CHILEAN JOURNAL
of AGRICULTURAL RESEARCH

RESEARCH ARTICLE

Genetic analysis of anthracnose resistant and heat tolerant chili inbreed lines based on morpho-physiological characteristics

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Received: 25 July 2022; Accepted: 12 October 2022; doi:10.4067/S0718-58392023000200168

ABSTRACT

A better understanding of the various desirable characteristics present in chili (*Capsicum annuum* L.) genotypes has aided in developing more effective selection methods for crop improvement. Identifying genetically superior parents is critical in selecting the best parents and inbred lines for breeding purposes. This study was conducted over two planting seasons in glasshouse using morpho-physiological parameters to evaluate the heritability variation of selected chili genotypes based on their genetic diversity for future breeding program. Significant variances were observed in all the studied parameters across the chili pepper accessions with an inclusive range of diversity. The highest genotypic coefficient of variation (≥ 20%) was observed for all physiological and yield characteristics. While the highest phenotypic coefficient of variation (≥ 20%) was seen for all examined characteristics. All studied parameter had high broad sense heritability (> 55%) except total number of branches per plant (47.9%) while the moderate to high genetic advance were observer for all studied traits demonstrating that the extents of heritability and variability are due to their genetic makeup and environment had little influence on these characters. The evaluated genotypes were grouped into seven clusters based on the cluster analysis and Group I recorded highest yield with eight genotypes while Groups III, IV, V, VI, and VII recorded one each. Plant height and total branch number showed a highly significant positive correlation with the number of fruits per plant and yield per plant. Similarly, the number of fruits per plant had a highly significant positive correlation with fruit yield per plant. The study revealed that genetic variability might be usefully exploited through selection for further breeding purposes to increase yield and production.

Key words: *Capsicum annuum*, genetic advance, genetic diversity, variability.

INTRODUCTION

Peppers (*Capsicum* spp.) are cultivated globally for ornamental, vegetable, medicinal, spice, and lachrymator purposes and are a good source of vitamins A and C (Chowdhury et al., 2020). Variability among the genotypes is the key point in understanding how to improve the genotypes (Usman et al., 2014). Characterization of chili genotypes based on their diverse phenotypic and genotypic selection are mandatory and help to increase chili production and mitigate the problem which are related to different stresses. Breeding programs for crop improvement are enabled by the availability and detailed characterization of genetically diverse germplasm (Usman et al., 2014; Patel et al., 2015; Ridzuan et al., 2019). Heritability is linked with some important traits and provides opportunities to improve new desirable plants (Lahbib et al., 2013; Patel et al., 2015). Heritability is the relative degree of transmitted characters from parent to offspring and also suggests the extent to which improvement is possible through selection (Datta and Das, 2013; Pandiyaraj, 2017). Genetic variability and degree of heritable characters are the principal basis of superior genotypes selection and researchers worked on high genetic variability on important yield characters in *C. annuum* genotypes and these finding revealed by Yatung et al. (2014), Bundela et al. (2017), Rahevar et al. (2019), and Indrabi et al. (2021).

The global average temperature is raising by 1 to 3.7 °C by the end of the twenty-first century and temperature change is now a major global concern that directly detrimental effect on crop yield (IPCC, 2013; Saidah et al., 2020). Plant physiological processes are also important and linked with the yield traits in particular cropping system and differences among them are due to the presence of sunlight in the specific area was measured, where plants were grown, or the number of varieties studied (Pandit and Adhikary, 2014; Rosado-Souza et al., 2015; Ghasemi et al., 2017). Developing worlds are trying to meet up their demand by increase cultivation but did not get good yield due to the poor performance of native chili genotypes under biotic and abiotic stress, such as chili anthracnose disease and high temperatures. Furthermore, the genetic diversity, heritability, and hereditary advancement of anthracnose resistant and heat tolerant inbreed lines and yield and yield contributing features remain unclear. Genetic analysis of chili genotypes would assist in improving the situation in terms of hybrid chili development through hybridization (Usman et al., 2014; Ridzuan et al., 2019; Chowdhury et al., 2020). In Malaysia, the estimated annual production of chili for 2020 was 28264 metric tons (Mt) from 3162 ha cultivated area (Department of Agriculture, 2020). While the self-sufficiency ratio is about 30.9%, indicating that domestic supplies are insufficient and also highest import dependency rate in both 2019 and 2020, with around 73.6% and 72.4%, respectively to meet up the domestic demand (Department of Statistics Malaysia, 2020). Moreover, abiotic (heat, drought, salt, and mineral toxicity) as well as biotic (phyto-pathogenic fungus, bacteria, viruses, root knot nematodes, insect like aphids, and thrips) stresses influence the chili output (Usman et al., 2017; Ridzuan et al., 2019). Morphological, physiological, and yield features of chili are giving information to represent hereditary variance and genetics advancement as amid inbreed lines for a forthcoming chili breeding program. Therefore, research is needed to identify chili genotypes for future hybridization programs to increase yield and productivity.

MATERIALS AND METHODS

The chili (*Capsicum annuum* L.) genotypes were cultivated in a glasshouse at field 15, Faculty of Agriculture, Universiti Putra Malaysia (UPM), Malaysia, throughout two seasons (October 2018 to January 2019 and March 2019 to June 2019). In the glasshouse, the average temperature ranged 30-45 °C on a regular basis. In this investigation, 16 *C. annuum* genotypes were cultivated (Table 1); genotypes were received from Department of Crop Science and Institute of Tropical Agriculture and Food Security, Faculty of Agriculture, Universiti Putra Malaysia.

Table 1. Chili research materials planted in this study including their pedigree, selection criteria, plant habit and mature fruits color. Sl: Serial number.

Sl	Inbreed lines, parents and control	Pedigree and sources	Selection criteria	Fruit color	Plant habit
1	CP-36	Chili Bangi 3 × AVPP0805	Resistant to anthracnose	Red	Erect
2	DP-37	Chili Bangi 3 × AVPP9813	Resistant to anthracnose	Red	Erect
3	DP-57	Chili Bangi 3 × AVPP9813	Resistant to anthracnose	Red	Erect
4	AP-25	Kulai 907 × AVPP0805	Resistant to anthracnose	Red	Erect
5	BP-23	Kulai 907 × AVPP9813	Resistant to anthracnose	Red	Erect
7	Putra chili 1	Kulai 907 × AVPP0702	Tolerance to heat	Red	Compact
8	Putra chili 4	Kulai 907 × AVPP0705	Tolerance to heat	Red	Compact
9	Putra chili 7	Kulai 907 × AVPP0708	Tolerance to heat	Red	Compact
10	Putra chili 9	Kulai 907 × AVPP0710	Tolerance to heat	Red	Compact
11	Putra chili 10	Kulai 907 × AVPP0711	Tolerance to heat	Red	Compact
12	Kulai 907	Malaysian local	N/A	Red	Erect
13	Chili Bangi 3	Malaysian local	N/A	Red	-
14	AVVO702	Taiwan genotypes	Tolerant to heat	Red	Spread
15	Control 1	Malaysian local	N/A	Red	Erect
16	Control 2	Malaysian local	N/A	Red	Erect

Seedlings raising, fertilization and others intercultural operations
The chili seeds were sun-dried for 8 h before being soaked in water and petri dish stored in the dark to germinate. The germinated seeds were placed in a plastic tray filled with peat moss; seedlings appeared within 1.5 wk after seeding. Seedling were transplanted 4 wk later when they reached the four- to six-leaf stage. Seven plants were planted per genotypes per replicate. The design of this study was a randomized complete block (RCBD) with three replicates. The first day of transplanting was designated as day 0. The polybags (20 cm × 20 cm) were filled with coco peat and spaced 75 and 150 cm and aligned east to west. The Malaysian Agricultural Research and Development Institute (MARDI) Fertigation System Manual was used to set up the fertigation system at the glasshouse (A'fifah et al., 2015). White flies, thrips, mites, and viral diseases all impacted negatively on chili plants. According to the manufacturer's recommendations, pesticides such as deltamethrin (Decis, Bayer, UK), imidacloprid (Confidor, Bayer), and fungicide dithiocarbamate (Kencozeb, Kenso Agcare, Tenerife, Australia) were used to maintain the plants at 7 d intervals. Neem and garlic extract are regularly sprayed to eliminate white flies and control fungal infections.

Table 2. Description of quantitative traits of chili genotypes measured in this study.

Characters	Denotation	Description
Plant height, cm	PH	A measuring tape was used to measure the height of each plant from the soil surface to the tip of the plant
Stem length, cm	SL	Each plant's stem length was measured using a measuring scale from the soil surface to the first branching point
Stem diameter, cm	SD	Diameter of the stem, taken 5 cm from the plant stalk's base, was measured with an Absolute Digimatic caliper (Mitutoyo, Kawasaki, Japan)
Total number of branches	BN	Number of counted branches per plant
Days to first flowering, d	DFF	Days of first flower initiation on the plant
Days to first maturation, d	DFM	Days of first fruit maturation on the plant
Number of fruits per plant, d	FN	Total number of fruits harvested from the first harvest to 90 d following transplantation
Fruits weight per plant, g	FW	Total weight of fruits harvested from the first harvest to 90 d following transplantation
Single fruit weight, g	SFW	Weight of one matured fruit per plant
Fruit length, cm	FL	Length of the one matured fruit from calyx to the tip of fruit
Fruit girth, cm	FG	Girth of one matured fruit (0.3 cm below the calyx)
Number of seeds per fruit	SN	Total number of seeds per fruit

Morpho-physiological parameters
At 90 d following transplanting, data on morphological, physiological, and yield characteristics were collected (IPGRI, AVRDC, CATIE, 1995) on five plants chosen at random from each replicate per genotype (Table 2).

Net photosynthetic rate, stomatal conductance, and transpiration rate were measured from the leaves of 45 d-old plants. The uppermost expanded leaves were selected for the measurement using an LI-6400XT portable photosynthesis system (LI-COR, Lincoln, Nebraska, USA). On the other hand, the relative chlorophyll content (RCC) of the third or fourth leaf from the tip was assessed using SPAD-502 Plus (Konica Minolta, Tokyo, Japan) (Ridzuan et al., 2019).

Variation in genetics, inheritance, and genetic gain
Genotypic and phenotypic variance were calculated using ANOVA as follows:

$$\sigma^2 g = MSG - MSE/r$$
$$\sigma^2 p = \delta^2 g + MSE$$

where, σ^2g and σ^2p represent genotypic variance and phenotypic variance, respectively; MSG is the mean square of genotypes, MSE is the mean square error, and r for replication. Genotypic coefficient of variance (GCV) and phenotypic coefficient of variance (PCV) were calculated according to Shweta et al. (2018) as follows and also classified as low (0%-10%), moderate (10%-20%), and high (20% and ≥ 20%):

$$\mathrm{PCV} = \frac{\sqrt{\sigma\ 2g}}{X} \times 100$$

$$\mathrm{GCV} = \frac{\sqrt{\sigma\ 2g}}{X} \times 100$$

Relative distance (RD) was calculated following the equation:

$$\mathrm{RD} = \frac{\mathrm{PCV-GCV}}{\mathrm{PCV}} \times 100$$

Broad sense heritability (h^2b) represents the ratio of genotypic variance (σ^2g) to phenotypic variance (σ^2p) calculated with the following formula is as follows. The heritability percentage were categorized as low (0%-30%), moderate (30%-60%), and high (≥ 60%) (Ridzuan et al., 2019).

$$h^2b\ (\%) = \frac{\sigma\ 2g}{\sigma\ 2p} \times 100$$

Genetic advance (GA) was calculated and selection intensity (K) was assumed to be 5% and μ is the characters mean. Genetic advance was classified as low (0%-10%), moderate (10%-20%), and high (> 20%) by following (Ridzuan et al., 2019; Constantino et al., 2020):

$$\mathrm{G}\ (\%) = \mathrm{K} \times \frac{\sigma\ 2p}{\mu} \times \mathrm{h2b} \times 100$$

Data analysis

Statistical Analysis Software (SAS) version 9.4 was used for data analysis (SAS Institute, Cary, North Carolina, USA). The genetic diversity data were evaluated using cluster analysis. NTSYS 2.1 was used to establish the genetic link between chili genotypes using the unweighted pair group method with arithmetic mean (UPGMA) algorithm and the sequential, agglomerative, hierarchic, and non-overlapping (SAHN) method (Numerical Taxonomy Multivariate Analysis System, Exeter Software, Setauket, New York, USA). Also, PC analysis was performed to create two and three-dimensional graphics.

RESULTS AND DISCUSSION

ANOVA of all studied growth characters, yield and yield contributing character and physiological parameters of 16 selected chili genotypes

In this experiment, 16 distinct morphological, physiological, yield and yield components were collected. All the genotypes showed significantly different performance regarding 16 studied characters over two planting seasons (Table 3). The crop yield was influenced by all of the characters, both favorably and adversely.

Mean performance of studied growth characters, yield and yield contributing character and physiological parameters of 16 selected chili genotypes

All the chili genotypes gave differentials mean performances regarding growth characters, yield and yield contributing and physiological characters (Table 4). The genotypes Control 1 and CP-36 produced the tallest plants, measuring 147.67 and 146.81 cm, respectively, and followed by DP-57 (139.24 cm), DP-37 (128.83 cm), and Putra chili 1 (128.55 cm), while other genotype AVVPO702 produced the shortest plants (69.31 cm) followed by Chili Bangi 3 (84.83 cm). The stem length ranged from 10.87 to 25.27 cm while stem diameter (SD) ranged from 0.85 to 1.60 cm. The varieties Putra chili 9 (81.78) and Putra Chili 10 (81.53) produced highest number of branch whereas AVVPO702 (56.28) bear lowest number of branches. In case of first flowering initiation, Putra Chili 1 have taken 23.17 d to produce flower, followed by AP-25 (28.5 d), Chili Bangi 3 (28.67 d) and Putra Chili 4 (29.83 d) while first fruit maturation happened in case of Putra Chili 1 (61.67 d) and AVVPO702 (66.5 d). The fruits number per plant ranged from 67.06 to 223.22. AVVPO702 gave the maximum number of fruits (223.22) with 348.54 g average yield per plant, followed by Putra Chili 1 (209.37) with 1123.60 g, AP-25 (201.11) with 831.22 g and CP-36 (198.97) with 1055.65 g, respectively. In this experiment, fruit length and fruit girth varied from 6.55 (AVVPO702) to 15.28 cm (AP-25) and 1.31 (AVVPO702) to 6.58 cm (Kulai 907), respectively. On the other hand, single fruit weight fluctuated from 1.31 to 8.23 g and seeds number per fruits from 20.18 (AVVPO702) to 75 (DP-57).

Table 3. Mean square of all studied growth, yield and yield attributing characters, and physiological parameters of 16 selected chili genotypes. *Significant ($p \leq 0.05$); **Highly significant ($p \leq 0.01$); SOV: source of variance; R: replicate; PH: plant height (cm); SL: stem length (cm); SD: diameter of stem (cm); BN: number of branches; DFF: days to first flowering; DFM: days to first fruit maturity; FN: fruit number per plant; FW: fruit weight (g); FL: fruit length (cm); FG: fruit girth (cm); SFW: single fruit weight (g); SN: seed number; PR: photosynthesis rate (µmol CO_2 m^{-2} s^{-1}); SC: stomatal conductance (µmol H_2O m^{-2} s^{-1}); TR: transpiration rate (SPAD units); RCC: relative chlorophyll content.

SOV	DF	PH	SL	SD	BN	DFF	DFM	FW	FY
Genotypes (G)	15	2577.56**	87.74**	0.21**	307.75**	59.08**	222.49**	9616.57**	373931.61**
Season (S)	1	3895.63**	23.11	0.23*	10605.85**	950.04**	442.04**	435472.97**	7735548.34**
R (R)	4	15.16	1.96	0.06	41.57	4.97	10.67	1330.96	15388.20
G × SS	15	637.89**	42.56**	0.12**	585.31**	76.78**	182.20**	9075.79**	227211.61**
Error	60	33.25	8.13	0.03	65.80	4.60	7.12	1149.38	22614.04
SOV	DF	FL	FG	SFW	SN	PR	SC	TR	RCC
Genotypes (G)	15	40.92**	7.69**	17.63**	862.68**	24.45**	0.03**	15.56**	467.67**
Season (S)	1	20.75**	0.043	20.30**	55.26	398.49**	0.01**	1.50	742.59**
R (R)	4	6.54	0.53	3.23	10.22	1.20	0.00	0.61	28.69
G × S	15	3.07*	1.52**	4.78**	347.84**	25.92**	0.02**	0.92*	125.92**
Error	60	1.72	0.45	1.01	51.66	1.18	0.00	0.44	20.80

Table 4. Mean performance for 16 different investigated attributes of the selected anthracnose resistant and heat tolerant chili genotypes during two cropping seasons. Different letters indicate significantly different through Duncan multiple range test (DMRT). CV: Coefficient of variance; PH: plant height (cm); SL: stem length (cm); SD: diameter of stem (cm); BN: number of branches; DFF: days to first flowering; DFM: days to first fruit maturity; FN: fruits number per plant; FW: fruits weight (g); FL: fruit length (cm); FG: fruit girth (cm); SFW: single fruit weight (g); SN: seeds number; PR: photosynthesis rate (μmol CO_2 m^{-2} s^{-1}); SC: stomatal conductance (μmol H_2O m^{-2} s^{-1}); TR: transpiration rate (SPAD units); RCC: relative chlorophyll content.

Genotypes	PH	SL	SD	BN	DFF	DFM	FN	FW	FL	FG	SFW	SN	PR	SC	TR	RCC
CP-36	146.80^{a}	16.82^{d}	1.48^{ab}	76.27^{ab}	35.00^{ab}	84.33^{a}	198.97^{ab}	1055.65^{a-c}	13.80^{a-c}	5.46^{bc}	8.23^{a}	65.28^{b}	13.42^{b}	0.17^{f}	3.60^{g}	30.13^{f}
DP-37	128.83^{c}	20.81^{bc}	1.15^{d-f}	72.12^{a-c}	32.50^{b-d}	78.67^{c}	169.83^{bc}	996.95^{a-d}	13.68^{a-c}	5.61^{b}	8.28^{a}	59.81^{bc}	14.34^{ab}	0.42^{a}	6.98^{b}	29.20^{f}
DP-57	139.24^{b}	22.47^{ab}	1.25^{c-f}	78.44^{a}	29.00^{ef}	74.67^{de}	179.92^{a-c}	1144.63^{a}	14.75^{ab}	4.73^{c-f}	7.41^{a-c}	75.53^{a}	9.79^{d}	0.20^{d-f}	3.75^{fg}	38.67^{c-e}
AP-25	116.97^{de}	15.99^{d}	1.34^{b-d}	71.28^{a-c}	28.50^{f}	76.67^{de}	201.11^{ab}	831.22^{d-f}	15.28^{a}	4.34^{d-f}	5.31^{ef}	59.95^{bc}	13.55^{b}	0.21^{c-f}	4.19^{fg}	39.27^{b-e}
BP-23	114.33^{e}	17.38^{cd}	1.12^{d-f}	64.03^{de}	31.17^{c-f}	78.50^{c}	191.53^{ab}	955.00^{a-d}	14.95^{a}	4.57^{d-f}	6.65^{b-d}	63.72^{b}	13.84^{ab}	0.24^{de}	3.62^{g}	38.90^{c-e}
AP-18	122.25^{de}	15.86^{d}	1.03^{fg}	71.64^{a-c}	31.67^{c-e}	79.33^{c}	163.31^{bc}	739.84^{ef}	14.08^{a-c}	4.65^{c-f}	6.16^{c-e}	46.78^{d}	9.84^{d}	0.22^{c-f}	2.58^{h}	39.17^{b-e}
Putra Chili 1	128.55^{c}	19.05^{b-d}	1.31^{b-e}	79.06^{a}	23.17^{g}	61.67^{h}	209.37^{ab}	1123.60^{ab}	14.96^{a}	4.21^{ef}	6.51^{c-e}	64.45^{b}	15.04^{a}	0.182^{ef}	7.49^{ab}	48.73^{a}
Putra Chili 4	119.59^{de}	16.78^{d}	1.16^{c-f}	79.08^{a}	29.83^{d-f}	71.67^{ef}	165.50^{bc}	819.17^{d-f}	14.26^{a-c}	4.55^{d-f}	5.83^{de}	57.08^{bc}	14.18^{ab}	0.37^{ab}	8.16^{a}	40.10^{b-d}
Putra Chili 7	112.83^{ef}	18.10^{cd}	1.31^{b-e}	76.11^{ab}	30.17^{d-f}	79.83^{bc}	186.25^{ab}	926.63^{c-e}	14.84^{a}	4.15^{c}	7.97^{ab}	58.14^{bc}	11.06^{dc}	0.24^{dc}	5.14^{de}	43.20^{a-c}
Putra Chili 9	117.61^{de}	16.15^{d}	1.21^{c-f}	81.78^{a}	36.17^{a}	82.83^{ab}	139.70^{dc}	476.38^{gh}	12.94^{dc}	5.47^{bc}	6.88^{b-d}	59.06^{bc}	14^{ab}	0.23^{c-e}	5.43^{dc}	36.43^{de}
Putra Chili 10	116.86^{de}	21.86^{ab}	1.37^{bc}	81.53^{a}	34.67^{ab}	69.17^{fg}	164.11^{bc}	947.58^{b-d}	13.04^{b-d}	5.12^{b-d}	7.263^{a-c}	66.14^{b}	10.52^{dc}	0.25^{c}	5.72^{dc}	43.17^{a-c}
Kulai 907	106.95^{f}	24.72^{a}	1.27^{b-e}	73.56^{a-c}	31.17^{c-f}	72.33^{ef}	113.96^{d}	827.97^{d-f}	12.76^{dc}	6.58^{a}	6.91^{b-d}	65.94^{b}	14.2^{ab}	0.35^{b}	7.44^{ab}	45.10^{ab}
Chili Bangi 3	84.83^{g}	15.82^{d}	1.10^{ef}	66.33^{b-d}	28.67^{f}	72.28^{ef}	67.06^{e}	341.21^{h}	8.22^{e}	5.59^{b}	5.59^{d-f}	51.50^{dc}	11.81^{c}	0.24 ^{dc}	5.29^{d}	20.13^{g}
AVVPO702	69.30^{h}	10.87^{e}	0.85^{g}	56.28^{d}	32.50^{b-d}	66.50^{g}	223.22^{a}	348.54^{h}	6.55^{f}	1.31^{g}	1.31^{g}	20.84^{e}	9.79^{d}	0.25^{dc}	5.63^{dc}	16.97^{g}
Control 1	147.67^{a}	21.91^{ab}	1.60^{a}	71.22^{a-c}	31.33^{c-f}	70.56^{f}	168.72^{bc}	648.95^{fg}	11.43^{d}	4.11^{f}	4.44^{f}	52.06^{dc}	9.81^{d}	0.37^{b}	4.48^{ef}	33.37^{ef}
Control 2	138.77^{b}	25.27^{a}	1.49^{ab}	63.83^{dc}	33.83^{a-c}	71.33^{ef}	120.28^{d}	810.01^{d-f}	9.45^{e}	5.07^{b-e}	5.58^{d-f}	57.56^{bc}	10.16^{d}	0.36^{b}	6.23^{c}	44.60^{a-c}
Mean	119.46	18.74	1.25	72.66	31.21	74.40	166.43	812.08	12.81	4.72	6.27	57.74	12.21	0.27	5.36	36.70
CV, %	19.99	27.23	22.01	23.68	18.84	11.52	54.80	53.86	22.79	28.10	33.95	25.97	29.47	39.89	31.89	29.34

Table 5. Assessment of genotypic variance (GV), phenotypic variance (PV), genotypic (GCV) and phenotypic coefficient of variance (PCV), broad sense heritability (BSH, h^2b), genetic advance (GA), relative differences (RD) among GCV and PCV, and genetic advance for 16 different morphological, physiological and yield and yield attributes of selected anthracnose resistance and heat tolerant chili genotypes. PH: Plant height (cm); SL: stem length (cm); SD: diameter of stem (cm); BN: number of branches; DFF: days to first flowering; DFM: days to first fruit maturity; FN: fruits number per plant; FW: fruits weight (g); FL: fruit length (cm); FG: fruit girth (cm); SFW: single fruit weight (g); SN: seeds number; PR: photosynthesis rate (μmol CO_2 m^2 s^{-1}); SC: stomatal conductance (μmol H_2O m^2 s^{-1}); TR: transpiration rate (SPAD units); RCC: relative chlorophyll content.

Traits	PH	SL	SD	BN	DFF	DFM	FN	FW	FL	FG	SFW	SN	PR	SC	TR	RCC
GV	636.08	19.90	0.05	60.49	13.62	53.84	2116.80	87829.39	9.80	1.81	4.16	202.76	5.82	0.01	3.78	111.72
PV	669.33	28.03	0.07	126.29	18.22	60.96	3266.18	110443.43	11.52	2.26	5.17	254.41	7.00	0.01	4.22	132.52
GCV, %	21.11	23.81	17.02	10.70	11.83	9.86	27.64	36.49	24.43	28.50	32.51	24.66	19.75	31.63	36.29	28.80
PCV, %	21.66	28.25	21.64	15.47	13.68	10.50	34.34	40.92	26.49	31.85	36.24	27.63	21.66	33.74	38.33	31.37
BSH, %	95.03	71.00	61.91	47.90	74.75	88.32	64.81	79.52	85.07	80.09	80.45	79.69	83.14	87.88	89.66	84.30
GA, %	42.40	41.32	27.59	15.26	21.06	19.09	45.85	67.04	46.42	52.54	60.06	45.35	37.10	61.09	70.79	54.48
% RD	2.52	15.74	21.32	30.79	13.54	6.02	19.50	10.82	7.77	10.51	10.31	10.73	8.82	6.26	5.31	8.18
Mean	119.46	18.74	1.25	72.66	31.21	74.40	166.43	812.08	12.81	4.72	6.27	57.74	12.21	0.27	5.36	36.70

In this study a significant level of diversity among chili genotypes revealed for the studied characters. Plant height was not the only key element directly influencing yield characteristics, but also branches number is another important component that influences fruit number and yield. It is possible that the differences in the investigated growth features are due to genetic variations and also given environmental condition. All the genotypes gave the moderate to higher yield per plant whereas the Malaysian local genotypes exhibited substantial yield performance. In contrast, Taiwan heat tolerant genotypes (AVVPO702) showed higher fruits number but gave lower yield per plant that might be due to the individual fruit length and weight of the respected genotypes. The size and weight of each fruit differed depending on the genotype examined, which was the main explanation. Some genotypes may yield enormous, heavy fruits, whereas others may produce smaller, lighter fruits. This variation is in conformity with the value of Usman et al. (2014), Bundela et al. (2017), Ridzuan et al. (2019), and Erwin et al. (2019). Among all the chili genotypes, Putra Chili 1 gave the highest photosynthesis rate (15.04 µmol CO_2 m^{-2} s^{-1}) while AVVPO702 gave the lowest rate (9.79 µmol CO_2 m^{-2} s^{-1}) which were followed by genotypes DP-57 (9.79 µmol CO_2 m^{-2} s^{-1}), AP-18 (9.79 µmol CO_2 m^{-2} s^{-1}), Control 1 (9.81 µmol CO_2 m^{-2} s^{-1}) and Control 2 (10.16 µmol CO_2 m^{-2} s^{-1}), respectively. On the other hand, DP-37 showed highly significant stomatal conductance (0.42 µmol H_2O m^{-2} s^{-1}) and the lowest was found for CP-36 (0.17 µmol H_2O m^{-2} s^{-1}). The transpiration rate (µmol H_2O m^{-2} s^{-1}) ranged from 2.58 (AP-18) to 8.16 (Putra Chili 4). The range of relative chlorophyll content was from 16.97 (AVVPO702, Taiwan released heat-tolerant genotype) to 48.73 (Putra Chili 1, heat-tolerant inbreed line). Plant physiological processes are regulated by different factors in the environment that directly or indirectly influence proper growth and development of plant. The environmental condition of a particular area in different cropping seasons may affect crop yield by increasing or decreasing the rate of plant physiology. These results are similar to the reported observation of Bijalwan and Madhvi (2016) and Meena et al. (2016).

Using phenotyping methods, plant species were categorized according to their photosynthetic pathways, growth types, and other characteristics that are directly related to yield. The problem of ensuring food security in the twenty-first century for advancements in phenotyping technologies that can easily and swiftly identify the effects of stresses on crops, particularly for yield characteristics. Crop genotypes that are climate resilient and can maintain similar yield productivity under both favorable and unfavorable conditions must be developed and quickly adopted. Advances in quantitative traits techniques that can quickly examine the effects of stress on physiological responses from a wide genetic range are necessary to understand plant characteristics required to sustain yield stability under anticipated future climatic conditions (Miao et al., 2017; Cotrozzi et al., 2020). This investigation was carried out in an effort to understand and address this problem with resistant or tolerance of crops.

GCV, PCV, heritability and genetic advances

The variance components are shown in Table 5. Among all the 16 studied characters, GCV values were more than 20% except for stem diameter (17.02%), total number of branches (10.70%), days to first flower initiation (11.83%), days to first fruit maturation (9.86%) and rate of photosynthesis (19.75%) whereas PCV values more than 20% except branches number (15.47%), days to first flower initiation (13.68%) and days to first fruit maturation (9.86%). Genotypic and phenotypic coefficient of variation were less than 20% except for plant height (GCV 21.11% and PCV 21.66%) and stem length (GCV 23.81% and PCV 28.25%). Fruit yield per plant (FY) had the highest GCV and PCV, with the value of 36.49% and 40.92%, respectively. Genotypic and phenotypic coefficient of variation for physiological characters were observed more than 20% except for photosynthesis rate (GCV 19.75% and PCV 21.66%). Relative difference (RD) is an assessment of the GCV and PCV association and ranged from 2.52% (plant height) to 30.79% (branches number per plant). The broad sense heritability for growth metrics was found to be greater than 47.90% (branches number). All of the yield and yield parameter and physiological character had high broad sense heritability (55%), demonstrating that the extents of heritability and variability are due to their genetic makeup. The fraction of overall variance of phenotypic features between individuals in a particular group related to genetic variation is known as heritability. Individual features provide stronger signals than higher GCV combined with high heritability and GA.

Low genotypic coefficients of variance were found in stem diameter, total number of branches, days to first flowering, days to first maturation, and photosynthesis rate, indicating that the environment has an influence on their phenotypic expression. Although plant development traits are intertwined with genotype and environment, the chances for picking these traits are limited. In this study, moderate to high heritability and genetic advance found in case of all genotypes, might play vital role in the assortment procedure subsequently they are precise through genetic factor. Several researchers validated this research by finding strong inheritance in various yield

Table 6. Correlation coefficient among 16 quantifiable characters for 16 different morphological, physiological and yield and yield attributes of selected anthracnose resistance and heat tolerant chili genotypes. *Significant ($p \leq 0.05$); **highly significant ($p \leq 0.01$); ^{ns}: nonsignificant; PH: plant height (cm); SL: stem length (cm); SD: diameter of stem (cm); BN: number of branches; DFF: days to first flowering; DFM: days to first fruit maturity; FN: fruits number per plant; FW: fruit weight (g); FL: fruit length (cm); FG: fruit girth (cm); SFW: single fruit weight (g); SN: seed number; PR: photosynthesis rate (µmol CO_2 m^2 s^{-1}); SC: stomatal conductance (µmol H_2O m^2 s^{-1}); TR: transpiration rate (SPAD units); RCC: relative chlorophyll content.

Traits	PH	SL	SD	BN	DFF	DFM	FN	FW	FL	FG	SFW	SN	PR	SC	TR	RCC
PH	1	0.45**	0.49**	0.37**	0.12^{ns}	0.30*	0.23*	0.47**	0.42**	0.25*	0.27**	0.409**	0.24*	0.05^{ns}	-0.07^{ns}	0.43**
SL		1	0.49**	0.18^{ns}	0.21*	0.08^{ns}	-0.05^{ns}	0.29*	0.08^{ns}	0.38**	0.12^{ns}	0.40**	0.04^{ns}	0.22*	0.19*	0.40**
SD			1	0.38**	0.13^{ns}	0.11^{ns}	0.23*	0.37**	0.10^{ns}	0.21*	0.05^{ns}	0.44**	0.04^{ns}	0.25*	0.09^{ns}	0.340**
BN				1	0.31**	0.21*	0.62**	0.62**	0.32**	0.25*	-0.05^{ns}	0.29*	0.43**	0.16^{ns}	0.19^{ns}	0.40**
DFF					1	0.49**	0.34**	0.23*	-0.06^{ns}	0.08^{ns}	-0.14^{ns}	-0.14^{ns}	0.31**	0.08^{ns}	-0.05^{ns}	-0.08^{ns}
DFM						1	0.15^{ns}	0.13^{ns}	0.22*	0.23*	0.11^{ns}	0.11^{ns}	0.28**	-0.13^{ns}	-0.29**	0.02^{ns}
FN							1	0.70**	0.30**	-0.17^{ns}	-0.22*	0.01^{ns}	0.39**	0.08^{ns}	-0.01^{ns}	0.27**
FY								1	0.47**	0.19^{ns}	0.15^{ns}	0.41**	0.43**	0.16^{ns}	0.04^{ns}	0.62**
FL									1	0.25*	0.51**	0.53**	0.24*	-0.09^{ns}	-0.12^{ns}	0.51**
FG										1	0.51**	0.47**	0.22*	0.25*	0.10^{ns}	0.32**
SFW											1	0.47**	-0.00^{ns}	-0.00^{ns}	-0.06^{ns}	0.22*
SN												1	0.06^{ns}	0.01^{ns}	0.07^{ns}	0.44**
PR													1	0.09^{ns}	0.32**	0.24*
SC														1	0.40**	0.12^{ns}
TR															1	0.15^{ns}
RCC																1

Table 7. Cluster mean of 16 quantitative variables for phenotypic, physiology, yield, and yield factors of anthracnose resistance and heat tolerance chili genotypes. PH: Plant height (cm); SL: stem length (cm); SD: diameter of stem (cm); BN: number of branches; DFF: days to first flowering; DFM: days to first fruit maturity; FN: fruits number per plant; FW: fruit weight (g); FL: fruit length (cm); FG: fruit girth (cm); SFW: single fruit weight (g); SN: seed number; PR: photosynthesis rate (µmol CO_2 m^2 s^{-1}); SC: stomatal conductance (µmol H_2O m^2 s^{-1}); TR: transpiration rate (SPAD units); RCC: relative chlorophyll content; C1: cluster I; C2: cluster II; C3: cluster III; C4: cluster IV; C5: cluster V; C6: cluster VI; C7: cluster VI.

Cluster	PH	SL	SD	BN	DFF	DFM	FN	FW	FL	FG	SFW	SN	PR	SC	TR	RCC
Cluster I	125.88	19.16	1.27	75.83	30.69	74.81	183.19	996.15	14.29	4.80	7.27	63.77	12.77	0.26	5.56	39.01
Cluster II	119.61	15.92	1.19	71.46	30.08	78.00	182.21	785.53	14.68	4.50	5.73	53.36	11.70	0.22	3.38	39.22
Cluster III	122.86	25.00	1.38	68.70	32.50	71.83	117.12	818.99	11.10	5.83	6.24	61.75	12.18	0.36	6.83	44.85
Cluster IV	117.61	16.15	1.21	81.78	36.17	82.83	139.70	476.38	12.94	5.47	6.88	59.06	14.00	0.23	5.43	36.43
Cluster V	84.83	15.82	1.10	66.33	28.67	72.28	67.06	341.21	8.22	5.59	5.59	51.50	11.81	0.24	5.29	20.13
Cluster VI	69.31	10.87	0.85	56.28	32.50	66.50	223.22	348.54	6.55	1.31	1.31	20.84	9.79	0.25	5.63	16.97
Cluster VII	147.67	21.91	1.60	71.22	31.33	70.56	168.72	648.95	11.43	4.11	4.44	52.06	9.81	0.37	4.48	33.37

characters such as number of fruits per plant, length of fruits, and yield of fruits per plant (Usman et al., 2014; Oladosu et al., 2014; Shweta et al., 2018; Ridzuan et al., 2019). The poor heritability and GA, suggest that non-additive genes play a role in these characters, which might be strengthened through heterosis breeding. As a result, choosing characteristics with higher GCV, heritability, and GA is crucial (Usman et al., 2017). Effective selection can be obtained only when additive effects are sufficiently greater than the environment impact (Usman et al., 2014; Ridzuan et al., 2019). From this study, RD values below less than 20%, indicating that variation is present among the morphological, yield and yield characters and physiological parameters because of a gene that has a better response to direct selection. This observation is appreciated with the investigation of Yatung et al. (2014).

Correlation between morpho-physiological and yield components

Pearson correlation coefficients were used to determine the correlations between the attributes, with the $p \leq 0.01$ significant level (Table 6). Plant height exhibited a significant positive link ($p \leq 0.05$) with stem length (0.45^{**}), stem diameter (0.49^{**}), total branch number (0.37^{**}), and days to first fruit maturation (0.30^{*}), whereas nonsignificant relationship was observed with days to first flowering (0.12^{ns}). Plant height showed highly significant positive ($p \leq 0.01$) relationship with all the yield and yield parameters like fruits number (0.23^{*}), fruit yield per plant (0.47^{**}), fruit length (0.42^{**}), fruit girth (0.25^{*}), single fruit weight (0.27^{**}) and number of seeds per fruit (0.409^{**}). Plant height showed nonsignificant negative relationship with transpiration rate (-0.07^{ns}) but highly significant positive ($p \leq 0.01$) relationship with relative chlorophyll content (0.43^{**}) and significant positive ($p \leq 0.05$) relationship with photosynthesis rate (0.24*). On the other hand, total number of branches also showed highly significant positive ($p \leq 0.01$) relationship with fruits number per plant (0.62^{**}) and fruit yield per plant (0.62^{**}). Days to first flowering had highly significant and significant positive ($p \leq 0.01$) relationship with the fruits number per plant (0.34^{**}) and fruits yield per plant (0.23^{*}). On the other hand, days to first maturation had nonsignificant relationship with fruits number per plant (0.15^{ns}) and fruit yield per plant (0.13^{ns}). Fruit number per plant showed highly significant positive correlation ($p \leq 0.01$) with fruit yield per plant (0.70^{**}). Except for days to first maturity, stomatal conductance, and transpiration rate, plant height showed a highly significant positive connection with most of the examined characters in this study.

Many researchers agree with this conclusion, and they discovered similar results. Number of branches, another crucial growth characteristic, was substantially associated with the number of fruits and yield per plant. With the investigation of Yatung et al. (2014), this observation is appreciated. The results are consistent with the observed values of Usman et al. (2017), Shweta et al. (2018) and Ridzuan et al. (2019), showing a highly beneficial relationship between yield and yield parameters (fruits number and yield per plant, fruit length, and fruit weight).

Cluster analysis of selected chili genotypes

In any breeding effort, genetic divergence analysis is required for parental selection to establish the quantity of variability present in selected genotypes. Sixteen distinct chili genotypes were evaluated in this study, and they were grouped into seven different groups based on their quantitative characteristics (Figure 1). Based on the two seasons combined analysis, selected chili genotypes were clustered into seven different groups, consisted with the genotypes cluster I (CP-36, Putra Chili 4, BP-23, Putra Chili 7, DP-37, DP-57, Putra Chili 10 and Putra Chili 1), cluster II (AP-25 and AP-18), cluster III (Kulai 907 and Control 2), cluster IV (Putra Chili 9), cluster V (Control 1), cluster VI (Chili Bangi 3) and cluster VII (AVVPO702). Analysis of principal component confirms cluster analysis by providing a two-dimensional demonstration (Figure 2) that constructed on the pooled data of different planting periods, utmost lines were extent at adjacent at PC1, though some were alienated at further distances. In Table 7, cluster I genotypes had the highest mean value for plant height (125.88 cm), while cluster VI genotypes had the lowest (69.31 cm), indicating that cluster I genotypes have the genetic ability to contribute to improving these traits in the chili breeding program. On the other hand, if shortness is desired, the lowest plant height mean from cluster VI should be used. Regarding total branch number per plant was highest in cluster IV (81.78) genotypes while lowest values belong to the cluster VI genotypes (56.28). In case of days to first flowering, blooming flowers early after the transplanting in cluster V (28.67) genotypes while first maturation or coloration occurred in cluster VI (66.50) genotypes. According to this research, cluster V and VI genotypes could be used in crossing for early flowering and maturation, respectively. Cluster I recorded the highest number (8) accessions with an average yield per plant (966.15 g), which were followed by cluster III with an average fruit yield per plant (818.99 g). Cluster II obtained 785.53 g fruit yield per plant, whereas cluster V obtained the lowest (341.21 g). Third highest fruit yield was recorded by cluster VI (648.95 g). Similar cluster distance analysis was found by many investigators and chili genotypes were grouped based on the morphological, physiological and yield traits and also genetic divergences were reported on chili genotypes and research suggest that genotypes with the best performance may be adopted in future breeding program (Usman et al., 2014; Meena et al., 2016; Erwin et al., 2019; Ridzuan et al., 2019).

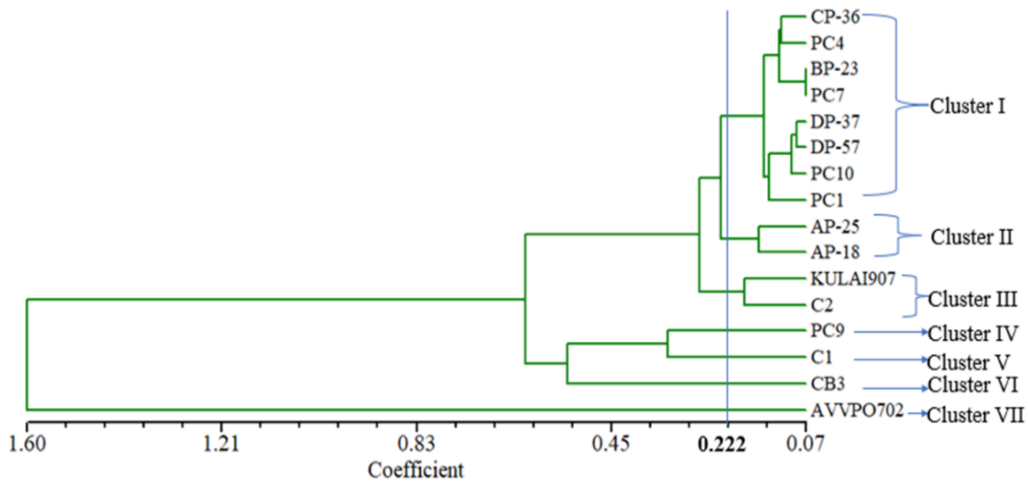

Figure 1. Relationship among the 16 chili genotypes based on 16 traits using SAHN clustering of UPGMA method.

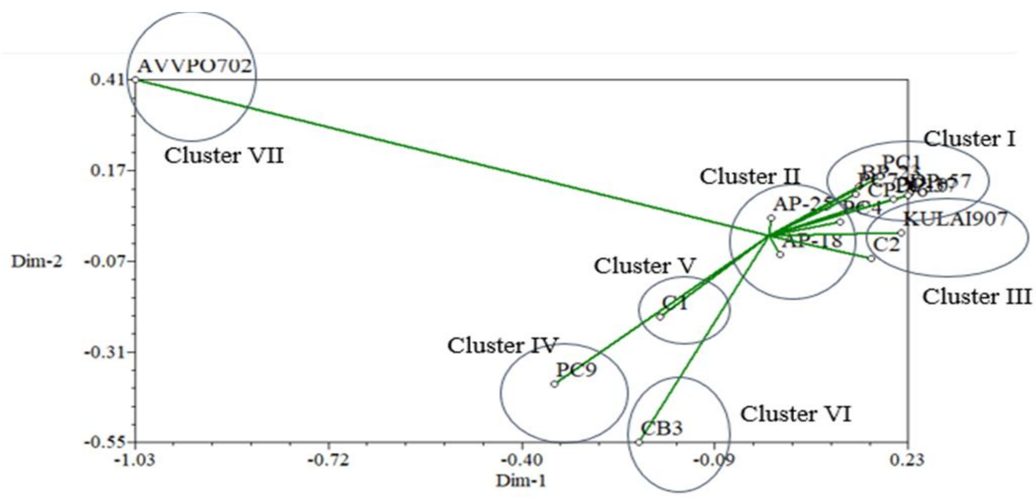

Figure 2. The association among 16 chili genotypes on the basis of 16 morphological and yield characters through a two-dimensional graphical presentation (2D) revealed by PC analysis.

CONCLUSIONS

In this experiment, ANOVA of the studied traits revealed that variation is due to the genetic make-up. From the *per se* performance, the genotypes CP-36 for plant height, Kulai 907 for stem length, DP-57 for total number of branches, Putra chili for early flowering and fruit maturation, AVVPO702 for number of fruits per plant, DP-57 for yield per plant, AP-25 for fruit length, Kulai-907 for fruit girth, CP-36 for single fruit weight and DP-57 for seeds number per plant seems to be better compared to the control and control 2. Among all the genotypes, anthracnose resistant genotypes DP-57, CP-36, DP-37, AP-25 and BP-23 (955.00 to 1144.63 g) and heat tolerant genotypes Putra chili 1, Putra chili 4, Putra chili 7 and Putra chili 9 (476.38 to 1123.60 g) produced better yield per plant that was directly correlated with fruit length, fruit girth single fruit weight and fruits number per plant. All the studied traits exhibited strong genotypic and phenotypic coefficients of variation (greater than 20%) and high broad sense heritability (more than 60%) that indicated that variability is due to their genotypic constitution. The correlation coefficient analysis revealed a significant positive link among morphological, yield, and yield and physiological parameters. The genetic variation among the genotypes were also detected by cluster and principal component analysis to clarify the associations among the studied traits. From this investigation, the anthracnose resistant genotypes (DP-57, CP-36, DP-37, AP-25 and BP-23) and heat tolerant genotypes (Putra chili 1, Putra chili 4, Putra chili 7, Putra chili 9 and Putra chili 10) can be regarded as suitable for future hybridization programs and used effectively to increase yield and productivity.

Author contributions

Conceptualization: M.F.N.C., M.Y.R. Methodology: M.Y.R. Software: M.Y.R. Validation: M.Y.R. Project administration: M.Y.R. Formal analysis: M.F.N.C., M.H., K.M.R.K. Funding acquisition: M.Y.R. Supervision: M.Y.R., S.I.I., S.I.R. Writing-original draft: M.F.N.C., M.H. Writing-review & editing: M.F.N.C., O.Y., R.R.

Acknowledgement

Mst Farhana Nazneen Chowdhury is grateful to the Organization for Women in Science for the Developing World (OWSD) for a Ph.D. fellowship at Universiti Putra Malaysia. This research was sponsored by a Long- Term Research Grant Scheme (LRGS/1/2019/UKM/01/5/4) from the ministry of Higher Education, Malaysia for food security and sustainable vegetable production technology in urban agriculture.

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