the top of the plant was measured as leaflet length in mm, whereas the width of the middle leaflet in the third leaf (LW) from the top of the plant was recorded as width in mm. The same leaflet was evaluated for the length and width of the leaflet. Plant growth habit (GH) was detected as a determinate or indeterminate growth habit for each genotype. All of these parameters were evaluated according to the characteristics contained in the common bean descriptor proposed by the International Board for Plant Genetic Resources IBPGR [39].

2.6. Agronomical Traits

Plant yield (PY) and plant biomass (PB) per plant were calculated as g for seed weight with the pods of each plant and total dry weight of a plant based on a single plant, respectively.

2.7. Physiological Traits

The fluorescence induction parameters of chlorophyll (Fo, Fm) were recorded in the dark phase without detaching the leaves from the plants. These parameters were recorded during the growth stage of the plant using a portable battery-powered fluorometer FluorPen FP 100 series, manufacture by Photon Systems Instruments (PSI) in the Czech Republic. For each sampled plant, the fully opened third leaf was fully wrapped for 20 min with aluminum foil. After this time, the aluminum foils were carefully removed (avoiding exposition of the leaf to light) by attaching clips constituting the support of the fluorometer. The clips were fixed onto the leaf so that the recording was carried out on the upper (adaxial) surface of the leaf. To maximize the effects of heat stress, the parameters were measured between 1 and 3 pm when temperatures were the highest. With these parameters, the ratio of the maximum quantum efficiency of photosystem II (PSII) was calculated according to the formula:

$$\mathrm{Fv} = \mathrm{Fm} - \mathrm{Fo} \text{ and } \mathrm{Fv/Fm} = (\mathrm{Fm} - \mathrm{Fo})/\mathrm{Fm} \quad (1)$$

where Fv is the variation of the fluorescence, Fm the maximum fluorescence, F0 the initial fluorescence, and Fv/Fm is the ratio of the maximum quantum efficiency of PSII. These parameters were measured using the modified method of [40].

To detect chlorophyll content (CC) of the leaves, the SPAD value was also determined using a chlorophyll measuring device (SPAD-502 Plus, manufacture by Konica Minolta, Tokyo, Japan). Measurements were taken during the growth stage on the 3rd fully open leaf from the top of the sampled plants. The measurements were taken between 1 pm and 3 pm to have the maximum response of plant chlorophyll to heat. During the measurement, the selected leaf was inserted into the spike of the SPAD-502 Plus so that the detector was in contact with the upper face of the leaf (adaxial).

2.8. Data Analyses

All statistical tests were performed using the R version 3.6.1 statistical software with the specific packages. Descriptive statistics for phenological, agro-morphological, and physiological traits were calculated, and Kruskal-Wallis tests and Mann-Whitney U tests

were performed to determine the magnitude of variation for all measured traits between genotypes and trials, respectively. Agglomerative hierarchical cluster (AHC) analysis with Ward's method was performed in the R statistical software and APE package Version: 5.6-2 to group bean genotypes according to their heat stress resistance level. Path analysis [34] was used to show direct and indirect relationships between heat stress resistance and the studied traits [41]. Principal component analysis based on the differences observed between the moderate heat stress and extreme heat stress conditions quantitative traits was performed using FactoMineR which is an R package dedicated to multivariate data analysis [42].

A generalized linear model with the restricted maximum likelihood (REML) was used for data analyses following the formula:

$$Yij = \beta 0 + \beta 1X1i + \beta 2X2j + \beta 3 * X3ij + bi + \varepsilon ij$$

where Yij is the response variable (traits of *Phaseolus* genotypes). β0 is the intercept term. β1, β2, and β3 are the fixed effects associated with the explanatory variables X1i, X2j, and X3ij, respectively. X1i represents the effect of the ith genotype. X2j represents the effect of the jth heat stress condition (field or greenhouse). X3ij represents the interaction effect between genotype i and heat stress condition j. bi is the random effect associated with the ith genotype, assumed to follow a normal distribution with mean 0 and variance σb^2. εij is the residual error term assumed to follow a normal distribution with mean 0 and variance σ^2.

At the end of the statistical analysis of each experiment, the homogeneity of error variances for both sites was tested (Bartlett) and the combined analysis of the data was conducted. The least significant difference (LSD, $p \leq 0.05$) was used to compare the mean of phenological, agro-morphological, and physiological data for all bean genotypes in each experiment.

3. Results

3.1. Climatic Parameters

Throughout the study period, maximum and minimum daily temperatures were higher in the greenhouse than in the field. Maximum temperatures in the greenhouse were noted as 43.4 °C in April, 47 °C in May, 52.2 °C in June, and 55 °C in July, while they were recorded in the rainfed field as 24.6 °C, 33.4 °C, 39.7 °C, and 40.3 °C in April, May, June, and July, respectively (Figure 1). The average daily temperature in the greenhouse and the field increased steadily from planting date to harvest. Temperatures in the flowering period started at 47 °C in the greenhouse and 37.2 °C in the field. The average daily relative humidity (RH) was very variable in the field, while it showed some consistency despite slight variations observed during the high temperature period in the greenhouse (Figure 1). According to maximum temperatures, the trials carried out in the field and greenhouse will be referred as to moderate heat stress and extreme heat stress conditions, respectively.

3.2. Soil Properties

Soil properties both in greenhouse and rainfed field trials were detailed before [35–37]. Nitrogen (N) and organic matter in both soils were detected to be at low levels. $CaCO_3$ and pH were measured as 26.8% and 7.62, respectively. Iron (Fe) and zinc (Zn) contents in both soils were found to be deficient because of the high pH of the soil. Remaining recorded macro and micro plant nutrition elements were considered to be balanced for bean production.

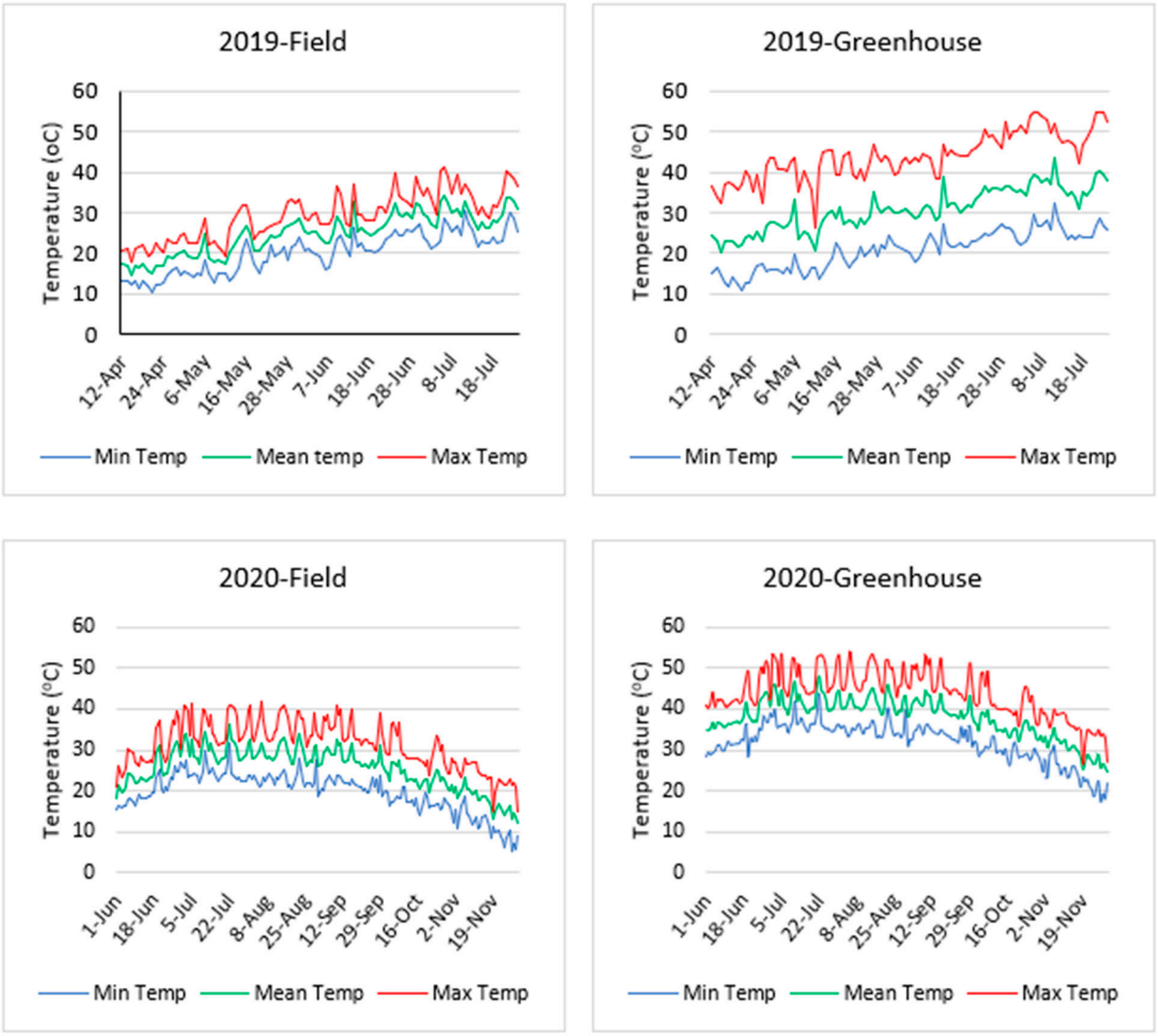


Figure 1. Weekly mean, maximum and minimum temperatures (°C) from sowing time to harvest under moderate heat stress (field) and extreme heat stress (greenhouse) conditions during 2019 and 2020.

3.3. Phenological Traits

The general phenological traits of the genotypes were determined and summarized in Figure 2. In 2019 days to flowering (DF) was recorded between 34 and 81 days under moderate heat stress (field) conditions and between 29 and 69 days under extreme heat stress (greenhouse) conditions, while in 2020 it was found between 21 and 54 days under moderate heat stress (field) conditions and between 29 and 41 days under extreme heat stress (greenhouse) conditions. In 2019, days to pods setting (DP) was recorded between 40 and 77 days under moderate heat stress (field) conditions, whereas it was recorded between 38 and 57 days under extreme heat stress (greenhouse) conditions. In 2020, on the other hand, DP was recorded between 44 and 59 days under moderate heat stress (field) conditions, whereas it was recorded between 33 and 58 days under extreme heat stress (greenhouse) conditions. A significant difference of the mean DF was not observed under moderate heat stress (field) conditions (47.7 days) and extreme heat stress (greenhouse) conditions (48 days) in 2019 trials, while they show a significant difference in 2020 trials (48.6 days in field and 34.7 days in greenhouse) ($p < 0.05$). The DP was significantly different between moderate heat stress (field) and extreme heat stress (greenhouse) in 2019 (51.5 days in field and 46 days in greenhouse) and 2020 (54.7 days in field and 40.5 days in greenhouse) trials ($p < 0.05$).

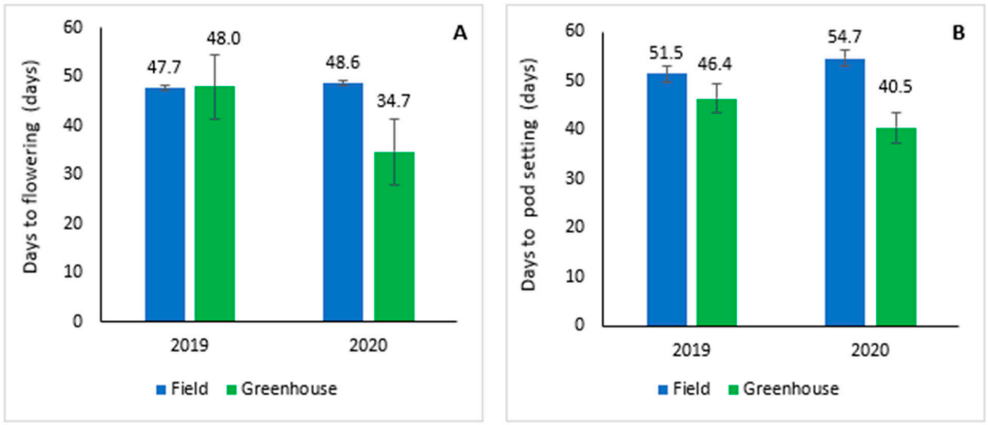


Figure 2. Variation for phenological traits including days to flowering (**A**) and days to pods setting (**B**) in *Phaseolus* genotypes under moderate heat stress (field) and extreme heat stress (greenhouse) conditions during 219 and 2020. Bars indicate means ± standard errors.

3.4. Morphological Traits

Some morphological traits including the number of stems (NS) per plant, plant height (PH), leaflet length (LL), and width (LW) were recorded under moderate heat stress (field) and extreme heat stress (greenhouse) conditions on the bean genotypes (Figure 3). Except for the mean of leaflets length, the morphological traits measured have presented a significant difference between moderate heat stress (field) conditions and extreme heat stress (greenhouse) conditions.

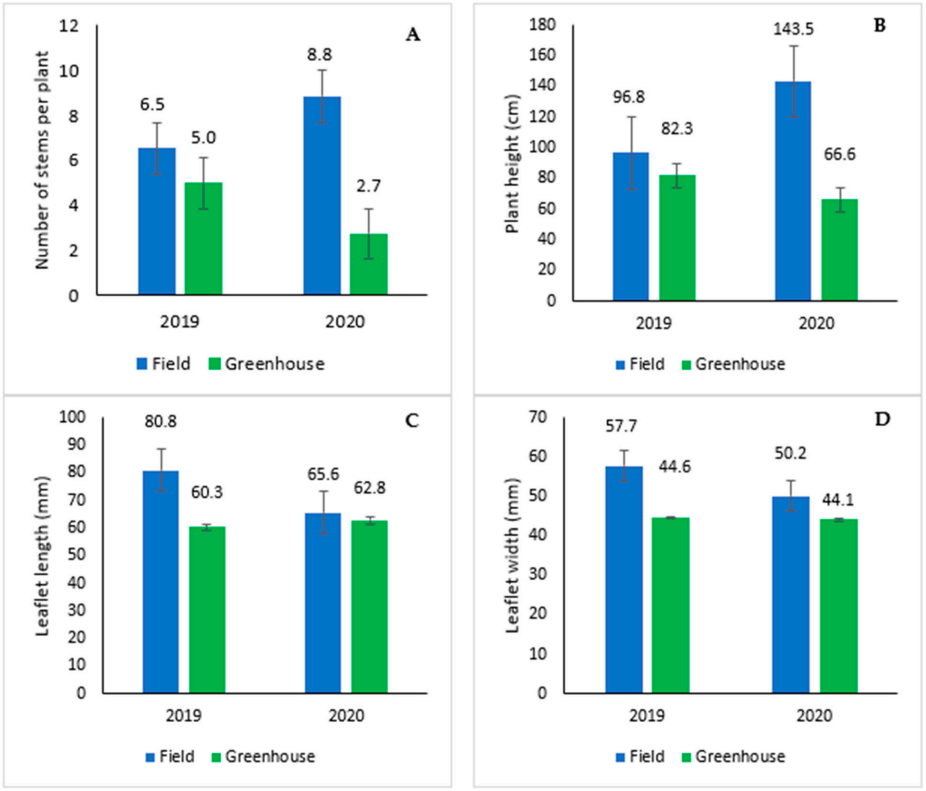


Figure 3. Variation for morphological traits including number of stems per plant (**A**), plant height (cm) (**B**), leaflet length (mm) (**C**) and leaflet width (mm) (**D**) in *Phaseolus* genotypes under moderate heat stress (field) and extreme heat stress (greenhouse) conditions during 2019 and 2020. Bars indicate means ± standard errors.

During the 2019 trials, the mean number of stems per plant was 6.5 stems under moderate heat stress (field) conditions and 5 stems under extreme heat stress (greenhouse) conditions, it was recorded under moderate heat stress (field) conditions and under extreme heat stress (greenhouse) conditions as 8.8 stems and 2.7 stems in 2020, respectively.

The mean plant height was 96.8 cm under moderate heat stress (field) conditions and 82 cm under extreme heat stress (greenhouse) conditions in 2019, whereas it was found as 143.5 cm and 66.6 cm under moderate heat stress (field) and extreme heat stress (greenhouse) conditions in 2020.

The mean leaflet length was 80.8 mm under moderate heat stress (field) conditions and 60.3 mm under extreme heat stress (greenhouse) conditions in 2019, while it was detected as 65.6 mm under moderate heat stress (field) conditions and 62.8 mm under extreme heat stress (greenhouse) conditions in 2020. The mean leaflet width was 57.7 mm under moderate heat stress (field) conditions and 44.6 mm under extreme heat stress (greenhouse) conditions, whereas during the 2020 trials, it was 50 mm under moderate heat stress (field) conditions and 44 mm under extreme heat stress (greenhouse) conditions (Figure 3).

3.5. Agronomical Traits

Plant yield and plant biomass of the bean genotypes significantly varied from moderate heat stress (field) to extreme heat stress (greenhouse) conditions during the 2019 and 2020 trials ($p < 0.05$) (Figure 4). The mean of plant biomass was also higher in moderate heat stress (field) conditions than that of extreme heat stress (greenhouse) conditions (55 g in the field and 18 g in the greenhouse) in 2019 and (191 g in the field and 8.7 g in the greenhouse) in 2020 trials. The means of plant yield were higher in moderate heat stress (field) conditions than that of extreme heat stress (greenhouse) conditions in 2019 (30.8 g in the field and 1.7 g in the greenhouse) and 2020 (94 g in the field and 3 g in the greenhouse) in Figure 4.

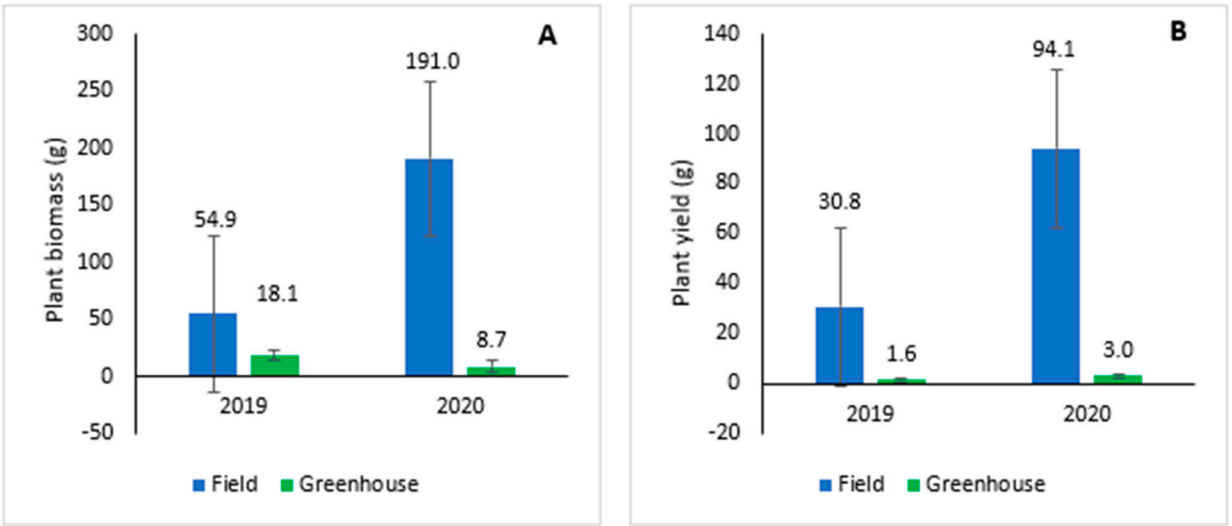


Figure 4. Variation for agronomical traits including plant biomass (g) (**A**) and plant yield (g) (**B**) in *Phaseolus* genotypes under extreme heat stress (greenhouse) and moderate heat stress conditions (field) during 2019 and 2020. Bars indicate means ± standard errors.

3.6. Physiological Traits

The means of maximum quantum efficiency of PSII (Fv/Fm) and the SPAD value showed a significant difference between moderate heat stress (field) and extreme heat stress (greenhouse) conditions ($p < 0.05$). The means of maximum quantum efficiency of PSII were higher in extreme heat stress (greenhouse) conditions (0.640 Fv/Fm) than that of moderate heat stress (field) conditions (0.600 Fv/Fm) in 2019. In 2020, maximum quantum efficiency

of PSII was recorded in moderate heat stress (field) and extreme heat stress (greenhouse) conditions as 0.730 and 720 Fv/Fm, respectively (Figure 5).

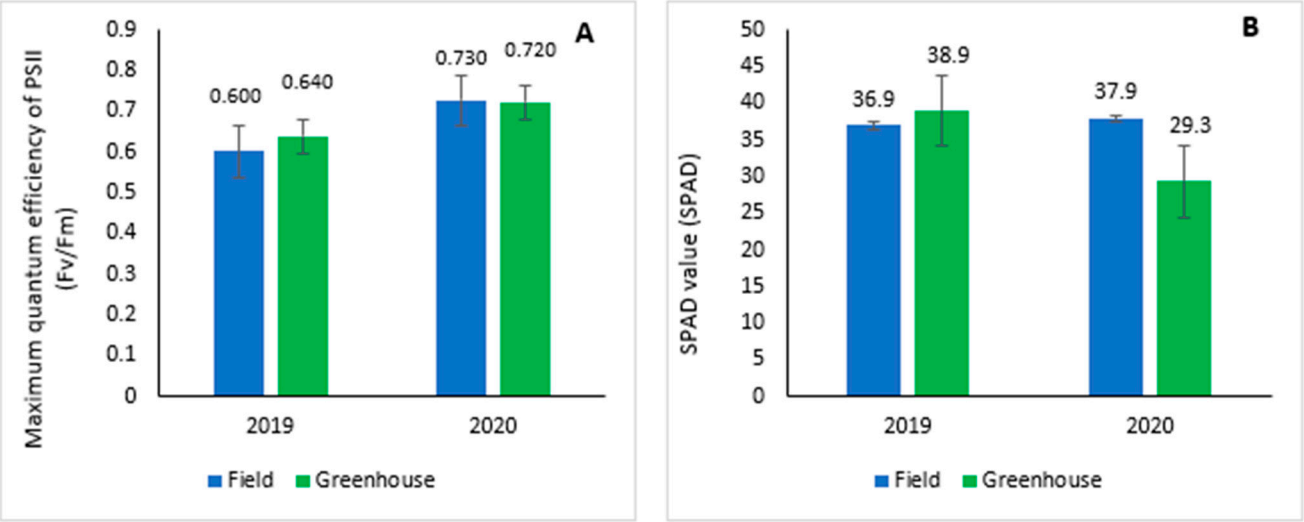


Figure 5. Variation for physiological traits including Maximum quantum efficiency of PSII (**A**) and chlorophyll content (SPAD) (**B**) in *Phaseolus* genotypes under moderate heat stress (field) and extreme heat stress (greenhouse) conditions during 2019 and 2020. Bars indicate means ± standard errors.

In both years, the measured parameters also showed a statistically significant difference among the genotypes ($p < 0.05$). The mean of the SPAD value showed a significant difference between heat stress (field) and extreme heat stress (greenhouse) conditions ($p < 0.05$). The mean SPAD value was higher in moderate heat stress (field) conditions (36.9 SPAD) than that of extreme heat stress (greenhouse) conditions (38.9 SPAD) in 2019. In 2020, it was 37.9 and 29.3 SPAD under moderate heat stress (field) and extreme heat stress (greenhouse) conditions, respectively (Figure 5).

3.7. Screening for Resistance to Heat Stress

According to Figure 6, the means of the values obtained from the visual scales for resistance to heat stress were below 4 in the moderate heat stress (field) and below 6 in the extreme heat stress (greenhouse) conditions in 2019. In 2020, these means were recorded as 7 on the value scale in both moderate heat stress (field) and extreme heat stress (greenhouse) conditions. It was observed that the means of the visual scale for resistance to heat stress were higher under extreme heat stress (greenhouse) conditions compared to moderate heat stress (field) conditions. In both 2019 and 2020 trials, a significant variation in the screening score for resistance to heat stress was observed among genotypes under both moderate heat stress (field) and extreme heat stress (greenhouse) conditions ($p < 0.05$).

In the heat stress (field) conditions of the 2019 trials, nine genotypes were found to be between 1–3 score, while in the extreme heat stress (greenhouse) conditions (Figure 6 B and C), 13 *Phaseolus* genotypes were identified as being between 1–3 score. Overall, Figure 6 showed that there were nine resistant *Phaseolus* genotypes, including G191 (*P. lunatus*), G183 (*P. acutifolius*), G123 (*P. vulgaris*), G13 (*P. vulgaris*), G50 (*P. vulgaris*), G59 (*P. vulgaris*), G192 (*P. lunatus*), G96 (*P. vulgaris*), and G181 (*P. coccineus*), with scores ranging from 1 to 3.

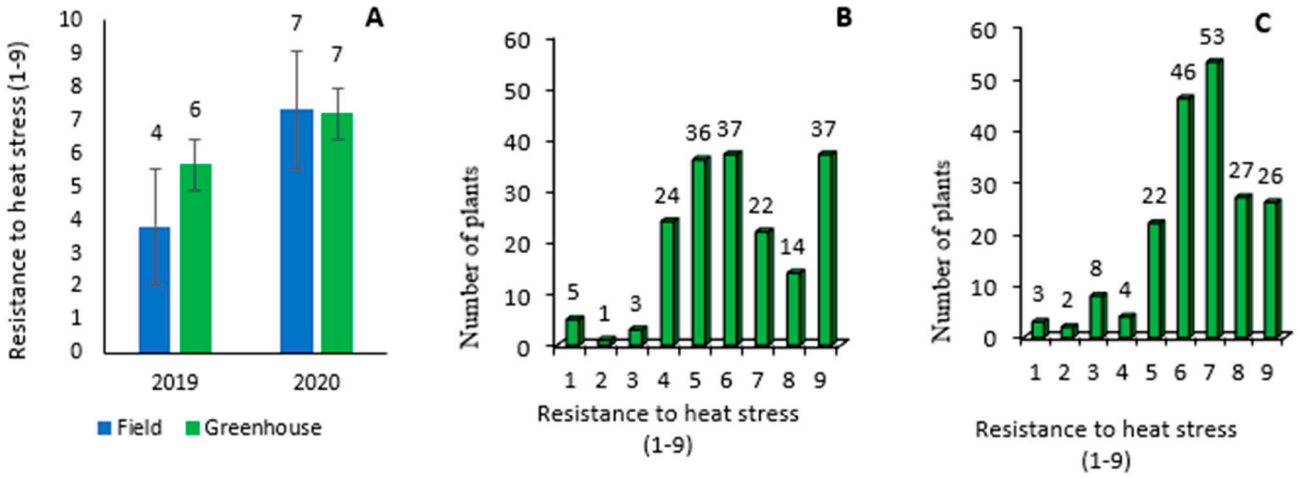


Figure 6. Variation for resistance to heat stress (**A**) and number of plants for resistance to heat stress in *Phaseolus* genotypes according to 1–9 visual scale under moderate heat stress (field) and extreme heat stress (greenhouse) conditions during 2019 (**B**) and 2020 (**C**). Bars indicate means ± standard errors. Three-dimensional bars indicate the number of plants in 2019 and 2020.

3.8. Direct and Indirect Relationships of Measured Traits with Heat Resistance

Path coefficients of the direct and indirect effects of the measured parameters on heat resistance obtained in moderate heat stress (field) conditions are given in Table 1. Leaflet length (p = 0.230 *), the number of stems per plant (p = −0.185 *), and leaflet width (p = −0.138 *) among morphological traits had significantly the highest negative direct effects on resistance heat stress in bean genotypes. Among physiological traits, the SPAD value (p = −0.073 *) and maximum quantum efficiency of PSII (p = −0.083 *) had significantly the highest negative direct effects on resistance to heat stress. Among agronomical traits, biomass (p = −0.058 *) had significantly the highest negative direct effect on heat resistance of bean genotypes under moderate heat stress (field) conditions (Table 1).

Table 1. Path coefficients of the direct and indirect effects of traits on resistance to heat stress in *Phaseolus* genotypes under moderate heat stress (field) conditions.

Traits *	DF	DP	PH	NS	LL	LW	CC	Fv/Fm	PB	PY
DF	**0.058**	0.474 *	−0.040	−0.006 *	−0.018	−0.026	−0.019	0.008	0.023	−0.006
DP	0.491 *	**0.073**	0.119 *	−0.073	0.016	0.053	−0.025	−0.024	0.051	0.017
PH	−0.049	0.140 *	**0.014**	0.279 *	0.422 *	−0.133 *	0.103 *	0.065	0.285 *	0.010
NS	−0.005	−0.061	0.199 *	**−0.185** *	−0.108 *	0.235 *	−0.033	0.024	−0.095 *	0.054
LL	−0.022	0.019	0.430 *	−0.155 *	**0.230** *	−0.241 *	−0.005	0.280 *	0.191 *	0.000
LW	−0.023	0.046	−0.098 *	0.244 *	−0.175 *	**−0.138** *	0.085 *	0.051	0.081 *	0.034
CC	−0.015	−0.019	0.065 *	−0.029	−0.003	0.073 *	**−0.073** *	−0.003	−0.020	−0.004
Fv/Fm	0.007	−0.019	0.044	0.023	0.188 *	0.047	−0.003	**−0.083** *	−0.042	−0.008
PB	0.021	0.045	0.215 *	−0.101 *	0.141 *	0.083 *	−0.024	−0.047	**−0.058** *	0.018
PY	−0.005	0.012	0.006	0.048	0.000	0.029	−0.004	−0.007	0.015	**−0.010**

DF: Days to flowering, DP: Days to pod setting, PH: Plant height, NS: Number of stems, LL: Leaflet length, LW: Leaflet width, PB: Plant biomass, PY: Plant yield, CC: SPAD value, and Fv/Fm: Maximum quantum efficiency of PSII, *: The value of the direct or indirect effect shows a significant difference ($p < 0.05$) between the two traits. Bold data represent the direct effect of traits on resistance to heat stress, while the other data indicate the indirect effects over the bold traits.

Path coefficients of the direct and indirect effects of the measured parameters on the resistance to heat stress score obtained in extreme heat stress (greenhouse) conditions were given in Table 2. Among morphological traits, plant height (p = −0.271 *), leaflet length (p = −0.208 *), and the number of stems per plant (p = −0.207 *) had significantly the highest negative direct effect on resistance heat stress score in bean genotypes, while the

SPAD value (p = −0.145 *) had the highest direct and negative effects among physiological traits. Among agronomical traits, biomass (p = −0.146 *) had the highest negative direct effects on the resistance to heat stress score. Via biomass, the SPAD value (p = 0.210 *) had the highest Indirect influence on the resistance to heat stress score (Table 2).

Table 2. Path coefficients of the direct and indirect effects of traits on resistance to heat stress in *Phaseolus* genotypes under extreme heat stress (greenhouse) conditions.

Traits *	DF	DP	PH	NS	LL	LW	CC	Fv/Fm	PB	PY
DF	**0.014**	0.165 *	0.013	−0.089 *	−0.055 *	0.036	0.119 *	−0.064	0.039	0.023
DP	0.164 *	**−0.057**	0.008	−0.056	−0.033	0.003	0.143 *	0.081 *	−0.024	−0.009
PH	0.013	0.009	**−0.271** *	0.104 *	−0.014	0.026	0.113 *	0.151 *	0.129 *	0.002
NS	−0.092	−0.058	0.106 *	**−0.207** *	0.031	−0.008	0.057	0.066	0.198 *	0.007
LL	−0.214 *	−0.128	−0.052	0.116	**−0.208** *	0.864 *	−0.087	0.195 *	−0.034	−0.017
LW	0.140	0.013	0.098	−0.032	0.863 *	**0.015**	0.227 *	−0.102	0.106	−0.012
CC	0.129 *	0.157 *	0.121 *	0.061	−0.024	0.064 *	**−0.140** *	−0.101 *	0.210 *	0.015
Fv/Fm	−0.062	0.079 *	0.144 *	0.062	0.049 *	−0.025	−0.090 *	**−0.040**	0.010	−0.025
PB	0.042	−0.026	0.137 *	0.208 *	−0.009	0.029	0.207 *	0.011	**−0.146** *	−0.002
PY	0.021	−0.008	0.002	0.006	−0.004	−0.003	0.012	−0.023	−0.002	**−0.018**

DF: Days to flowering, DP: Days to pod setting, PH: Plant height, NS: Number of stems, LL: Leaflet length, LW: Leaflet width, PB: Plant biomass, PY: Plant yield, CC: SPAD value, and Fv/Fm: Maximum quantum efficiency of PSII, *: The value of the direct or indirect effect shows a significant difference ($p < 0.05$) between the two traits. Bold data represent the direct effect of traits on resistance to heat stress, while the other data indicate the indirect effects over the bold traits.

3.9. Principal Component Analysis

Principal component analysis-Biplot (PCA-Biplot) was performed to obtain more reliable information on how to identify groups of genotypes with desirable traits associated with heat sensitivity on the one hand and helps to differentiate significant relationships between traits in other hand. Seven PCs out of a total twelve had eigenvalue >1 and contributed to 98.31% of the total variability. We realized that from component 1 to component 7 the percentage of contribution to variability was: 44.63%, 68.68%, 81.16%, 90.69%, 94.94%, 97.11%, and 98.31%, respectively. These variabilities were positively and negatively affected by the different traits used. The main traits causing variability in the different components were: biomass yield for PC1 (0.7), plant height for PC2 (−0.84), plant biomass PC3 (0.57), plant yield for PC4 (−0.59), days to pods set for PC5 (−0.578), days to flowering for PC6 (0.4), days to pods set for PC7 (−0.64), the SPAD value for PC8 (0.811), fv/fm for PC9 (0.93), leaves' widths for PC10 (0.78), the number of stems for PC11 (0.89) and heat resistance for PC12 (0.91). This biplot demonstrated that most of the variation was accounted for by nine main traits: Maximum quantum efficiency of PSII (Fluo), biomass yield (PB), the number of stems per plant (SN), days to pods setting (DP), days to flowering (DF), leaflet length (LL), leaflet width (LW), resistance to heat stress score (HR), and the SPAD value (CC) (Figure 7).

3.10. Agglomerative Hierarchical Clustering

The agglomerative hierarchical clustering (AHC) dendrogram was constructed using Euclidean distance as the measure of dissimilarity between each genotype. This approach considers each group as distinct from the others before deciding which groupings should be joined. The clustering was performed using Ward's method, which aims to minimize the sum of squared differences within each cluster.

The resulting dendrogram was used to classify the genotypes into eight groups. The first group contained two genotypes (G188 and G184), while the second group contained 36 genotypes. The third group contained eight genotypes, the fourth group contained 13 genotypes, the fifth group contained 55 genotypes, the sixth group contained 12 genotypes, the seventh group contained four genotypes (G181, G191, G190, and G193), and the eighth group contained 66 genotypes.

Overall, the AHC dendrogram and the resulting genotype classifications were determined using a combination of Euclidean distance, Ward's method, and the agglomerative hierarchical clustering approach. (Figures 8 and S1).

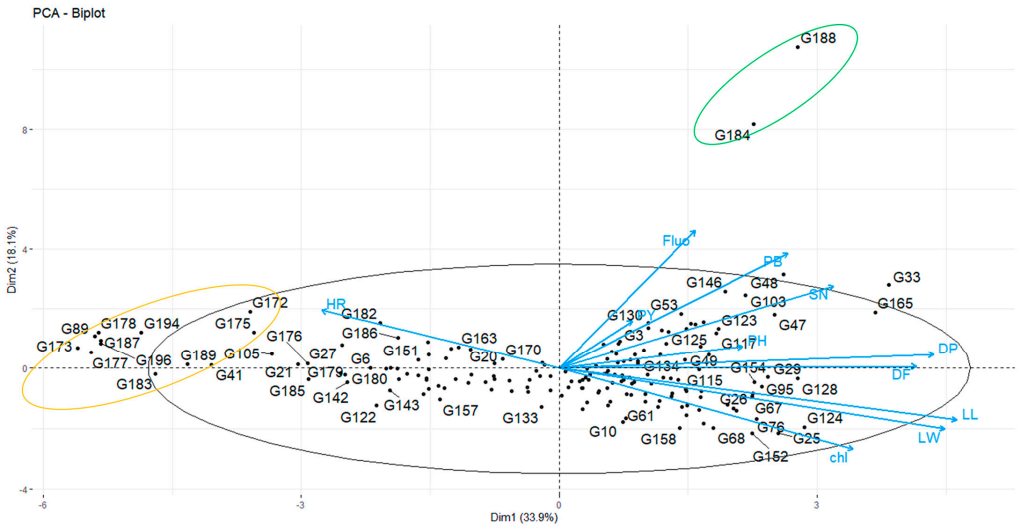


Figure 7. PCA-biplot of the contribution of the quantitative traits recorded on *Phaseolus* species in the moderate and extreme heat stress growth conditions. The first two components explained 52% of the observed variation. The black, green, and yellow ellipses represent different groups of genotypes with similar trait variation. The arrows are the vector of the eigenvalue which represents the contribution of each trait. Arrow length and direction indicate trait magnitude and direction of contribution, respectively. Longer arrows indicate greater trait contribution.

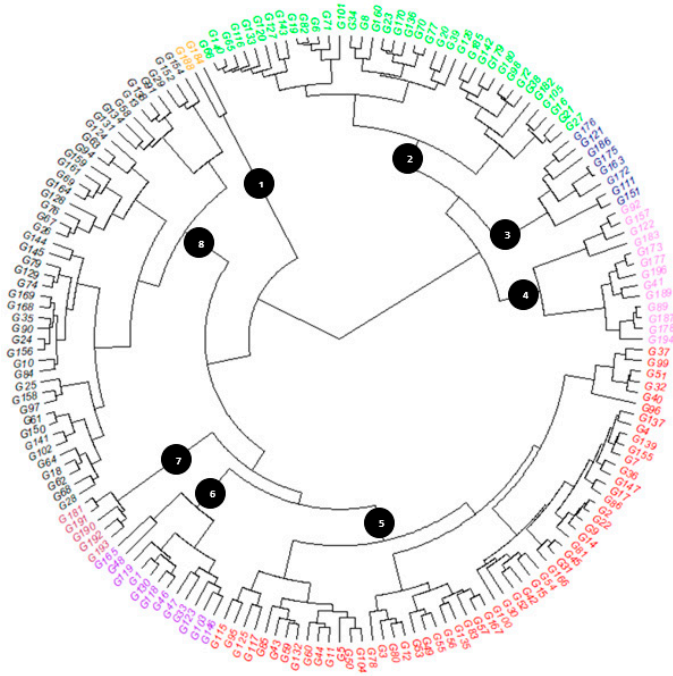


Figure 8. Circular agglomerative hierarchical clustering (CAHC) of *Phaseolus* genotypes under moderate heat stress (field) and extreme heat stress (greenhouse) conditions and during 2019 and 2020. The numbers from 1 to 8 associated with a specific color represent the 8 groups of genotypes showing little or no significant variation according to the given traits.

4. Discussion

Phaseolus genotypes were exposed to excessive heat stress throughout their development cycle in both greenhouse and field conditions. The heat stress increased gradually as the plants grew, with the maximum temperature being reached during flowering and pod filling. The stages of flowering and pod filling were particularly sensitive to heat stress, resulting in a low rate of flowering and fruiting under extreme heat stress conditions in the greenhouse. However, many genotypes that were unable to produce flowers and pods in the greenhouse were able to produce well-filled pods under field conditions. The daily maximum temperature in the greenhouse was 43.9 °C, while in moderate heat stress conditions in the field, it was 29.2 °C. This is higher than the optimum growth temperature for common beans, which is between 20 and 25 °C according to previous research [20–23]. The heat stress led to a significant reduction in yield under extreme heat stress conditions in the greenhouse, compared to moderate heat stress conditions in the field.

According to the results of their works on faba bean (*Vicia faba* L.), Bishop, Potts [43] reported some explanation of the reduction of yield as a result of the long exposure of the plants to the heat stress. They stated that flowers were the most affected part of the plant under heat stress conditions, due to reduced pollen viability and germinability in many crop plants [44–49]. Many researchers demonstrated that although the male and female reproductive organs of the common bean were the most sensitive to heat stress, the male organs suffered more damage [20,50]. Heat stress can have negative effects on male reproductive organs in plants, leading to a reduction in pollen maturation, germination, and pollen tube formation. This, in turn, can result in a failure of pollination and subsequent non-fertilization of eggs. In addition to environmental factors, the specific genetic makeup of plants also plays a role in determining their ability to withstand heat stress. Quantitative phenological traits, such as days to flowering, days to pod filling, and maturity time can be used to assess the impact of heat stress on plant growth and development (Figure 2). These traits can be influenced by both the plant genotype and environmental conditions. Plants that exhibit early expression of these traits may have a greater tolerance to heat stress, as they are able to escape from stress by reducing their duration of exposure to high temperatures. The effects of heat stress on plant reproductive organs and growth can be complex and multifaceted and depend on a variety of genetic and environmental factors. Understanding these factors is important for developing strategies to mitigate the negative effects of heat stress on crop production and yield [51–53]. Days to flowering and days to pod filling were longer in moderate heat stress (field) compared to extreme heat stress (greenhouse) in both years (Figure 2). Despite high temperatures in the greenhouse, the low fruiting rate suggests that earliness was due to a low density of flowering and fructification. Previous studies suggest that high temperatures can initiate certain developmental stages and promote early growth in plants [31,54]. Three heat stress resistance mechanisms have been identified: earliness, avoidance through protective morphological traits, and tolerance through accumulation of heat-related solutes [55]. Early flowering *Phaseolus* genotypes have an advantage in escaping heat stress as their critical stages occur before the high temperature period in Figure 2 [56].

The expression of quantitative morphological traits of each genotype varies under moderate and extreme heat stress conditions. This could imply that the effects of heat stress on the growth and development of common beans are dependent on genotype, and this information could be useful for breeding programs aimed at developing heat-tolerant varieties. The grouping of common beans into determinate and indeterminate growth genotypes could be helpful for understanding the growth habits of these plants. Determinate genotypes have a limited growth period and produce a set number of pods, while indeterminate genotypes continue to grow and produce pods throughout the growing season. This information could also be useful for breeding programs aimed at developing plants with specific growth habits or yield characteristics [39]. The plant's growth habit is a key property that influences its tolerance to heat stress, allowing it to adjust growth in response to low or high temperatures. In extreme heat stress conditions, some genotypes with a deter-

minate growth habit produced mature pods, while climbing genotypes experienced flower degeneration. Growth habits include indeterminate with erect/prostrate/semi-climbing main stem, moderate indeterminate climbing, and indeterminate with main semi-climbing stem [39,57,58].

There are two types of *Phaseolus* beans based on their size and the number of knots: the dwarf type and the climbing type. Dwarf genotypes typically have between three and ten knots on the main stem, with the stem always ending in a group of flowers. Once the flowers are formed, growth stops. On the other hand, climbing types have 11 to 35 knots on the main stem, and their stems grow in a climbing style, which can be either accelerated or moderate depending on the case. These morphological differences between the two types of common bean can have significant implications for their cultivation, as well as for their use in cooking and nutrition [57]. On the other hand, other genotypes that are of indeterminate type are not climbers and tend to spread on the ground [59,60]. Whether in one or the other type, their size is strongly influenced by the interaction of genetic and environmental factors [60]. However, these morphological characteristics may rather be the result of an established natural adaptation resulting from genotype by environment interactions. In this regard, Cortés and Blair [61] indicated that candidate genes such as *DREB*, *ASR*, and *ERECTA* had associated with drought tolerance. It is possible that genotypes that exhibit certain traits under extreme heat stress conditions have inherited genes responsible for those traits through selective pressures. This is known as adaptation, where certain traits become more prevalent in a population due to environmental pressures. However, it is important to note that the acquisition of traits can also occur through genetic mutations, recombination, and other mechanisms. It is also worth noting that while domestication centers may be characterized by arid regions, not all wild species from these regions may necessarily exhibit the same traits. Additionally, there could be other factors at play, such as human selection for certain traits during the domestication process [61,62].

Yield losses due to heat stress were higher in extreme heat stress (greenhouse) conditions than that of moderate heat stress (field) conditions and up to 100% in several genotypes (Figures 4 and 6). Since the effects of heat stress have become different from region-to-region in the world [29], *Phaseolus* beans that are resistant for extreme temperature conditions will be needed as in this study. In this sense, average and extreme maximum temperatures have not only increased in the southern part of Anatolia in the last years, but rainfall was also recorded as irregular and insufficient [63]. The south part of Anatolia is predicted to be one of the most heat-affected regions by climate change. Yield reduction due to the heat stress effects was also similar to that which was explained by Nemeskéri, Remenyik [64], who showed that a decrease in yield is the result of the alteration of the reproductive organs, which are particularly affected by heat stress [20,26,65–67]. The role of genes in the tolerance of bean species to heat stress is complex and can vary depending on the specific species and trait being examined. Shonnard and Gepts [68] found that in the case of the common bean, heat stress resulted in quantitative inheritance, meaning that the inheritance of the trait was due to continuous variation in flower bud abortion and reduced pod fill. They found that significant additive effects were present, suggesting that selection for heat tolerance in common beans could be possible for these two traits. On the other hand, in snap bean, a high rate of abscission in the reproductive organs in response to heat stress was found to be controlled by major genes. This means that the inheritance of this trait is determined by a small number of genes with significant effects, rather than by continuous variation in multiple genes [65]. Our study has found that extreme heat stress in the greenhouse led to both flower shedding and pod abortion, which resulted in the lowest yield compared to moderate heat stress in the field. This observation is supported by the data presented in Figures 4 and 6. It is important to note the impact of environmental conditions on plant growth and development, and how extreme stress can significantly affect crop yield. Further research may be needed to investigate ways to mitigate the negative effects of heat stress on plant growth and yield in greenhouse conditions.

Temperature is one of the most important environmental factors affecting plant growth and development. The effects of temperature on plant growth and development can be both direct and indirect. Direct effects of temperature include the stimulation of enzymatic activity and hormone production, which are essential for plant growth and development. Indirect effects of temperature include changes in the humidity around the plants, which can affect the water balance of the plant and its ability to carry out photosynthesis. These direct and indirect effects of temperature can ultimately affect the phenological, agro-morphological, and physiological traits of plants [54,69]. Plants thrive in a specific temperature range, and anything outside of this range can be harmful to their growth and survival. Temperatures above 45 °C can damage plant cells and lead to plant death, but some temperatures can also benefit plants [69]. For instance, low temperatures can stimulate seed germination by inducing physiological changes. Coping with high temperatures and environmental stress depends on both genetic and environmental factors. Certain plant genotypes may adapt better and complete their life cycle faster in response to stress, while others may be more vulnerable and prone to damage [31].

Due to more heat stress pressure in the greenhouse when compared to the rainfed field, yield was zero for almost all genotypes, except for genotypes G191, G183, G123, G13, G50, G59, G192, G96, and G181 with scores between 1.0 and 3.0. These results are in agreement with those of da Silva, dos Reis [66]. *P. acutifolius* was more resistant to heat stress among bean genotypes despite late flowering. For some species, such as tepary bean, this can be explained by the fact that its origination from the arid regions between Mexico and the United States would have undergone several selective pressures during which it developed the mechanisms of adaptation to abiotic stresses such as drought and heat stress [37,70]. This characteristic of tepary bean in comparison to the common bean could be exploited to enrich the sources of hereditary trait variation in the improvement of the bean against abiotic stresses in general and heat stress specifically. Genotypes of *P. lunatus* and *P. coccineus* had escape ability because of early flowering (Figures 2 and 3). Suárez, Polanía [71] identified that some genotypes of *P. acutifolius*, *P. vulgaris*, and lines derived from inter- and intra-specific crosses between *P. vulgaris* × *P. acutifolius* and *P. vulgaris* × *P. acutifolius* × *P. coccineus* had better adaptation to high temperature. This could prove that the accessions of *P. acutifolius* used in this study would have the heat stress tolerance genes since the tolerance of *P. acutifolius* could be associated with its highly adapted plant architecture in drought prone environments [72], accompanying heat stress. As in the other studies, some bean genotypes that were tolerant to heat stress were reported [65,73–76] and these genotypes have been improved using intra- and inter-specific crosses of the common bean, with other *Phaseolus* species including *P. acutifolius*, *P. coccineus*, and *P. dumosus* [71].

Path analysis has been suggested to show direct and indirect relationships between agro-morphological traits of plants or yield components [30–33] and stress tolerance [41,77]. According to the available literature, this is the first study using the detection of direct and indirect associations between resistance to heat stress and agro-morphological traits or physiological traits using path analysis in *Phaseolus* species and genotypes [35]. Porch [21] showed that the 100-seed weight, the number of pods per plant, and the harvest index were agronomical factors that could better influence the yield when the plant is subjected to heat stress. In this study, biomass had the highest effect on the heat resistance score under heat stress conditions (Tables 1 and 2). Petkova, Denev [78] showed that heat stress causes a loss of water in the cells and causes a narrowing of the leaves, as in this study. These morphological traits are consistent with results reported by Rana, Sharma [79] in the expression of genetic diversity in common beans. The SPAD values and maximum quantum efficiency of PSII are physiological parameters that are strongly influenced by heat stress and are important for classifying plant resistance to heat stress [24]. According to path analyses, the SPAD values and maximum quantum efficiency of PSII as physiological traits had the highest significant effect on heat stress resistance scores (Tables 1 and 2). Maximum quantum efficiency of PSII has already been correlated with stresses in many plant species [80,81] and were suggested as a considerable selection criterion under heat

stress conditions [46,82]. As for physiological traits, the SPAD value and maximum quantum efficiency of PSII can be considered as selection criteria for resistance to heat stress in bean-breeding programs.

Principal component analysis of quantitative morphological traits revealed the main traits that most affected genotypes' variability between the most stressed (greenhouse) and the least stressed (field). This is easy to understand because, due to heat stress in the greenhouse, yields were zero for almost all genotypes. These results are in agreement with those of Porch [21], da Silva, dos Reis [66] which showed that the 100-seed weight, the number of pods per plant, and the harvest index were agronomic factors that could better influence the yield when the plant is subjected to heat stress. *P. coccineus* species with intermediate genotypes performed better in the field.

Correspondence between the morphological and agronomical traits and between the genotypes led to the grouping of genotypes in four main clusters. In keeping with our goal of identifying genotypes with heat stress tolerance traits, genotypes that had a better expression of the different components of performance in a stressed environment attracted the most attention. However, in field conditions, heat stress often coincides with drought and exacerbates the effects of drought stress, making it difficult to establish a true boundary between the two in terms of tolerance and allocation of biomass and yield [19,21]. Heat stress, usually occurring at the same time as drought stress, contributes to increased drought damage [83]. In addition, the responses of plants to heat stress and drought are the same as for other abiotic stresses. López-Hernández and Cortés [28] in their studies isolated nine genes that they felt were associated with biological processes associated with tolerance to high temperatures in common beans among which two transcription factors in Pv08 and the YTH protein domains in Pv06 were involved in plant development, and the response to abiotic stresses such as drought and heat. To get rid of the drought effects on beans, plants were regularly irrigated in this study. Heat-related traits in this study are considered to be introgressed from resistant donor *Phaseolus* beans into desirable bean cultivars (Cortés and López-Hernández [84]). Like faba bean [85], the selected resistant bean genotypes had direct growing potential under extreme heat stress conditions especially in the Mediterranean region of Turkey as the second crop.

5. Conclusions

Heat stress significantly affected all quantitative agro-morphological traits in bean plants, resulting in high-yield losses. However, some *Phaseolus* genotypes showed heat resistance and continued to produce pods and seeds even in extreme temperatures. *P. acutifolius*, *P. coccineus*, and *P. lunatus* genotypes were found to be superior to heat stress, while some genotypes flowered earlier or later than usual. Traits such as biomass, plant height, and the heat resistance visual scale favored better resistance to heat stress. Biomass, leaflet length, and width had the highest significant direct effects on resistance to heat stress, while the SPAD value and maximum quantum efficiency of PSII had a significant direct effect on heat stress resistance. This variability and suggested traits can be useful in plant breeding programs for improving heat stress resistance.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture13050953/s1, Figure S1: Effects of heat stress on the *Phaseolus* beans leaves (A and B), pods (C), and Whole plant (D). Table S1: *Phaseolus* bean genotypes used for heat tolerance under moderate (field) and extreme (greenhouse) heat stress conditions.

Author Contributions: T.M.T. contributed as the first authorship. H.S. contributed to perform the statistical analysis and to write the first draft of the manuscript. H.C., A.M., and T.E. contributed to conception and design of the study. C.T., supervised the PhD thesis. All authors have read and agreed to the published version of the manuscript.

Funding: This study is the first part of the PhD thesis of the first author (TMT), and it was financially supported by Akdeniz University Scientific Research Project Coordination Unit (FDK-2022-5866).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data can be obtained by contacting the corresponding author.

Acknowledgments: I would like to thank "Akdeniz University Scientific Research Project Coordination" for the financial support that made this study possible.

Conflicts of Interest: The authors declare no conflict of interest. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Freytag, G.F.; Debouck, D.G. *Taxonomy, Distribution, and Ecology of the Genus Phaseolus (Leguminosae-Papilionoideae) in North America, Mexico and Central America* Central America; Botanical Research Institute of Texas (BRIT): Fort Worth, TX, USA, 2002; Volume 23, p. 300.
2. Debouck, D.G. Phaseolus beans (*Leguminosae*, *Phaseoleae*): A checklist and notes on their taxonomy and ecology. *J. Bot. Res. Inst. Tex.* **2021**, *15*, 73–111. [CrossRef]
3. Delgado-Salinas, A.; Bibler, R.; Lavin, M. Phylogeny of the genus *Phaseolus* (*Leguminosae*): A recent diversification in an ancient landscape. *Syst. Bot.* **2006**, *31*, 779–791. [CrossRef]
4. Singh, S.P. *Common Bean Improvement in the Twenty-First Century*; Springer Science & Business Media: Berlin, Germany, 2013; Volume 7.
5. Broughton, W.J.; Hernandez, G.; Blair, M.; Beebe, S.; Gepts, P.; Vanderleyden, J. Beans (*Phaseolus* spp.)—Model food legumes. *Plant Soil* **2003**, *252*, 55–128. [CrossRef]
6. Alcázar-Valle, M.; García-Morales, S.; Mojica, L.; Morales-Hernández, N.; Sánchez-Osorio, E.; Flores-López, L.; Enríquez-Vara, J.N.; Lugo-Cervantes, E. Nutritional, antinutritional compounds and nutraceutical significance of native bean species (*Phaseolus* spp.) of mexican cultivars. *Agriculture* **2021**, *11*, 1031. [CrossRef]
7. Celmeli, T.; Sari, H.; Canci, H.; Sari, D.; Adak, A.; Eker, T.; Toker, C. The nutritional content of common bean (*Phaseolus vulgaris* L.) landraces in comparison to modern varieties. *Agronomy* **2018**, *8*, 166. [CrossRef]
8. Food and Agriculture Organization of the United Nations. *FAOSTAT Statistical Database*; FAO: Rome, Italy, 2022.
9. Miklas, P.N.; Kelly, J.D.; Beebe, S.E.; Blair, M.W. Common bean breeding for resistance against biotic and abiotic stresses: From classical to MAS breeding. *Euphytica* **2006**, *147*, 105–131. [CrossRef]
10. Porch, T.G.; Beaver, J.S.; Debouck, D.G.; Jackson, S.; Kelly, J.D.; Dempewolf, H. Use of wild relatives and closely related species to adapt common bean to climate change. *Agronomy* **2013**, *3*, 433–461. [CrossRef]
11. Latef, A.A.H.A.; Ahmad, P. Legumes and breeding under abiotic stress: An overview. In *Legumes under Environmental Stress: Yield, Improvement and Adaptations*; John Wiley & Sons: Hoboken, NJ, USA, 2015; pp. 1–20.
12. Bomers, S.; Sehr, E.M.; Adam, E.; von Gehren, P.; Hansel-Hohl, K.; Prat, N.; Ribarits, A. Towards heat tolerant runner bean (*Phaseolus coccineus* L.) by utilizing plant genetic resources. *Agronomy* **2022**, *12*, 612. [CrossRef]
13. Suárez, J.C.; Contreras, A.T.; Anzola, J.A.; Vanegas, J.I.; Rao, I.M. Physiological characteristics of cultivated tepary bean (*Phaseolus acutifolius* A. Gray) and its wild relatives grown at high temperature and acid soil stress conditions in the amazon region of colombia. *Plants* **2021**, *11*, 116. [CrossRef]
14. Sehgal, A.; Sita, K.; Kumar, J.; Kumar, S.; Singh, S.; Siddique, K.H.; Nayyar, H. Effects of drought, heat and their interaction on the growth, yield and photosynthetic function of lentil (*Lens culinaris* Medikus) genotypes varying in heat and drought sensitivity. *Front. Plant Sci.* **2017**, *8*, 1776. [CrossRef]
15. Prasad, P.; Staggenborg, S.; Ristic, Z. Impacts of drought and/or heat stress on physiological, developmental, growth, and yield processes of crop plants. In *Response of Crops to Limited Water: Understanding and Modeling Water Stress Effects on Plant Growth Processes*; American Society of Agronomy, Inc.: Madison, WI, USA; Crop Science Society of America, Inc.: Madison, WI, USA; Soil Science Society of America, Inc.: Madison, WI, USA, 2008; Volume 1, pp. 301–355.
16. Kotak, S.; Larkindale, J.; Lee, U.; von Koskull-Döring, P.; Vierling, E.; Scharf, K.-D. Complexity of the heat stress response in plants. *Curr. Opin. Plant Biol.* **2007**, *10*, 310–316. [CrossRef]
17. Parankusam, S.; Adimulam, S.S.; Bhatnagar-Mathur, P.; Sharma, K.K. Nitric oxide (NO) in plant heat stress tolerance: Current knowledge and perspectives. *Front. Plant Sci.* **2017**, *8*, 1582. [CrossRef] [PubMed]
18. Zahra, N.; Hafeez, M.B.; Ghafaar, A.; Kausar, A.; Al Zeidi, M.; Siddique, K.; Farooq, M. Plant photosynthesis under heat stress: Effects and management. *Environ. Exp. Bot.* **2023**, *206*, 105178. [CrossRef]
19. Traub, J.; Porch, T.; Naeem, M.; Urrea, C.A.; Austic, G.; Kelly, J.D.; Loescher, W. Screening for heat tolerance in *Phaseolus* spp. Using multiple methods. *Crop Sci.* **2018**, *58*, 2459–2469. [CrossRef]
20. Porch, T.; Jahn, M. Effects of high-temperature stress on microsporogenesis in heat-sensitive and heat-tolerant genotypes of *Phaseolus vulgaris*. *Plant Cell Environ.* **2001**, *24*, 723–731. [CrossRef]
21. Porch, T.G. Application of stress indices for heat tolerance screening of common bean. *J. Agron. Crop Sci.* **2006**, *192*, 390–394. [CrossRef]
22. Stefanov, D.; Petkova, V.; Denev, I.D. Screening for heat tolerance in common bean (*Phaseolus vulgaris* L.) lines and cultivars using jip-test. *Sci. Hortic.* **2011**, *128*, 1–6. [CrossRef]
23. Singh, M.; Bisht, I.S.; Dutta, M. *Broadening the Genetic Base of Grain Legumes*; Springer: New Delhi, India, 2014; p. 215.

24. Chavez-Arias, C.C.; Ligarreto-Moreno, G.A.; Restrepo-Díaz, H. Evaluation of heat stress period duration and the interaction of daytime temperature and cultivar on common bean. *Environ. Exp. Bot.* **2018**, *155*, 600–608. [CrossRef]
25. Verma, S.; Kumar, N.; Verma, A.; Singh, H.; Siddique, K.H.; Singh, N.P. Novel approaches to mitigate heat stress impacts on crop growth and development. *Plant Physiol. Rep.* **2020**, *25*, 627–644. [CrossRef]
26. Vargas, Y.; Mayor-Duran, V.M.; Buendia, H.F.; Ruiz-Guzman, H.; Raatz, B. Physiological and genetic characterization of heat stress effects in a common bean RIL population. *PLoS ONE* **2021**, *16*, e0249859. [CrossRef]
27. Yahaya, M.A.; Shimelis, H. Drought stress in sorghum: Mitigation strategies, breeding methods and technologies—A review. *J. Agron. Crop Sci.* **2022**, *208*, 127–142. [CrossRef]
28. López-Hernández, F.; Cortés, A.J. Last-generation genome–environment associations reveal the genetic basis of heat tolerance in common bean (*Phaseolus vulgaris* L.). *Front. Genet.* **2019**, *10*, 954. [CrossRef] [PubMed]
29. IPCC. *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group ii to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2022; p. 3056.
30. Darkwa, K.; Ambachew, D.; Mohammed, H.; Asfaw, A.; Blair, M.W. Evaluation of common bean (*Phaseolus vulgaris* L.) genotypes for drought stress adaptation in ethiopia. *Crop J.* **2016**, *4*, 367–376. [CrossRef]
31. Neto, N.B.M.; Prioli, M.R.; Gatti, A.B.; Cardoso, V.J.M. Temperature effects on seed germination in races of common beans (*Phaseolus vulgaris* L.). *Acta Scientiarum. Agron.* **2006**, *28*, 155–164.
32. Asfaw, D.; Neka, M. Factors affecting adoption of soil and water conservation practices: The case of wereillu woreda (district), south wollo zone, amhara region, ethiopia. *Int. Soil Water Conserv. Res.* **2017**, *5*, 273–279. [CrossRef]
33. Ambachew, D.; Mekbib, F.; Asfaw, A.; Beebe, S.E.; Blair, M.W. Trait associations in common bean genotypes grown under drought stress and field infestation by BSM bean fly. *Crop J.* **2015**, *3*, 305–316. [CrossRef]
34. Wright, S. The theory of path coefficients a reply to Niles's criticism. *Genetics* **1923**, *8*, 239. [CrossRef]
35. Agbeleye, O.A.; Akinyosoye, S.T.; Adetumbi, J.A. Correlation, path coefficient and principal component analysis of yield components in mung bean [*Vigna radiata* (L.) Wilcezk] accessions. *Trop. Agric.* **2020**, *97*, 212–218.
36. Blair, M.W.; Soler, A.; Cortes, A.J. Diversification and population structure in common beans (*Phaseolus vulgaris* L.). *PLoS ONE* **2012**, *7*, e49488. [CrossRef]
37. Buitrago-Bitar, M.A.; Cortés, A.J.; López-Hernández, F.; Londoño-Caicedo, J.M.; Muñoz-Florez, J.E.; Muñoz, L.C.; Blair, M.W. Allelic diversity at abiotic stress responsive genes in relationship to ecological drought indices for cultivated tepary bean, *Phaseolus* acutifolius a. Gray, and its wild relatives. *Genes* **2021**, *12*, 556. [CrossRef]
38. Canci, H.; Toker, C. Evaluation of yield criteria for drought and heat resistance in chickpea (*Cicer arietinum* L.). *J. Agron. Crop Sci.* **2009**, *195*, 47–54. [CrossRef]
39. IBPGR. *Descriptors for Phaseolus vulgaris*; IBPGR: Rome, Italy, 1982; p. 37.
40. Marler, T.E.; Lawton, P.D. Error in interpreting field chlorophyll fluorescence measurements: Heat gain from solar radiation. *HortScience* **1994**, *29*, 1172–1174. [CrossRef]
41. Eker, T.; Sari, H.; Sari, D.; Canci, H.; Arslan, M.; Aydinoglu, B.; Ozay, H.; Toker, C. Advantage of multiple pods and compound leaf in kabuli chickpea under heat stress conditions. *Agronomy* **2022**, *12*, 557. [CrossRef]
42. Lê, S.; Josse, J.; Husson, F. Factominer: An r package for multivariate analysis. *J. Stat. Softw.* **2008**, *25*, 1–18. [CrossRef]
43. Bishop, J.; Potts, S.G.; Jones, H.E. Susceptibility of faba bean (*Vicia faba* L.) to heat stress during floral development and anthesis. *J. Agron. Crop Sci.* **2016**, *202*, 508–517. [CrossRef] [PubMed]
44. Bokshi, A.I.; Thistlethwaite, R.J.; Chaplin, E.D.; Kirii, E.; Trethowan, R.M.; Tan, D.K. Physiological traits for evaluating heat-tolerance of australian spring wheat cultivars at elevated CO_2. *J. Agron. Crop Sci.* **2022**, *208*, 178–196. [CrossRef]
45. Tamindžić, G.; Ignjatov, M.; Miljaković, D.; Červenski, J.; Milošević, D.; Nikolić, Z.; Vasiljević, S. Seed priming treatments to improve heat stress tolerance of garden pea (*Pisum sativum* L.). *Agriculture* **2023**, *13*, 439. [CrossRef]
46. Devi, P.; Jha, U.C.; Prakash, V.; Kumar, S.; Parida, S.K.; Paul, P.J.; Prasad, P.; Sharma, K.D.; Siddique, K.H.; Nayyar, H. Response of physiological, reproductive function and yield traits in cultivated chickpea (*Cicer arietinum* L.) under heat stress. *Front. Plant Sci.* **2022**, *1148*, 880519. [CrossRef]
47. Liu, M.; Sheng, D.; Liu, X.; Wang, Y.; Hou, X.; Wang, Y.; Wang, P.; Guan, L.; Dong, X.; Huang, S. Dissecting heat tolerance and yield stability in maize from greenhouse and field experiments. *J. Agron. Crop Sci.* **2022**, *208*, 348–361. [CrossRef]
48. Lohani, N.; Singh, M.B.; Bhalla, P.L. Short-term heat stress during flowering results in a decline in canola seed productivity. *J. Agron. Crop Sci.* **2021**, *208*, 486–496. [CrossRef]
49. Ullah, A.; Nadeem, F.; Nawaz, A.; Siddique, K.H.; Farooq, M. Heat stress effects on the reproductive physiology and yield of wheat. *J. Agron. Crop Sci.* **2022**, *208*, 1–17. [CrossRef]
50. Konsens, I.; Ofir, M.; Kigel, J. The effect of temperature on the production and abscission of flowers and pods in snap bean (*Phaseolus vulgaris* L.). *Ann. Bot.* **1991**, *67*, 391–399. [CrossRef]
51. Hasanuzzaman, M.; Nahar, K.; Alam, M.M.; Roychowdhury, R.; Fujita, M. Physiological, biochemical, and molecular mechanisms of heat stress tolerance in plants. *Int. J. Mol. Sci.* **2013**, *14*, 9643–9684. [CrossRef] [PubMed]
52. Takeno, K. Stress-induced flowering: The third category of flowering response. *J. Exp. Bot.* **2016**, *67*, 4925–4934. [CrossRef] [PubMed]
53. Begcy, K.; Sandhu, J.; Walia, H. Transient heat stress during early seed development primes germination and seedling establishment in rice. *Front. Plant Sci.* **2018**, *9*, 1768. [CrossRef]

54. Dubal, I.; Troyjack, C.; Aisenberg, G.R.; Koch, F.; Szareski, V.J.; Pimentel, J.R.; Nardino, M.; Carvalho, I.; Olivoto, T.; Souza, V. Effect of temperature on bean seed germination: Vigor and isozyme expression. *Am. J. Agric. Res.* **2016**, *1*, 1–9.
55. Toker, C.; Lluch, C.; Tejera, N.A.; Serraj, R.; Siddique, K.H.M. Abiotic stresses. In *Chickpea Breeding and Management*; Yadav, S.S., Chen, W., Eds.; CAB Int.: Wallingford, UK, 2007; pp. 474–496.
56. Matías, J.; Rodríguez, M.J.; Cruz, V.; Calvo, P.; Reguera, M. Heat stress lowers yields, alters nutrient uptake and changes seed quality in quinoa grown under mediterranean field conditions. *J. Agron. Crop Sci.* **2021**, *207*, 481–491. [CrossRef]
57. Bozoğlu, H.; Sözen, Ö. Some agronomic properties of the local population of common bean (*Phaseolus vulgaris* L.) of artvin province. *Turk. J. Agric. For.* **2007**, *31*, 327–334.
58. Kornegay, J.; White, J.W.; de la Cruz, O.O. Growth habit and gene pool effects on inheritance of yield in common bean. *Euphytica* **1992**, *62*, 171–180. [CrossRef]
59. Repinski, S.; Kwak, M.; Gepts, P. The common bean growth habit gene PvTFL1y is a functional homolog of arabidopsis tfl1. *Theor. Appl. Genet.* **2012**, *124*, 1539–1547. [CrossRef]
60. Michelangeli, J.A.C.; Ricaurte, J.; Sinclair, T.R.; Rao, I.M.; Beebe, S.E. Influence of plant density and growth habit of common bean on leaf area development and n accumulation. *J. Crop Improv.* **2019**, *33*, 620–632. [CrossRef]
61. Cortés, A.J.; Blair, M.W. Genotyping by sequencing and genome–environment associations in wild common bean predict widespread divergent adaptation to drought. *Front. Plant Sci.* **2018**, *9*, 128. [CrossRef] [PubMed]
62. Cortés, A.J.; Skeen, P.; Blair, M.W.; Chacón-Sánchez, M.I. Does the genomic landscape of species divergence in *Phaseolus* beans coerce parallel signatures of adaptation and domestication? *Front. Plant Sci.* **2018**, *9*, 1816. [CrossRef] [PubMed]
63. Yönten Balaban, A.; Akman, K. Climate change adaptation policies of metropolitan municipalities in Turkey. *Vision. E-J.Vizyoner Derg.* **2022**, *13*, 1132–1149. [CrossRef]
64. Nemeskéri, E.; Remenyik, J.; Fári, M. Studies on the drought and heat stress response of green bean (*Phaseolus vulgaris* L.) varieties under phytotronic conditions. *Acta Agron. Hung.* **2008**, *56*, 321–328. [CrossRef]
65. Rainey, K.M.; Griffiths, P.D. Inheritance of heat tolerance during reproductive development in snap bean (*Phaseolus vulgaris* L.). *J. Am. Soc. Hortic. Sci.* **2005**, *130*, 700–706. [CrossRef]
66. da Silva, D.A.; dos Reis, R.L.d.M.; Gonçalves, J.G.R.; Carbonell, S.A.M.; Chiorato, A.F. Effect of heat stress on common bean under natural growing conditions in three locations in different climate zones in the state of so paulo, brazil. *J. Plant Breed. Crop Sci.* **2018**, *10*, 134–145.
67. Mohapatra, C.; Chand, R.; Tiwari, J.K.; Singh, A.K. Effect of heat stress during flowering and pod formation in pea (*Phaseolus vulgaris* L.). *Physiol. Mol. Biol. Plants* **2020**, *26*, 1119–1125. [CrossRef]
68. Shonnard, G.C.; Gepts, P. Genetics of heat tolerance during reproductive development in common bean. *Crop Sci.* **1994**, *34*, 1168–1175. [CrossRef]
69. Essemine, J.; Ammar, S.; Bouzid, S. Impact of heat stress on germination and growth in higher plants: Physiological, biochemical and molecular repercussions and mechanisms of defence. *J. Biol. Sci.* **2010**, *10*, 565–572. [CrossRef]
70. Cortés, A.J.; López-Hernández, F.; Osorio-Rodriguez, D. Predicting thermal adaptation by looking into populations' genomic past. *Front. Genet.* **2020**, *11*, 564515. [CrossRef] [PubMed]
71. Suárez, J.C.; Polanía, J.A.; Contreras, A.T.; Rodríguez, L.; Machado, L.; Ordoñez, C.; Beebe, S.; Rao, I.M. Adaptation of common bean lines to high temperature conditions: Genotypic differences in phenological and agronomic performance. *Euphytica* **2020**, *216*, 1–20. [CrossRef]
72. Burbano-Erazo, E.; León-Pacheco, R.I.; Cordero-Cordero, C.C.; López-Hernández, F.; Cortés, A.J.; Tofiño-Rivera, A.P. Multi-environment yield components in advanced common bean (*Phaseolus vulgaris* L.)× tepary bean (*P. acutifolius A. Gray*) interspecific lines for heat and drought tolerance. *Agronomy* **2021**, *11*, 1978. [CrossRef]
73. Beebe, S. Common bean breeding in the tropics. In *Plant breeding reviews*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2012; pp. 357–426.
74. Beebe, S.E.; Rao, I.M.; Cajiao, C.; Grajales, M. Selection for drought resistance in common bean also improves yield in phosphorus limited and favorable environments. *Crop Sci.* **2008**, *48*, 582–592. [CrossRef]
75. Omae, H.; Kumar, A.; Kashiwaba, K.; Shono, M. Influence of high temperature on morphological characters, biomass allocation, and yield components in snap bean (*Phaseolus vulgaris* L.). *Plant Prod. Sci.* **2006**, *9*, 200–205. [CrossRef]
76. Rao, I.; Beebe, S.; Polanía, J.; Grajales, M.; Cajiao, C.; García, R.; Ricaurte, J.; Rivera, M. Physiological basis of improved drought resistance in common bean: The contribution of photosynthate mobilization to grain. In Proceedings of the Interdrought III: The 3rd International Conference on Integrated Approaches to Improve Crop Production under Drought-Prone Environments, Shanghai, China, 11–16 October 2009; pp. 11–16.
77. Chrigui, N.; Sari, D.; Sari, H.; Eker, T.; Cengiz, M.F.; Ikten, C.; Toker, C. Introgression of resistance to leafminer (*Liriomyza cicerina* Rondani) from Cicer reticulatum Ladiz. To C. Arietinum L. and relationships between potential biochemical selection criteria. *Agronomy* **2020**, *11*, 57. [CrossRef]
78. Petkova, V.; Denev, I.D.; Cholakov, D.; Porjazov, I. Field screening for heat tolerant common bean cultivars (*Phaseolus vulgaris* L.) by measuring of chlorophyll fluorescence induction parameters. *Sci. Hortic.* **2007**, *111*, 101–106. [CrossRef]
79. Rana, J.; Sharma, T.; Tyagi, R.; Chahota, R.; Gautam, N.; Singh, M.; Sharma, P.; Ojha, S. Characterisation of 4274 accessions of common bean (*Phaseolus vulgaris* L.) germplasm conserved in the indian gene bank for phenological, morphological and agricultural traits. *Euphytica* **2015**, *205*, 441–457. [CrossRef]

80. Kettler, B.A.; Carrera, C.S.; Nalli Sonzogni, F.D.; Trachsel, S.; Andrade, F.H.; Neiff, N. High night temperature during maize post-flowering increases night respiration and reduces photosynthesis, growth and kernel number. *J. Agron. Crop Sci.* **2022**, *208*, 335–347. [CrossRef]
81. Yun, H.; Cai, L.; Du, D.; Guo, Y.; Sun, H.; Zhong, X.; Peng, X.; Dai, J.; Zhang, C. Fine mapping and phenotype assessment of the novel lesion mimic and early senescence lmes5 mutant in rice. *Euphytica* **2022**, *218*, 1–13. [CrossRef]
82. Zhou, R.; Hyldgaard, B.; Yu, X.; Rosenqvist, E.; Ugarte, R.M.; Yu, S.; Wu, Z.; Ottosen, C.-O.; Zhao, T. Phenotyping of faba beans (*Vicia faba* L.) under cold and heat stresses using chlorophyll fluorescence. *Euphytica* **2018**, *214*, 1–13. [CrossRef]
83. Beebe, S.E.; Rao, I.M.; Blair, M.W.; Acosta-Gallegos, J.A. Phenotyping common beans for adaptation to drought. *Front. Physiol.* **2013**, *4*, 35. [CrossRef] [PubMed]
84. Cortés, A.J.; López-Hernández, F. Harnessing crop wild diversity for climate change adaptation. *Genes* **2021**, *12*, 783. [CrossRef]
85. Akgun, D.; Canci, H. Selection of Faba Bean (*Vicia faba* L.) Genotypes for High Yield, Essential Amino Acids and Low Untinutritional Factors. *Agriculture*, 2023; *accepted*.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.