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Selection of tomato breeding lines based on morphological traits associated with high yield potential in double-cross population

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Abstract. *Anisa WN, Afifah EN, Murti RH. 2022. Selection of tomato breeding lines based on morphological traits associated with high yield potential in double-cross population. Biodiversitas 23: 2973-2980.* Low tomato production is a global problem. Plant breeding has been intensified to develop high-yield varieties and meet the high production of vegetable crops. Selection is an essential part of plant breeding to evaluate desirable traits of breeding lines. This study aimed to identify tomato breeding lines with high yield potential from 13 breeding lines and 2 commercial tomatoes. Collected data were analyzed using analysis of variance, post hoc, path, and principal component analysis. Results showed that 9 tomato lines, namely, BV-1, BV-2, BV-3, BV-6, BV-7, BV-9, BV-11, BV-12, and BV-13 had a high yield potential based on the number of fruits per plant and fruit weight. Given their high path coefficient value and significant correlation ($P<0.05$) with the yield potential, these two characteristics are highly recommended to be used as selection criteria for the high yield potential of tomato plants. The following characteristics had a high value of heritability: fruit weight, fruit length, fruit diameter, fruit firmness, fruit locules, fruit pericarp thickness, total soluble solid, number of flowers per bunch, number of fruits per bunch, number of fruits per plant, and harvesting age.

Keywords: Breeding, double-cross, production, pure line, selection, tomato

Abbreviations: DAT: Day after transplanting, PCA: Principal Component Analysis

INTRODUCTION

Tomato is one of the vegetable crops most widely consumed worldwide because its fruit contains plenty of vitamins, antioxidants, and nutrients that are important to meet human nutrition (Zhao et al. 2018). The demand for tomatoes has increased with the growth of the human population (Chaudhary et al. 2019). Mustafa et al. (2018) stated that tomato productivity in Indonesia is still unstable. Therefore, productivity must be elevated by improving good varieties with high production rates and quality. New high-yield tomato varieties have become an important source for human consumption and the basis for the development of various industrial products worldwide (Hassan et al. 2021).

Plant breeding research is intensified to improve varieties with desirable traits and meet high yield and quality (Qaim 2020). Achieving high-yield lines and hybrids is the ultimate goal of the plant breeding project (Lenaerts et al. 2019). Breeding methods have the following roles: creating genetic variations using conventional and biotechnological methods; selecting recombinants with great potential according to performance data, pedigree records, and genetic information; and selecting the appropriate breeding program to create variations (Shashibhushan and Muchanthula 2021). The high-yield trait can be achieved by the interspecific crossing of cultivated tomatoes and commercial hybrid tomatoes that exhibit morphological characteristics related to yield potential (Resende et al. 2020).

Selection and evaluation in plant breeding programs are urgently needed to examine breeding lines with good production and quality (Afifah et al. 2021). Detailed characterization and selection of breeding lines are required to support breeding goals. Phenotypical selection is an essential step in assessing genetic diversity through breeding lines and is also important to achieving a good variety (Grozeva et al. 2021). The selection consists of recording all the characteristics of breeding lines that are highly heritable, easy to observe by the naked eye, and expressed in all environments (Salim et al. 2020).

Selecting high yield traits in plant breeding is not easy to achieve because yield performance is generally strongly influenced by the characteristics of the yield component. Yield and component characteristics are regulated by many genes, and their expression is strongly influenced by environmental factors (Mustafa et al. 2018). Therefore, selection will only be effective when the right characteristics are used to show the superiority of a genotype. Selection criteria and heritability estimates can be employed to successfully select desirable traits (Bernardo 2020). Simultaneous selection to improve tomato yield is more efficient than selection using one or two characteristic combinations. Therefore, this study evaluated the morphological characteristics associated with the yield potential of tomato lines that resulted from double-crossing.

The breeding program in the Faculty of Agriculture, Universitas Gadjah Mada, Indonesia successfully developed tomato recombinants through double-crossing. This project supports the road map of the Faculty regarding Smart Eco-Bioproduction in producing lowland tomato cultivars with high productivity. An F2 tomato generation was obtained from double-crossing. A double-cross is generated from a two-stage crossing involving two pairs of inbreeds. Plants from a double-cross hybrid are not genetically uniform (heterozygous) (Pereira da Costa et al. 2016). Evaluation and selection are required to achieve high homozygosity with superior traits (Chung and Liao 2020). The F1 of double-cross plants with high variability was previously evaluated and produced the best 13 individuals of tomato lines. However, the selection of further generations is still highly required. These lines must be selected and evaluated according to their morphological traits associated with yield potential (production). Thus, this study aimed to evaluate and select the tomato lines with high-yield potential in F2 double-cross population.

MATERIALS AND METHODS

Plant materials and research condition

This study was carried out at the Horticultural Seed and Agribusiness Development and Promotion Centre, Department of Agriculture, Sleman District, Special Region of Yogyakarta, Indonesia with an elevation of 700 above sea level, the daily temperature of 25°C ± 4°C, and rainfall average of 120 mm/month. The 13 selected breeding lines of the F2 double cross consisted of BV-1, BV-2, BV-3, BV-4, BV-5, BV-6, BV-7, BV-8, BV-9, BV-10, BV-11, BV-12, and BV-13. Commercial varieties Betavila and Gustavi (as a control), two famous tomato hybrids produced by East-West Seed Indonesia, were also used as plant materials.

Experimental procedure

This experiment was laid out in a completely randomized block design. Three blocks were prepared as replications, and each consisted of 20 plants per tomato line. The total number of plants in each accession was 60 plants. Tomato seeds were shown in the mixture media consisting of soil, sand, and cocopeat with a ratio of 1:1:1 (w/w). The seedlings were transplanted in the field 24 days after germination. The plants were cultivated in the field enriched with organic fertilizer of 2.5 kg per plant, nitrogen, phosphorus, and potassium at a ratio of 16:16:16 (15 g per plant), potassium chloride (25 g per plant), and urea (50 g per plant) and planted in a space of 50 cm × 50 cm in 1 m × 10 m beds covered with plastic mulch. This field experiment was followed with cultivation procedures including transplanting; watering; fertilizing; pruning; controlling weeds, pests, and diseases; and harvesting.

Data collection

Ten plants per accession per replication were observed for fruit weight, fruit weight per plant, fruit length, fruit diameter, fruit firmness, fruit locules, fruit pericarp thickness, total soluble solids (TSS, ºbrix), number of flowers per bunch, number of fruits per bunch, fruit sett, number of flower bunches per plant, number of fruit bunches per plant, number of fruits per plant, vitamin c, flowering age, harvesting age, and yield. The flowering period of tomato flowers was determined as the time when 50% of tomato flowers in each cultivar and replication had bloomed. Fruit locules and pericarp thickness were conducted by the following steps; Three fruits per plant were cut into two pieces and counted for their locules and pericarp thickness. Vitamin C content was analyzed using the titration method according to Afifah et al. (2021). Fruit firmness was assessed with a digital penetrometer (GY-4 Digital Fruit Hardness) by penetrating the fruit pericarp through the fruit locules using a cylindrical probe at a diameter of 11 mm at a constant speed of 10 $mm.s^{-1}$. A hand refractometer was used to measure the TSS of tomato fruits. Yield potential was calculated using the following formula: Yield potential = fruit weight per plant × number of plant population in a hectare.

Statistical analysis

The collected data were statistically analyzed using analysis of variance and Tukey's HSD test to determine the significant difference with α=5%. Path analysis was also conducted to determine the characteristics that have a direct and indirect correlation with yield. Principle component analysis (PCA) was adopted to select the best tomato breeding lines on the basis of the morphological characteristics associated with high yield potential. The broad-sense heritability (H^2) of each characteristic was analyzed using a formula $H^2 = \frac{\sigma_g^2}{\sigma_p^2}$ with the following criteria: H^2 > 0.5 as high heritability, 0.2 > H^2≥ 0.5 as medium heritability, and low heritability if H^2≤ 0.2 (Roy and Shil 2020). Heritability value was used to determine the morphological characteristics that can be used as selection criteria for tomato plants with high yield potential (productivity).

RESULTS AND DISCUSSION

Quantitative characteristics of tomato breeding lines

Table 1 presents the number of flowers per bunch, number of flower bunches per plant, flowering age, harvesting age, and fruit set of tomato breeding lines. The average number of flowers per bunch in all tomato plants was 6-8. BV-3 had the highest average number of flowers per bunch at 8.56 flowers, but this value was not significantly different from that of Betavila (as a commercial variety) at 8.48 and Gustavi (a commercial variety) at 8.04. This finding implied that the number of flowers per bunch of BV-3 was comparable with that of the control. Most of the selected lines showed similar numbers of flower bunches per plant. The highest average number of flower bunches per plant was found in BV-12 and BV-9 at around 21.10 and 20.90, respectively, but the difference was not statistically significant. As shown in Table 1, BV-3 had the lowest value of flowering age, and the difference was statistically significant. BV-3 started flowering at 66.67 days after transplanting (DAT), and the other lines started their flowering stage at around 72 DAT. The number of fruit sets was not significantly different among the breeding lines and commercial varieties. This finding indicated that all of the tomato plants have the same number of fruit sets (%). In general, the flowering characteristics of selected lines breeding were comparable with those of the control.

Table 2 shows that BV-7, BV-1, BV-6, and BV-9 had high fruit weights of 93.83, 90.66, 89.49, and 89.08 g, respectively, and these values were significantly higher than those of the commercial varieties Betavila and Gustavi at 76.93 and 74.56 g, respectively. BV-2, BV-3, BV-6, BV-7, and BV-12 had the highest fruit lengths at 4.79, 5.56, 5.47, 5.55, and 5.61 cm, respectively, and these values were significantly different from that of commercial variety Gustavi at around 4.92 cm. BV-1, BV-6, BV-7, and BV-9 had high fruit diameter at around 5.4 cm, which was significantly higher than those of Betavila and Gustavi at around 5.11 and 4.81 cm, respectively. BV-6 had a significantly higher pericarp thickness at 0.66 cm compared with the commercial varieties at around 0.58 and 0.6 cm.

Table 3 shows the fruit weight per plant, number of fruits per bunch, number of fruit bunches per plant, number of fruits per plant, and yield of the tomato breeding lines. BV-7 and BV-9 had the highest average fruit weight per plant at 3.23 and 3.20 kg, respectively, which were not significantly different from those of the commercial varieties Betavila and Gustavi at 2.89 and 3.02 kg, respectively. BV-7 and BV-9 also had the highest yield potential at around 86.17 and 85.27 tons. ha^{-1}, but these values were not significantly different from those of the commercial varieties. This finding indicated that BV-7 and BV-9 had a high yield potential as commercial varieties.

Table 1. Number of flowers per bunch, number of flower bunches per plant, flowering age, harvesting age, and fruit set of tomato breeding lines

Tomato lines	Number of flowers per bunch	Number of flower bunches per plant	Flowering age (DAT)	Harvesting age (DAT)	Fruit set (%)
BV-1	7.81 abcd	18.80 abc	28.00 ab	70.67 abcd	82.12 a
BV-2	7.21 cd	16.53 c	28.33 ab	70.67 abcd	82.07 a
BV-3	8.56 a	19.13 abc	25.67 b	66.67 d	80.88 a
BV-4	7.62 abcd	19.70 ab	28.33 ab	71.00 abc	82.75 a
BV-5	7.51 abcd	20.60 ab	27.33 ab	71.33 abc	83.42 a
BV-6	6.69 d	18.80 abc	28.33 ab	72.33 abc	85.77 a
BV-7	7.83 abc	18.07 abc	27.67 ab	74.33 a	86.78 a
BV-8	7.11 cd	17.37 bc	27.00 ab	73.00 ab	85.17 a
BV-9	7.46 abcd	20.90 a	28.67 ab	72.33 abc	85.60 a
BV-10	7.80 abcd	19.17 abc	27.00 ab	69.67 bcd	82.39 a
BV-11	7.74 abcd	19.00 abc	27.00 ab	68.67 cd	82.07 a
BV-12	7.58 abcd	21.10 a	28.67 ab	72.33 abc	83.43 a
BV-13	7.41 bcd	20.73 ab	27.67 ab	72.33 abc	81.18 a
Betavila	8.48 ab	16.87 abc	29.00 a	74.67 a	83.80 a
Gustavi	8.04 abc	17.87 abc	28.33 ab	73.00 ab	82.44 a

Notes: Numbers followed with the same letters are not significantly different according to Tukey's HSD test at α=5%; DAT: Day after transplanting

Table 2. Fruit weight, fruit length, fruit diameter, and fruit pericarp thickness of tomato breeding lines

Tomato lines	Fruit weight (g)	Fruit length (cm)	Fruit diameter (cm)	Fruit pericarp thickness (cm)
BV-1	90.66 ab	5.32 abc	5.41 a	0.62 abcde
BV-2	85.34 abc	4.79 e	5.35 ab	0.59 bcdef
BV-3	78.41 cde	5.56 ab	4.99 def	0.59 bcdef
BV-4	78.19 cde	5.26 abcd	5.06 cde	0.55 f
BV-5	75.89 cdef	5.06 cde	5.03 de	0.58 cdef
BV-6	89.49 ab	5.47 ab	5.40 a	0.66 a
BV-7	93.83 a	5.55 ab	5.44 a	0.63 abc
BV-8	82.92 bcd	5.06 cde	5.32 abc	0.64 ab
BV-9	89.08 ab	5.26 abcd	5.41 a	0.62 abcd
BV-10	79.19 cde	5.26 abcd	5.16 abcd	0.58 def
BV-11	66.05 f	5.19 bcd	4.78 ef	0.57 ef
BV-12	69.60 ef	5.61 a	4.72 f	0.55 f
BV-13	76.80 cde	5.21 bcd	5.17 abcd	0.61 abcde
Betavila	76.93 cde	5.23 abcd	5.11 bcd	0.58 def
Gustavi	74.56 def	4.92 de	4.81 ef	0.60 abcdef

Note: Numbers followed with the same letters are not significantly different according to Tukey's HSD test at α=5%

All of the tomato plants had around 5-6 fruits per bunch. Commercial variety Betavila had the highest number of fruits per bunch at 6.99, but this value was not significantly different compared with those of BV-1, BV-3, BV-7, BV-9, BV-10, BV-11, BV-12, and Gustavi. This finding indicated that BV-1, BV-3, BV-7, BV-9, BV-10, BV-11, and BV-12 had the same number of fruits per bunch as the commercial varieties. Table 1 shows that BV-3, BV-9, BV-12, and BV-13 had a high number of fruit bunches per plant at 17.47, 16.73, 17.00, and 16.67, respectively. Betavila had around 13 fruit bunches per plant, and this value was significantly lower than those of BV-3, BV-9, BV-12, and BV-13 but was not significantly different from that of Gustavi. Furthermore, BV-7 and BV-9 had the highest number of fruits per plant at 86.17 and 85.27, respectively, but these values were not significantly higher than those of commercial varieties and BV-1, BV-4, BV-5, BV-6, BV-8, BV-9, BV-10, BV-12, and BV-13. Therefore, these lines can produce a high number of fruits per plant as commercial varieties.

Table 4 shows that fruit firmness ranged from 27.7 N (Gustavi) to 36.64 N (BV-13). The fruit firmness of BV-13 was significantly higher than those of the commercial varieties Gustavi and Betavila but was not significantly different from those of BV-1, BV-4, BV-7, and BV-10. This finding indicated that these five tomato breeding lines had a good fruit firmness quality. Furthermore, the number of fruit locules ranged from 2.21 to 2.81. Nine tomato lines, namely, BV-1, Bv-2, Bv-3, BV-4, BV-5, Bv-6, BV-7, BV-10, and BV-11 had significantly higher numbers of fruit locules at 2.71, 2.73, 2.61, 2.79, 2.61, 2.62, 2.69, 2.81, and 2.67, respectively, compared with the commercial varieties at around 2.31 and 2.29. Vitamin C content was not significantly different between the varieties and tomato lines. All the tested tomatoes had the same level of vitamin C. Meanwhile, a significant difference in TSS was found between BV-13 and Betavila. The TSS of BV-13 was not significantly different from that of BV-1, BV-2, BV-4, BV-5, and Gustavi. Gustavi had the highest TSS value at 4.33% Brix.

Table 3. Fruit weight per plant, number of fruits per bunch, number of fruit bunches per plant, number of fruits per plant, and yield of tomato breeding lines

Tomato lines	Fruit weight per plant (kg)	Number of fruits per bunch	Number of fruit bunches per plant	Number of fruits per plant	Yield (ton. ha^{-1})
BV-1	2.87 abcd	6.31 abcde	14.40 ab	57.20 abc	76.55 abcd
BV-2	2.34 cd	5.82 de	14.80 ab	49.50 c	62.48 cd
BV-3	2.14 d	6.68 abc	17.47 a	52.97 bc	57.07 d
BV-4	2.88 abcd	6.18 bcde	15.40 ab	64.60 ab	76.80 abcd
BV-5	2.99 abc	6.09 bcde	15.73 ab	65.27 ab	79.62 abc
BV-6	3.04 abc	5.66 e	15.27 ab	58.90 abc	81.00 abc
BV-7	3.23 a	6.71 ab	14.17 ab	62.00 abc	86.17 a
BV-8	2.75 abcd	5.84 de	14.53 ab	60.20 abc	73.33 abcd
BV-9	3.20 ab	6.27 abcde	16.73 a	67.13 a	85.27 ab
BV-10	2.65 abcd	6.26 abcde	14.60 ab	61.53 abc	70.60 abcd
BV-11	2.46 bcd	6.20 abcde	15.00 ab	65.90 ab	65.50 bcd
BV-12	2.69 abcd	6.20 abcde	17.00 a	71.87 a	71.64 abc
BV-13	2.99 abc	5.90 cde	16.67 a	63.07 abc	79.63 abc
Betavila	2.89 abc	6.99 a	13.00 b	63.53 ab	77.19 abc
Gustavi	3.02 abc	6.60 abcd	14.03 ab	70.47 a	80.64 abc

Note: Numbers followed with the same letters are not significantly different according to Tukey's HSD test at α=5%

Table 4. Fruit firmness, fruit locules, vitamin C, and total of soluble solid (TSS) of tomato breeding lines

Tomato lines	Fruit firmness (N)	Fruit locules	Vitamin C	TSS (% brix)
BV-1	32.91 abc	2.71 abc	160.4 a	4.12 abc
BV-2	29.80 cd	2.73 abc	192.9 a	3.95 abcd
BV-3	30.17 cd	2.61 abc	169.47 a	3.64 defg
BV-4	32.77 abc	2.79 ab	168.6 a	4.10 abc
BV-5	31.29 bcd	2.61 abc	183.1 a	4.09 abc
BV-6	32.05 bc	2.62 abc	169.9 a	3.50 efg
BV-7	34.32 ab	2.69 abc	144.07 a	3.40 g
BV-8	32.32 bc	2.47 cde	133.57 a	3.34 g
BV-9	31.44 bcd	2.52 bcd	136.77 a	3.57 defg
BV-10	32.80 abc	2.81 a	166.87 a	3.81 cdef
BV-11	30.85 bcd	2.67 abc	157.37 a	3.73 cdefg
BV-12	30.73 bcd	2.48 cde	152.87 a	3.88 bcde
BV-13	36.64 a	2.21 e	173.03 a	4.25 ab
Betavila	32.54 bc	2.31 de	154.5 a	3.44 fg
Gustavi	27.70 d	2.29 de	202.4 a	4.33 a

Note: Numbers followed with the same letters are not significantly different according to Tukey's HSD test at α=5%

Path analysis and PCA

Path analysis in Table 5 showed that most of the morphological characteristics contributed to the yield potential. However, each character had a direct or indirect correlation with the yield potential. The number of fruits per plant had the highest positive direct effect on the yield potential at a value of 0.58 and was significantly correlated with the yield potential with a correlation coefficient of 0.68. The second characteristic with the highest positive direct effect on the yield potential was fruit weight at a value of 0.24 with a correlation coefficient of 0.28. The number of flower bunches per plant had the third-highest of direct effect on the yield potential at a value of 0.2 and a correlation value of 0.53. By contrast, fruit length, fruit diameter, fruit firmness, fruit locules, fruit pericarp thickness, TSS, number of flowers per bunch, number of fruits per bunch, number of flower bunches per plant, number of fruit bunches per plant, and fruit set had a low direct contribution to the yield potential at values of −0.01, 0.09, −0.09, 0.1, 0.2, 0.00, and −0.02, respectively. Nevertheless, these characteristics had a high indirect effect on the yield potential.

The biplot component analysis depicted in Figure 1A shows that the number of fruits per plant, number of flower bunches per plant, and number of fruit bunches per plant were in line with the yield potential. According to Table 5, these characteristics also had a significantly positive correlation with the yield potential. The PCA biplot showed that yield, fruit weight per plant, number of fruits per plant, number of flower bunches per plant, number of fruit bunches per plant, fruit weight, fruit diameter, and fruit thickness had a long vector. However, fruit length, fruit locules, TSS, fruit set, fruit firmness, number of flowers per bunch, and number of fruits per bunch had a short vector. In addition, the PCA in Figure 1B shows the location of tomato individuals. Tomato lines 5 (BV-1), 18 (BV2-), 66 (BV-7), 79 (BV-8), 89 (BV-9), 201 (BV-6), 215 (BV-7), 217 (BV7-), 220 (BV-7), 236 (BV-9), 254 (BV-11), 262 (BV-12), 273 (BV-13), 302 (BV-1). 352 (BV-6), 365(BV-7), and 368 (BV7-) had a red or deep red color, indicating their higher characteristic value compared with the tomato number with a light orange or yellow color.

Broad sense heritability (H^2) value

Table 6 shows the broad-sense heritability of each characteristic of the tomato breeding lines. According to Roy and Shil (2020) criteria, fruit weight, fruit length, fruit diameter, fruit firmness, fruit locules, fruit pericarp thickness, TSS, number of flowers per bunch, number of fruits per bunch, number of fruits per plant, and harvesting age had high heritability values of 0.998 0.678, 0.756, 0.818, 0.875, 0.775, 0.731, 0.921, 0.543, and 0.702, respectively. Meanwhile, fruit weight per plant, fruit set, number of fruit bunches per plant, number of fruits per plant, vitamin c, flowering age, and yield had medium values of broad-sense heritability at 0.412, 0.209, 0.283, 0.328, 0.202, 0.268, and 0.411, respectively. The number of fruit bunches per plant had a low value of broad-sense heritability at 0.052.

Discussion

Tomato plant breeding has been intensified to develop tomato varieties with high quality and quantity and meet the global demand for tomatoes (Avdikos et al. 2021). Tomato lines with high production have been developed by double-crossing tomato hybrids to generate genetic recombination. According to Matos et al. (2021), double-cross hybrids show heterozygous and genetic variability among progenies and phenotypic differences in their yield traits. Therefore, the selection of progenies derived from double-crossing is highly required to understand their agronomic features and select the best plant-based on its yield potential. Avdikos et al. (2021) stated that according to the breeding methodology, a breeder has to simultaneously conduct selection and evaluation to develop a new variety.

This study selected 13 individual accessions of F2 tomatoes derived from double-crossing and evaluated them based on the following morphological characteristics: fruit weight, fruit weight per plant, fruit length, fruit diameter, fruit firmness, fruit locules, fruit pericarp thickness, TSS, number of flowers per bunch, number of fruits per bunch, fruit sett, number of flower bunches per plant, number of fruit bunches per plant, number of fruits per plant, vitamin c, flowering age, harvesting age, and yield.

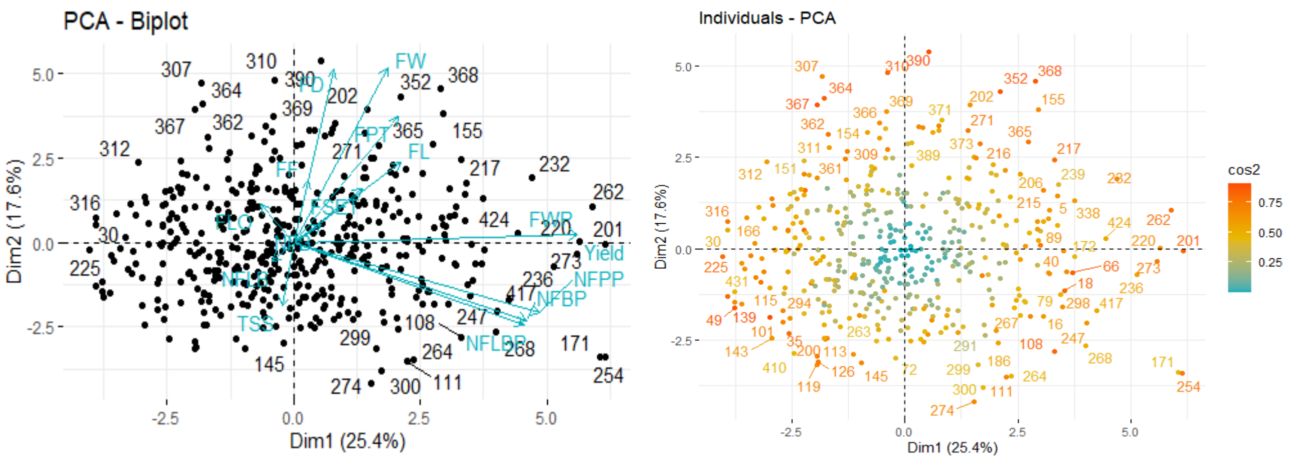
According to these morphological characteristics, the performance of F2 tomato lines varied significantly. Statistical analysis showed that BV-1, BV-2, BV-3, BV-6, BV-7, BV-9, BV-11, BV-12, and BV-13 had the highest fruit weight, fruit weight per plant, fruit length, fruit diameter, fruit firmness, fruit locules, fruit pericarp thickness, TSS, number of flowers per bunch, number of fruits per bunch, fruit sett, number of flower bunches per plant, number of fruit bunches per plant, number of fruits per plant, vitamin c, flowering age, harvesting age, and yield. Therefore, these tomato breeding lines had different characteristics and better performances than commercial varieties. However, several characteristics were the same between the tomato lines and tomato varieties, implying that the selected breeding lines were comparable with commercial hybrid varieties as control.

Mustafa et al. (2018) argued that selection based on yield potential requires complex effort to achieve the best result because of its dependence on the yield component characteristic. This problem can be eliminated using selection criteria, which can be determined by identifying the characteristics that are highly associated with the yield potential. Furthermore, the effectiveness of selection can be achieved using the value of heritability (Sautomo and Syukur 2017). Heritability estimates are useful as the first step in the selection of segregation plants (Klápšte et al. 2020). The present study used path analysis, PCA biplot, and heritability estimation as guidance in determining selection criteria and selecting the best individuals among progenies. Path analysis is highly required for selecting plants with high yield performance. Direct and indirect selection can be estimated using several characteristics associated with the yield potential (Mustafa et al. 2018).

Table 5. Direct (in bold font) and indirect effects of various component characteristics on the yield of tomato breeding lines

Characteristics	FW	FL	FD	FLO	FPT	NFLBP	NFBP	FSET	NFPP	Yield
FW	0.24	0.00	0.07	−0.01	0.05	−0.01	0.00	0.00	−0.04	0.28 **
FL	0.09	−0.01	0.02	0.01	0.03	0.02	0.00	0.00	0.07	0.23 **
FD	0.18	0.00	0.09	−0.02	0.04	−0.03	0.00	0.00	−0.12	0.14 **
FLO	0.04	0.00	0.02	−0.09	−0.01	−0.01	0.00	0.00	−0.06	−0.11 *
FPT	0.12	0.00	0.04	0.01	0.10	0.01	0.00	0.00	0.02	0.28 **
NFLBP	−0.01	0.00	−0.01	0.00	0.00	0.20	0.00	0.00	0.35	0.53 **
NFBP	−0.01	0.00	−0.01	0.00	0.00	0.17	0.00	0.00	0.37	0.52 **
FSET	0.05	0.00	0.01	0.00	0.02	0.00	0.00	−0.02	0.09	0.14 **
NFPP	−0.02	0.00	−0.02	0.01	0.00	0.12	0.00	0.00	0.58	0.68 **

Notes: **significantly different at α=5%, FW: Fruit weight, FWP: Fruit weight per plant, FL: Fruit length, FD: Fruit diameter, FLO: Fruit locules, FPT: Fruit pericarp thickness, TSS: Total soluble solid, NFLB: Number of flowers per bunch, NFB: Number of fruits per bunch, NFLBP: Number of flower bunches per plant, NFBP: Number of fruit bunches per plant, FSET: Fruit set, and NFPP: Number of fruits per plant



A

B

Figure 1. A. Biplot and Individuals Principle Component Analysis (PCA). B. Observed morphological characteristics. FW: Fruit weight, FWP: Fruit weight per plant, FL: Fruit length, FD: Fruit diameter, FF: Fruit firmness, FLO: Fruit locules, FPT: Fruit pericarp thickness, TSS: Total soluble solid, NFLB: Number of flowers per bunch, NFB: Number of fruits per bunch, NFLBP: Number of flower bunches per plant, NFBP: Number of fruit bunches per plant, FSET: Fruit set, NFPP: Number of fruits per plant

Table 6. Broad sense heritability of tomato characteristics

Characteristics	σ^2_g	σ^2_p	H^2	Remarks
Fruit weight	59.18	59.30	0.998	high
Fruit weight per plant	0.046	0.112	0.412	moderate
Fruit length	0.041	0.061	0.678	high
Fruit diameter	0.051	0.068	0.756	high
Fruit firmness	3.305	4.042	0.818	high
Fruit locules	0.030	0.034	0.875	high
Fruit pericarp thickness	0.001	0.001	0.775	high
Total soluble solids	0.086	0.118	0.731	high
Number of flowers per bunch	0.174	0.189	0.921	high
Number of fruits per bunch	0.106	0.195	0.543	high
Fruit set	2.694	12.874	0.209	moderate
Number of flower bunches per plant	0.205	3.925	0.052	low
Number of fruit bunches per plant	0.554	1.955	0.283	moderate
Number of fruits per plant	16.111	49.058	0.328	moderate
Vitamin C	15.337	75.920	0.202	moderate
Flowering age	0.039	0.146	0.268	moderate
Harvesting age	0.383	0.545	0.702	high
Yield	32.563	79.185	0.411	moderate

Notes: According to Roy and Shil (2020), H^2>0.5 is categorized as high heritability, 0.2>H^2 ≥0.5 as medium heritability, and H^2 ≤0.2 as low heritability

According to Roy and Shil (2020) criteria for the broad sense of heritability, fruit weight, fruit length, fruit diameter, fruit firmness, fruit locules, fruit pericarp thickness, TSS, number of flowers per bunch, number of fruits per bunch, number of fruits per plant, and harvesting age had a high heritability value. Characteristics with high heritability values have more genetic control than environmental effects. Kesumawati et al. (2022) defined the heritability value as the proportion of phenotypic variance due to heritable genetic effects among individuals in a population. Heritability provides an accurate visualization of genetically or environmentally affected traits and can be further used to study the genetic association between two parents and derived offspring. This finding is in line with the study of Hakim and Suyamto (2017). Hence, heritability and genetic diversity are useful and allow plant breeders to design efficient breeding strategies for selection (Adhikari et al. 2018).

Path analysis showed that fruit weight, number of fruits per plant, and number of flower bunches per plant had a positive direct effect on the yield potential. Therefore, these characteristics can be used for the selection of tomatoes with high yield potential. The direct estimation of desirable traits will increase the efficacy of selection in plant breeding. Cobb et al. (2019) mentioned that the direct estimation of genetic trends in plants is one of the best methods for assessing long-term selection in a breeding program. This information can be relatively easily captured when the breeding program continuously evaluates newly released materials in on-farm agronomy trials.

The selected individual of tomato accession can be determined using PCA biplot and PCA-individuals. The characteristics located in the shortest vector had a low contribution to plant diversity, and those in the long vector had a significant contribution to plant diversity. Yield, fruit weight per plant, number of fruits per plant, number of flower bunches per plant, number of fruit bunches per plant, fruit weight, fruit diameter, and fruit thickness had a long vector and therefore can be used as selection criteria for the best tomato lines with high yield potential. As shown in Figure 1B, the tomato lines can be selected according to the color visualization in the PCA individuals. The red or deep red color indicates that the individual has a high characteristic value, and the light orange or yellow color indicates that the individual has a low characteristic value. Finally, the following 17 individual tomatoes were selected according to the morphological traits associated with the yield potential: 5 (BV-1), 18 (BV2-), 66 (BV-7), 79 (BV-8), 89 (BV-9), 201 (BV-6), 215 (BV-7), 217 (BV7-), 220 (BV-7), 236 (BV-9), 254 (BV-11), 262 (BV-12), 273 (BV-13), 302 (BV-1). 352 (BV-6), 365(BV-7), and 368 (BV7-). The selected accession can be applied to the subsequent breeding process to achieve high homozygosity and can be used as plant breeding materials or released as new varieties.

In conclusion, the following 17 individuals were obtained from the selection of tomato lines based on the characteristics with a direct effect on the yield potential including the number of flower bunches per plant, the number of fruits per plant, and fruit weight: tomato number 5 (BV-1), 18 (BV-2), 66 (BV-7), 79 (BV-8), 89 (BV-9), 201 (BV-6), 215 (BV-7), 217 (BV7-), 220 (BV-7), 236 (BV-9), 254 (BV-11), 262 (BV-12), 273 (BV-13), 302 (BV-1). 352 (BV-6), 365(BV-7), and 368 (BV7-). Fruit weight, fruit length, fruit diameter, fruit firmness, fruit locules, fruit pericarp thickness, TSS, number of flowers per bunch, number of fruits per bunch, number of fruits per plant, and harvesting age have a high heritability value and therefore are recommended to be used as selection criteria for tomato plants with high yield potential.

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