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Full Length Article

Genetic Diversity Studies of Twenty Eggplant (*Solanum* spp.) Accessions and their Performance against Root-Knot Nematode (*Meloidogyne incognita*) Infestation

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Abstract

Eggplant (*Solanum melongena* L.) is one of the most widely consumed vegetables in Malaysia. The information of eggplant genetic diversity and its resistant to root-knot nematode (RKN) (*Meloidogyne incognita*) is essential for the eggplant improvement programs in Malaysia. In this study, 20 Malaysian eggplant (*Solanum* spp.) accessions were evaluated for ten morpho-agronomical and RKN susceptibility traits. The experiment was conducted in Malaysian Agricultural Research and Development Institute (MARDI), Serdang, Selang or using randomized complete block design (RCBD) with four replications. Data on morpho-agronomical and *M. incognita* reproduction were collected and analyzed using SAS statistical software v. 9.3 (SAS Institute, Cary, NC). The results showed a significant variation among eggplant accessions for all studied traits ($P \leq 0.01$). All yield-related traits except for number of fruits were positively and significantly correlated with yield per plant. Their correlation coefficient values ranged from 0.679 (fruit length) to 0.923 (fruit weight). Unweighted pair group method with arithmetic mean (UPGMA) dendrogram grouped these 20 eggplant accessions into four clusters, with cluster IV recording the highest mean of yield and yield component traits. *Meloidogyne incognita* infection caused root gall symptoms on all the *Solanum* spp. accessions except for *S. torvum* accessions, NTH 08-0024 and NTH 08-0041, thus these two accessions were considered as immune to RKN. In addition to that, two *S. melongena* accessions, DINO 03-0200 and DINO 03-0056 were found highly resistant while another accession, NTH 08-0131 was categorized as tolerant. High-yielding and RKN-resistant accession, DINO 03-0056 was identified as the most important accession due to both its high yield and RKN resistance.

Keywords: *Meloidogyne incognita*; Morpho-agronomical traits; Root gall; *Solanum* spp.; Yield components

Introduction

Eggplant is among the important nutritious vegetables, and cultivated across tropical and sub-tropical region, with more than 1.79-million-hectare (ha) of lands being used for brinjal cultivation (Kumar *et al.* 2020). Eggplant is believed to originate from India, and spread throughout the world where currently, 90% of the global eggplant production is concentrated in Asian region, with India and China as the main producer (Kumar *et al.* 2020; Wei *et al.* 2020). It is one of the important sources for fiber diets, vitamins, minerals, and antioxidant compounds in vegetables. Anthocyanins in eggplant provide antioxidants and free radical scavengers, which are able to reduce disease risks such as cancer, cardiovascular disease, hypertension and diabetes (Famuwagun *et al.* 2021; Zhou *et al.* 2021). Due to the high nutritive value, eggplant is consumed as a staple food to tackle malnutrition problems in certain regions in Africa (Famuwagun *et al.* 2021).

Eggplant production suffers reduced in plant growth and yield due to various pests and diseases problems, including parasitic nematodes infection. The root-knot nematode (RKN), *Meloidogyne incognita* occurs globally, with a broad host range including *Solanaceae* group (Papolu *et al.* 2020). This nematode has been reported infecting various types of fruit and vegetable crops in Malaysia, and a broad host range including eggplant (Musa *et al.* 2020; Leong *et al.* 2021). Previous studies have reported on RKN

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infestation on eggplant genotypes, causing a significant plant growth and yield reduction (Musa *et al.* 2020; Papolu *et al.* 2020). Infection of *Meloidogyne* spp. together with other pathogens, such as Fusarium and Verticillium has been reported to cause eggplant yield reduction by up to 78% (Musa *et al.* 2020). Until now, the eggplant production heavily relies on the application of chemicals to combat pests and diseases, including nematode-related problems, resulting in development of resistance in the targeted pests or pathogen (Sim *et al.* 2019; Musa *et al.* 2020). While chemical application is the most effective method, it is known to adversely affect the environment and human health. Hazardous nematicides such as Oxamyl have been withdrawn from the local market due to possible contamination of groundwater and health issues (Khairiah *et al.* 2016; Musa *et al.* 2020). Therefore, utilization of resistant varieties is considered the best alternative to chemical application to overcome nematode infestation in an integrated management of nematode. Use of the resistant varieties can encourage the proliferation of local natural enemies while reducing the overall production costs (Ogunnupebi *et al.* 2020).

Together with the plant genetic diversity analysis, this information is important for crop management and improvement through breeding technique. A successful selection depends on the value of heritability and genetic advance in relation to the average performance of the trait. Compared to cultivated species, the wild accession of eggplant shows a broader genetic diversity, especially in tolerance to abiotic stresses, pests and diseases (Kaushik *et al.* 2016; Sargın and Devran 2021). However, the lack of information about disease-resistant varieties, especially nematode-caused diseases, has driven this study. Eggplants have also shown a great level of genetic polymorphisms, especially in vegetative traits such as fruit shape and color. Therefore, the objectives of this study are to determine the genetic diversity of 20 local Malaysian eggplant (*Solanum* spp.) accessions based on their morpho-agronomical traits, and to identify the most promising accessions with high yield and RKN-resistant traits.

Materials and Methods

Plant materials and cultural practices

The experiment was conducted in the Greenhouse Unit, Horticulture Research Centre, Malaysia Agriculture and Development Institute (MARDI) Serdang, Selangor, Malaysia which was located on latitude 101º46'E, and longitude 3º17'N with an average temperature of 24–30 ± 2ºC and 70–81% relative humidity. The experiments were conducted for two planting seasons, from January to June 2018 for the first season and from July to December 2018 for the second season. Twenty eggplant (*Solanum* spp.) accessions were obtained from MARDI eggplant germplasm collection. The accessions name, species type and fruit morphology descriptions are shown in Table 1. The eggplant seeds were pre-germinated in 30-hole seed tray prefilled with peat moss and maintained for four weeks. Healthy four-week-old seedlings with five to six true leaves were selected and transplanted into individual 1900 mL pots containing sterilized soil mixture (70% topsoil: 15% sand: 15% organic matter). Each eggplant plant was fertilized manually once in two weeks at the rate of 30 g per plant (NPK 16:16:16) for the first time before continuing with 40 g per plant of NPK 12:12:17 until the experiment ended. Standard cultural practices and other plant maintenance, such as pest and disease control management and weeding were carried out as needed.

Morpho-agronomical screening

Four-week-old plants were selected and subjected to the randomized complete block design (RCBD) with four replications. Each replication contained five plants per accession, and each was planted 90 cm between plants. Data on plant height (PH), days to 50% flowering (DT50F), plant spread (PS), stem diameter (SD), number of primary branches (NB), number of fruits per plant (NF), fruit weight (FW), fruit length (FL), fruit girth (FG) and yield per plant (YLD) were collected at 12 weeks after transplanting.

Meloidogyne incognita inoculum preparation

The *M. incognita* inoculum used in the study was obtained from RKN cultures deposited in the nematology greenhouse at MARDI Serdang, Malaysia where they were maintained on susceptible eggplant (*S. melongena*) cv. black purple round. The infested eggplant roots were uprooted, gently washed, and chopped into 1–2 cm sections before being vigorously shaken in 0.5% NaOCl for five minutes (Hussey and Barker 1973). Root fragments were washed through 45 µm sieve and suspended in 100 mL distilled water to collect the nematode eggs. A 10 mL sample of suspension was taken, and the eggs were counted under stereomicroscope to estimate the egg population. Final eggs inoculum concentration was adjusted to obtain approximately 5,000 eggs in a 10 mL test tube.

Evaluation of susceptibility against *Meloidogyne incognita*

Five plants from each accession were selected and arranged in a randomized complete block design (RCBD) with four replications. Two weeks after planting, 5,000 *M. incognita* eggs were inoculated at the surrounding of the plant base. The experiment was terminated eight weeks after the nematode inoculation. At the end of the experiments, roots from each plant were harvested and gently washed under tap water until cleaned before being observed under dissecting microscope and rated to gall index (GI) (Bridge and Page 1980) from 0 (no galls) to 10 (100% galled) scale.

Nematode eggs were extracted using 1% NaOCl (Hussey and Barker 1973) and the numbers of eggs per gram root (ER) were recorded.

Statistical analysis

The genetic variability among the 20 local eggplant (*Solanum* spp.) accessions, broad sense heritability (h^2_B) and other genetic parameters were calculated using the following equations (Burton 1952; Burton and Vane 1953; Johnson *et al.* 1955; Allard 1960):

(a) Genotypic variance (σ^2_g):

$$\sigma^2_g = (MS_g - MS_e)/r$$

(b) Phenotypic variance (σ^2_p):

$$\sigma^2_p = \sigma^2_g + \sigma^2_e$$

(c) Genotypic coefficient of variance (GCV):

$$GCV = \sqrt{\sigma^2_g} / \bar{X} \times 100$$

(d) Phenotypic coefficient of variance (PCV):

$$PCV = \sqrt{\sigma^2_p} / \bar{X} \times 100$$

(e) Broad sense heritability (h^2_B):

$$h^2_B\ (\%) = \sigma^2_g/\sigma^2_p \times 100$$

(f) Expected genetic advance (GA):

$$GA\% = k \times \sqrt{\sigma^2_p} / \bar{X} \times h^2_B \times 100$$

where σ^2_g is the genotypic variance, σ^2_e and MS_e are the mean squares of error, MS_g is the mean square of accessions, r is number of replications, σ^2_p is the phenotypic variance, $\bar{X}$ is the grand mean of the traits, h^2_B is the heritability, k is the standardized selection differential at 5% selection intensity (2.063), and σ_p is the phenotypic standard deviation.

Unweighted pair group method with arithmetic mean (UPGMA) and sequential agglomerative hierarchical non-overlapping (SAHN) clustering method were applied using NTSYS-pc software version 2.10 (Rohlf 2000) to calculate the genetic relationships among the eggplant accessions. The morpho-agronomical data were statistically analyzed using one-way analysis of variance (ANOVA) with means separated by New Duncan Multiple Range Test (NDMRT) using the SAS statistical software v. 9.3 (SAS Institute, Cary, NC) to determine different responses of eggplant accessions in terms of its morpho-agronomical traits. The correlation coefficient was analyzed to determine the relationships among traits using Pearson's correlation. The nematode reproduction data were analyzed using SAS statistical software v. 9.3 (SAS Institute, Cary, NC). Data of ER and gall index (GI) were log transformed [log10(x+1)] to homogenize the variances before subjecting them to one-way ANOVA with means separated by Tukey's HSD tests ($P \le 0.05$).

Results

Variation among local Malaysian eggplant accessions

The analysis of variance (ANOVA) revealed that the mean squares due to accessions (A) were highly significant ($P < 0.01$) for all morpho-agronomical traits observed in this study. However, non-significant mean squares due to season (S) and season by accession interaction (S × A) were also obtained for all studied traits (Table 2). The coefficient of variation (CV) was low to high (ranged from 6.53 to 39.62%). The data of days to 50% flowering ranged from 37.83 days to 67.93 days with mean of 49.22 days, with the earliest and the latest flowering accession being DINO 03-0062 and DINO 03-0009, respectively (Table 3). Accession DINO 03-0222 had the lowest value for plant height (36.17 cm) and plant spread (19.24 cm) while accession NTH 08-0041 had the highest value of plant height and plant spread (158.79 cm and 84.47 cm, respectively). Stem diameter ranged from 2.57 cm to 6.11 cm with mean of 3.77 cm while the number of primary branches ranged from 5.75 to 14.05. Accession NTH 08-0024 had the highest number of fruits per plant (67.30) while accession MTe-01 had the lowest value for number of fruits per plant (13.73). In terms of yield and its components, accession MTe-02 recorded the highest values for three important traits, which were yield per plant (1,819.58 g), fruit weight (134.70 g) and fruit girth (18.83 cm) while accession NTH 08-0041 recorded the lowest values for fruit weight (2.50 g), fruit length (0.74 cm), fruit girth (1.25 cm) and yield per plant (178.34 g).

Correlation among traits

Pearson's correlation coefficients between ten quantitative traits of the 20 eggplant accessions are shown in Table 4. The yield per plant was highly significant and positively correlated ($P \le 0.01$) with its components, such as fruit weight (0.958), fruit girth (0.904) and fruit length (0.670) but significantly and negatively correlated with the number of fruits per plant (-0.502, $P \le 0.05$). Plant vegetative traits were negatively correlated with yield per plant, ranging between -0.095 (days to 50% flowering) and -0.492 (stem diameter).

Genetic analysis, broad-sense heritability and genetic advance

In this study, genotypic variances ranged from 0.76 (stem diameter) to 310,540.35 (yield per plant) and phenotypic variances ranged from 0.93 (stem diameter) to 375,619.68 (yield per plant) (Table 5). High genotypic variance values of 310,540.35, 1,651.63 and 785.44 were obtained for yield per plant, fruit weight and plant height, respectively. Similarly, high phenotypic variance values of 375,619.68, 1,958.39 and 824.38 were obtained for yield per plant, fruit weight and plant height, respectively. In this study,

Table 1: Description of the 20 Malaysian eggplant (*Solanum* spp.) accessions

No.	Accessions Name	Species	Description of the eggplant fruit
1	NTH 08-0024	*S. torvum*	Tiny, round, green colour
2	NTH 08-0041	*S. torvum*	Tiny, round, green colour
3	DINO 03-0200	*S. melongena*	Small, round, yellow colour
4	DINO 03-0056	*S. melongena*	Big, round, white colour
5	NTH 08-0077	*S. melongena*	Small, round, purple colour
6	DINO 03-0223	*S. melongena*	Small, round, purple colour
7	DINO 03-0014	*S. melongena*	Medium, oblong, green colour
8	DINO 03-0009	*S. melongena*	Medium, oblong, green colour
9	DINO 03-0028	*S. melongena*	Medium, oblong, green colour
10	DINO 03-0038	*S. melongena*	Medium, oblong, green colour
11	DINO 03-0045	*S. melongena*	Medium, oblong, green colour
12	DINO 03-0144	*S. macrocarpon*	Big, round, yellow colour
13	DINO 03-0222	*S. melongena*	Medium, Long, purple colour
14	NTH 08-0131	*S. melongena*	Medium, Long, purple colour
15	DINO 03-0075	*S. ferox*	Small, round, yellow colour
16	DINO 03-0091	*S. ferox*	Small, round, yellow colour
17	DINO 03-0062	*S. melongena*	Small, round, white colour
18	DINO 03-0162	*S. macrocarpon*	Big, round, yellow colour
19	MTe-01	*S. melongena*	Long, purple colour
20	MTe-02	*S. melongena*	Big, round, purple colour

Table 2: Analysis of variance of morpho-agronomical traits of 20 eggplant (*Solanum* spp.) accessions

Sources of Variation	Season (S)	Replication (R)	Accession (A)	S x A	Error	CV (%)
DF	1	3	19	19	117	
DT50F (days)	41.88^{ns}	198.58^{**}	357.41^{**}	23.04^{ns}	10.32	6.53
PH (cm)	9.11^{ns}	766.62^{**}	6322.47^{**}	117.52^{ns}	38.94	13.63
PS(cm)	2.57^{ns}	217.07^{**}	906.91^{**}	33.25^{ns}	19.81	13.63
SD (cm)	0.08^{ns}	1.4^{**}	6.26^{**}	0.34^{ns}	0.17	10.97
NB	0.06^{ns}	10.56^{**}	51.96^{**}	2.54^{ns}	1.23	12.35
NF	$18.63n^{ns}$	100.83^{**}	847.46^{**}	14.62^{ns}	17.32	15.97
FW(g)	55.93^{ns}	6.23^{**}	13519.77^{**}	91.05^{ns}	306.76	39.62
FL (cm)	78.69^{ns}	12.25^{ns}	350.56^{**}	19.66^{ns}	7.81	27.57
FG (cm)	9.58^{ns}	11.46^{**}	228.06^{**}	22.41^{ns}	5.37	24.02
YLD (g)	$33{,}180.48^{ns}$	$21{,}090.43^{**}$	$2{,}549{,}402.12^{**}$	$176{,}819.09^{ns}$	65,079.33	31.66

DT50F: days to 50 % flowering (day); PH: plant height 12 weeks after transplant (cm); PS: plant spread 12 weeks after transplant (cm); SD: stem diameter 12 weeks after transplant (cm); NB: number of primary branches 12 weeks after transplant; NF: number of fruits per plant; FW: fruit weight (g); FL: fruit length (cm); FG: fruit girth (cm); YLD: yield per plant (g)
**Significant at $P \leq 0.01$; ^{ns}Non-significant at $P > 0.05$; DF: degree of freedom at 0.05; CV (%): coefficient of variation (%)

genotypic coefficient variation (GCV) for yield and its related traits were medium to high, ranging from 39.08 to 91.94% while for vegetative traits, the values ranged from 13.40 to 45.64% (low to medium). Higher phenotypic coefficient variation (PCV) was also recorded for yield and yield-related traits (ranged from 42.22 to 100.11%) compared to vegetative traits (ranged from 14.91 to 46.76%). Two vegetative traits, days to 50% flowering (GCV = 13.40%, PCV = 14.91%) and fruit weight (GCV = 91.94%, PCV = 100.11%) had the lowest and highest of genotypic and phenotypic coefficient variation values, respectively.

High broad sense heritability (h^2_B) estimates were between medium and high for most traits, with the highest heritability value recorded for plant height (95.28%), followed by number of fruits per plant (85.70%) and plant spread (84.84%). The highest and the lowest heritability values were recorded for plant height (95.28%) and fruit girth (78.94%), respectively. The genetic advance (GA) values ranged from 24.80% for days to 50% flowering to 173.92% for fruit weight, but in general, the genetic advance values for vegetative traits were higher than the GA values for yield and its components.

Clustering analysis

Twenty accessions of local Malaysian eggplant were clustered into four clusters with a similarity coefficient of 0.21 (Fig. 1). Cluster I was the smallest group that consisted of both *S. torvum* accessions (NTH 08-0024 and NTH 08-0041). Cluster II was the biggest cluster with eight members, comprising of accessions DINO 03-0075, DINO 03-0091, DINO 03-0162, DINO 03-0144, DINO 03-0062, DINO 03-0200 NTH 08-0077 and DINO 03-0223. Both cluster III and IV shared the same number of accessions which was five accessions per cluster. Cluster III was comprised of accession DINO 03-0009, DINO 03-0014, DINO 03-0028, DINO 03-0038 and DINO 03-0045 while cluster IV consisted of accession MTe-02, DINO 03-0056, DINO 03-0222, NTH 08-0131 and MTe-01.

Both accessions from cluster I showed the highest value of plant vegetative traits (plant height, plant spread,

Table 3: Means for 10 morpho-agronomical traits of the 20 eggplant accessions

Accessions	DT50F (day)	PH (cm)	PS (cm)	SD (cm)	NB	NF	FW (g)	FL (cm)	FG (cm)	YLD (g)
NTH 08-0024	50.88 ± 5.96 ed	109.38 ± 22.11 b	58.18 ± 11.08 a	4.34 ± 0.9 d	12.35 ± 2.03 d	67.3 ± 7.57 a	2.89 ± 0.48 d	0.75 ± 0.12 h	1.28 ± 0.21 l	240.51 ± 40.58 hi
NTH 08-0041	47.13 ± 5.82 eghf	158.79 ± 34.1 a	84.47 ± 9.93 b	5.16 ± 1.1 c	10.26 ± 1.88 d	61.95 ± 7.26 b	2.5 ± 0.4 d	0.74 ± 0.11 h	1.25 ± 0.2 l	178.34 ± 28.36 i
DINO 03-0200	49.95 ± 6.18 ikj	70.2 ± 7.76 l	37.34 ± 3.88 i	3.51 ± 0.74 hg	7.84 ± 1.16 fe	29.65 ± 5.49 c	23.6 ± 4.55 c	9.37 ± 0.86 gf	6.94 ± 1.34 j	615.87 ± 133.62 c
DINO 03-0056	49.85 ± 10.57 edf	54.82 ± 12.63 g	29.16 ± 6.98 c	3.06 ± 0.67 ji	8.04 ± 1.15 fe	18.98 ± 4.74 hgi	132.96 ± 57.13 a	15.33 ± 2.55 e	19.34 ± 4.61 a	1955.92 ± 430.32 a
NTH 08-0077	45.88 ± 5.34 eghf	65.84 ± 8.69 lk	35.02 ± 4.58 ed	4.06 ± 0.82 e	8.87 ± 1.07 f	28.35 ± 3.42 ed	23.33 ± 4.26 c	3.72 ± 0.84 gf	7.65 ± 2.09 gf	511.49 ± 131.11 c
DINO 03-0223	43.48 ± 4.83 ihj	71.66 ± 9.36 jk	38.12 ± 1.25 hi	3.41 ± 0.71 hi	7.16 ± 1.19 fe	24.73 ± 4.2 hgf	20.1 ± 2.47 dc	3.73 ± 0.78 gf	10.91 ± 2.34 ef	672.35 ± 91.18 fge
DINO 03-0014	50.13 ± 10.89 edf	43.59 ± 5.09 e	23.19 ± 3.74 f	2.99 ± 0.63 jk	7.08 ± 1.19 fe	19.23 ± 6.82 ji	14 ± 3.85 dc	13.51 ± 2.88 dc	8.01 ± 1.83 ih	417.74 ± 139.37 c
DINO 03-0009	67.93 ± 8.74 a	73.11 ± 15.7 de	38.89 ± 3.63 f	3.76 ± 0.8 fe	7.31 ± 1.38 fe	23.28 ± 3.82 hgf	17.71 ± 3.83 dc	14 ± 2.97 dc	9.07 ± 2.27 gh	551.25 ± 118.47 dce
DINO 03-0028	51.43 ± 5.65 ed	77.56 ± 16.65 dc	41.26 ± 5.05 hi	3.6 ± 0.77 fg	7.5 ± 1.47 e	24.88 ± 4.56 ef	19.27 ± 3.53 dc	14.43 ± 3.05 dc	7.88 ± 1.77 ih	589.45 ± 125 c
DINO 03-0038	58.35 ± 6.88 b	67.17 ± 14.43 fe	35.73 ± 1.36 hi	3.08 ± 0.66 j	8.11 ± 1.28 fe	20.3 ± 6.96 hgi	14.76 ± 2.69 dc	15.24 ± 3.41 c	7.13 ± 1.51 ij	526.82 ± 122.27 dc
DINO 03-0045	56.33 ± 6.26 cb	69.81 ± 14.99 e	37.13 ± 1.33 hi	3.5 ± 0.74 hg	7.52 ± 1.21 fe	25.38 ± 4.76 edf	19.56 ± 3.49 dc	14.07 ± 3.23 dc	6.74 ± 1.43ij	645.99 ± 139.28 c
DINO 03-0144	45.75 ± 4.95 ghf	40.46 ± 7.28 c	21.52 ± 6.37 c	3.95 ± 0.84 e	14.05 ± 2.21 d	38.1 ± 4.73 kj	31.64 ± 6.06 c	5.33 ± 1.16 f	11.87 ± 2.65 ed	499.65 ± 105.65 b
DINO 03-0222	42.95 ± 4.98 ghf	36.17 ± 14.46 fe	19.24 ± 3.93 ef	2.83 ± 0.6 k	8.61 ± 1.34 fe	15.78 ± 1.72 kj	102.57 ± 28.51 b	12.66 ± 2.72 de	18.36 ± 3.91 d	1794.4 ± 342.06 b
NTH 08-0131	50 ± 6.16 edf	47.79 ± 10.26 ji	25.42 ± 1.77 hg	2.57 ± 0.55 l	6.88 ± 2.87 c	16.93 ± 2.98 kji	115.63 ± 31.4 b	20.37 ± 4.33 b	14.84 ± 3.27 c	1593.01 ± 362.75 a
DINO 03-0075	48.53 ± 5.35 egdf	61.43 ± 13.19 fg	32.68 ± 3.91 ef	5.74 ± 1.22 b	12.09 ± 7.18 a	24.75 ± 3.37 egf	20.48 ± 3.93 dc	4.27 ± 1 gf	6.88 ± 1.47 ij	292.35 ± 91.11 dfge
DINO 03-0091	52.18 ± 5.44 cd	40.46 ± 8.69 lk	21.52 ± 4.74 d	3.95 ± 0.24 e	14.05 ± 1.01 d	29.2 ± 3.15 d	23.71 ± 4.38 dc	3.31 ± 0.74 g	4.58 ± 1.02 k	294.34 ± 73.64 hgi
DINO 03-0062	37.83 ± 6.08 k	41.16 ± 8.84 lk	21.9 ± 1.2 hi	3.04 ± 0.65 jk	5.75 ± 0.74 g	20.33 ± 2.98 hi	16.81 ± 3.89 dc	3.38 ± 0.76 g	4.36 ± 0.98 k	295.77 ± 69.31 hgi
DINO 03-0162	44.7 ± 4.54i gh	51.87 ± 11.14 hi	27.59 ± 4.03 ef	6.11 ± 1.3 a	13.05 ± 3.28 b	25.63 ± 3.72 edf	± 3.63 dc	3.2 ± 0.7 g	6.41 ± 1.48 ij	365.36 ± 79.18 hfg
MTe-01	51.6 ± 6.45 ed	55.87 ± 12 hg	29.72 ± 2.21 g	2.98 ± 0.63 jk	6.23 ± 1.28 fe	13.73 ± 1.72 kji	97.67 ± 25.77 b	27.28 ± 5.8 a	13.13 ± 2.7 9 d	1876.56 ± 396.11 a
MTe-02	39.48 ± 9.91 kj	50.76 ± 10.9 hi	27 ± 1.89 hi	3.76 ± 0.8 fe	7.85 ± 1.13 fe	20.6 ± 4.16 hi	134.7 ± 39.7 a	13.05 ± 2.82d e	18.83 ± 4.37 b	1819.58 ± 396.81 a
Mean S1	49.77	64.16	34.13	3.79	9.09	27.11	41.83	10.33	9.14	782.23
Mean S2	48.66	64.63	34.38	3.75	8.97	27.79	43.61	9.44	9.40	791.45
Total mean	49.22	64.39	34.25	3.77	9.03	27.45	42.72	9.89	9.27	786.84

DT50F: days to 50 % flowering (day); PH: plant height 12 weeks after transplant (cm); PS: plant spread 12 weeks after transplant (cm); SD: stem diameter 12 weeks after transplant (cm); NB: number of primary branches 12 weeks after transplant; NF: number of fruits per plant; FW: fruit weight (g); FL: fruit length (cm); FG: fruit girth (cm); YLD: yield per plant (g)

Means ± standard deviation followed by the same letter did not differ according to DNMRT tests ($P > 0.05$)

Table 4. Correlation coefficient analysis among morpho-agronomical traits for 20 eggplant accessions

	PH	PS	SD	NB	NF	FW	FL	FG	YLD
DT50F	0.209	0.209	0.028	0.043	0.025	-0.174	0.389**	-0.106	-0.095
PH		1.000**	0.397**	0.077	0.752**	-0.377**	-0.314**	-0.474**	-0.342**
PS			0.397**	0.077	0.752**	-0.377**	-0.314**	-0.474**	-0.342**
SD				0.674**	0.468**	-0.391**	-0.558**	-0.419**	-0.492**
NB					0.525**	-0.259*	-0.535**	-0.286**	-0.378**
NF						-0.459**	-0.621**	-0.583**	-0.502**
FW							0.558**	0.904**	0.958**
FL								0.543**	0.670**
FG									0.904**

DT50F: days to 50 % flowering (day); PH: plant height 12 weeks after transplant (cm); PS: plant spread 12 weeks after transplant (cm); SD: stem diameter 12 weeks after transplant (cm); NB: number of primary branches 12 weeks after transplant; NF: number of fruits per plant; FW: fruit weight (g); FL: fruit length (cm); FG: fruit girth (cm); YLD: yield per plant (g)

*Significant at $P \leq 0.05$. **Significant at $P \leq 0.01$

stem diameter and number of primary branches), but had the lowest yield per plant (0.175 kg) and yield related traits (fruit weight, fruit girth and fruit length) except for number of fruits per plant (Table 6). Cluster II was comprised of three different eggplant species, including *S. melongena*, *S. macrocarpon* and *S. ferox*. This cluster was characterized with the earliest flowering, and highest mean of stem diameter, number of primary branches and fruit girth. Cluster III was characterized by small plant appearance (lowest plant height and plant spread mean) and late flowering while cluster IV showed an average performance in terms of plant vegetation, but better in fruit morphology and yield.

Evaluation of 20 eggplant accessions against *Meloidogyne incognita* infection

The inoculation of *M. incognita* eggs on the eggplant plants showed a significant response among the tested accessions at eight weeks after the nematode inoculation ($P \leq 0.05$) (Table 7). Generally, most of the eggplant accessions showed a gall symptom on the root system except for *S. torvum* accessions (NTH 08-0024 and NTH 08-0041). The eggs per gram root was higher than the initial egg inoculation (5,000 eggs) for other eggplant accessions, with accession DINO 03-0062 being the most susceptible with the highest production of eggs per gram root (32,209 eggs). The gall index values ranged between 1.11 and 7.52, with accession MTe-01 showing the highest value.

Among the eggplant accessions, accession DINO 03-0200 and DINO 03-0056 showed a highly-resistant response against *M. incognita* with the lowest eggs per gram root (ER) (839 eggs and 915 eggs, respectively), followed by accession NTH 08-0077 (4,371 eggs); they showed significant difference ($P \leq 0.05$) compared to the other eggplant accessions (Table 6). Both accession DINO 03-0200 and DINO 03-0056 also produced the lowest gall index (1.11 and 1.63, respectively) ($P \leq 0.05$). Four accessions (NTH 08-0077, DINO 03-0009, DINO 03-0038 and DINO 03-0028) produced below 50% eggs per gram root compared to accession DINO 03-0062, indicating a moderate resistant. Twelve eggplant accessions were susceptible, with egg production ranging between 16,228 and 32,209 eggs per gram root while the gall index ranged between 3.53 and 7.52. Accession MTe-01 and MTe-02 showed the highest gall index (7.52 and 6.92, respectively)

Table 5: Analysis of genetic variance, broad-sense heritability, and genetic advance for ten morpho-agronomical traits in 20 eggplant (*Solanum* spp.) accessions

Traits	Mean	σ^2g	σ^2p	GCV (%)	PCV (%)	H^2_B (%)	GA (%)
DT50F	49.17	43.39	53.71	13.4	14.91	80.78	24.8
PH	61.4	785.44	824.38	45.64	46.76	95.28	91.77
PS	32.66	110.89	130.7	32.24	35	84.84	61.17
SD	3.74	0.76	0.93	23.33	25.78	81.91	43.5
NB	8.97	6.34	7.57	28.06	30.66	83.77	52.9
NF	26.06	103.77	121.09	39.08	42.22	85.7	74.53
FW	44.21	1651.63	1958.39	91.94	100.11	84.34	173.92
FL	10.14	42.84	50.66	64.56	70.2	84.58	122.31
FG	9.65	20.13	25.5	46.5	52.34	78.94	85.12
YLD	805.85	310540	375620	69.15	76.05	82.67	129.53

σ^2g: genotypic variation; σ^2p: phenotypic variation; GCV: genotypic coefficient variation; PCV: phenotypic coefficient variation; H^2_B: broad-sense heritability; GA: genetic advance; DT50F: days to 50 % flowering (day); PH: plant height 12 weeks after transplant (cm); PS: plant spread 12 weeks after transplant (cm); SD: stem diameter 12 weeks after transplant (cm); NB: number of primary branches 12 weeks after transplant; NF: number of fruits per plant; FW: fruit weight (g); FL: fruit length (cm); FG: fruit girth (cm); YLD: yield per plant (g)

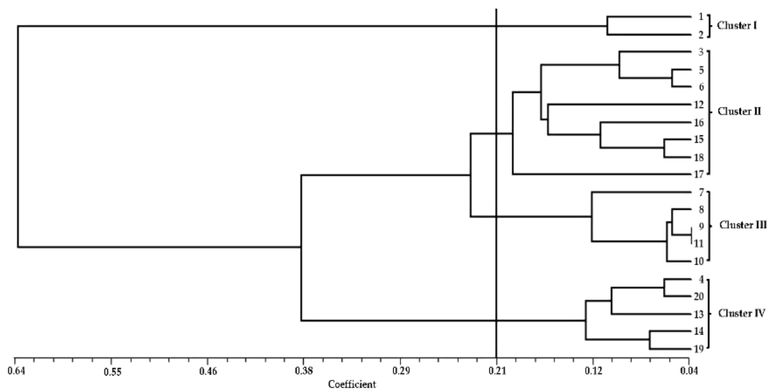

Fig. 1: Relationship among the 20 eggplant (*Solanum* spp.) accessions based on ten quantitative traits using unweighted pair group method with arithmetic mean (UPGMA) at a 0.21 similarity coefficient

($P \leq 0.05$). In these studies, we found that more than half of the eggplant accessions were susceptible because the *M. incognita* successfully reproduced compared to the initial inoculation population.

Discussion

The combined analyses of variance for morphology and yield traits from two cropping seasons showed a highly significant difference ($P \leq 0.01$) among the accessions for all parameters measured. These results strongly indicated that some tested eggplant accessions had a potential to be used as parents in the eggplant breeding program either to enhance yield or vegetative traits. However, there was no significant difference ($P > 0.05$) between cropping seasons and season by accession interaction (S × A) for all parameters, revealing that the cropping season did not affect the performance of eggplant accessions. A high value of CV for fruit weight and yield per plant indicates that these two traits are important to differentiate between the eggplant accessions used in this study. This result was expected as these accessions were selected from different eggplant *Solanum* species. Sulaiman *et al.* (2020) also reported a significant difference on these two traits, and concluded that it was related to the origin of each eggplant accession. A similar study by Caguiat and Hautea (2014) has also shown the same results on the phenotypic variation among eggplant accessions. Naujeer (2009) strongly suggested that eggplant breeding programs could be enhanced through direct selection of yield and its components to produce superior hybrids. Generally, accession NTH 08-0041 showed a better performance in terms of morphology while accession DINO 03-0056 had the best overall performance, especially for yield and yield-related traits except for the number of fruits in both cropping seasons. Accession NTH 08-0041 which belongs to species *S. torvum* is known for its bigger size compared to other eggplant species, but it lacks fruit characteristics and yield. Meanwhile, accession DINO 03–0056 from species *S. melongena* was proven to be a commercial species for eggplant with higher yield and better fruit appearance. Naujeer (2009) also found similar correlations between *S. torvum* and *S. melongena* species in terms of their morphology, yield and fruit appearances. Other than that, *S. torvum* is more resistant to pest and disease compared to other eggplant species, and suggested as alternative rootstock for more susceptible eggplant species (Leong *et al.* 2021).

Table 6: Cluster group and quantitative traits mean

Cluster	DT50F	PH	PS	SD	NB	NF	FW	FL	FG	YLD
I	49.47	130.87	69.61	4.71	11.50	65.27	2.69	0.74	1.25	211.01
II	45.47	55.23	29.38	4.05	9.85	27.25	22.18	4.95	7.63	452.75
III	58.49	71.91	38.25	3.48	7.61	23.46	17.82	14.43	7.70	578.38
IV	46.79	49.88	26.53	3.06	7.58	17.56	119.63	17.08	17.31	1821.48

DT50F: days to 50 % flowering (day); PH: plant height 12 weeks after transplant (cm); PS: plant spread 12 weeks after transplant (cm); SD: stem diameter 12 weeks after transplant (cm); NB: number of primary branches 12 weeks after transplant; NF: number of fruits per plant; FW: fruit weight (g); FL: fruit length (cm); FG: fruit girth (cm); YLD: yield per plant (g)

Table 7: Means comparison of three different nematode reproduction index on 20 eggplant (*Solanum* spp.) accessions

Accession	ER	GI	Host status
NTH 08-0024	0 i	0 i	I
NTH 08-0041	0 i	0 i	I
DINO 03-0200	839 ± 6 i	1.11 ± 0.19 h	HR
DINO 03-0056	915 ± 36 i	1.63 ± 0.21 h	HR
NTH 08-0077	4371 ± 80 h	3.38 ± 0.25 g	MR
DINO 03-0223	18663 ± 458 def	3.98 ± 0.46 feg	S
DINO 03-0014	17514 ± 1123 def	3.53 ± 0.29 fg	S
DINO 03-0009	12717 ± 388 g	3.75 ± 0.72 fg	MR
DINO 03-0028	11738 ± 469 g	3.71 ± 0.37 fg	MR
DINO 03-0038	12386 ± 474 g	3.79 ± 0.66 feg	MR
DINO 03-0045	22229 ± 957 c	3.80 ± 0.47 feg	S
DINO 03-0144	17216 ± 1812 ef	4.74 ± 0.42 ced	S
DINO 03-0222	16228 ± 1266 f	4.35 ± 0.77 fed	S
NTH 08-0131	16860 ± 675 ef	5.07 ± 0.53 cbd	S
DINO 03-0075	19960 ± 1365 dc	5.03 ± 0.21 cbd	S
DINO 03-0091	19204 ± 1643 de	5.65 ± 1.64 cbd	S
DINO 03-0062	32209 ± 4847 a	5.72 ± 0.52 b	S
DINO 03-0162	21901 ± 395 c	5.78 ± 0.54 b	S
MTe-01	26992 ± 1178 b	7.52 ± 0.48 a	S
MTe-02	27352 ± 1787 b	6.92 ± 0.37 a	S

ER: eggs per gram root; GI: gall index; Host status is based on production of eggs per gram root relative to the most susceptible accession (DINO 03-0062) where no egg detected = immune (I), eggs per gram root < 10% = highly resistant (HR), eggs per gram root < 50% = moderately resistant (MR), eggs per gram root > 50% = susceptible (S)
Means ± standard deviation followed by the same letter did not differ according to Tukey's HSD tests ($P > 0.05$)

The highly significant correlation values between the yield and its components except for the number of fruits indicated that improvements in these yield-related traits can lead to improvements in eggplant yield per plant. A highly significant and positive correlation ($P \leq 0.01$) between yield per plant and its components (fruit weight, fruit length and fruit girth) have also been reported earlier (Singh *et al.* 2018; Arti *et al.* 2019). Fruit weight, fruit length and fruit girth were the main contributing traits towards yield per plant, and selection based on these secondary traits might be effective for developing high-yielding eggplant cultivars. The negative correlation between vegetative morphology with yield per plant showed that a small-size eggplant accession such as DINO 03-0056 and DINO 03-0222 could produce a higher yield per plant. The significant negative correlation between yield and vegetative morphology was also observed by Thangamani and Jansirani (2012). However, days to 50% flowering and number of primary branches traits showed slightly positive impact on yield per plant for some eggplant accession. Previous studies also observed a positive correlation between days to 50% flowering and number of primary branches (NB) (Akpan *et al.* 2016; Onyia *et al.* 2020). This contrasting finding might be due to the different species of eggplant and accessions used in the experiment.

The estimation of the GCV showed a low to high value, indicated by days to 50% flowering and fruit weight, respectively. In this study, high GCV values were obtained in fruit weight and yield per plant, indicating that there was considerable genetic variations in both traits that could be used in the future selection to produce better eggplant cultivars, especially in terms of yield improvement. Meanwhile, the lowest GCV was recorded by days to 50% flowering, indicating a limited genetic selection and that the trait phenotypic expression was highly influenced by the environment. The PCV also recorded a low to high value, with the highest value indicated by fruit weight. The selection based on high value of PCV, such as in fruit weight and yield per plant indicates a greater potential is expected in the selection of this traits, depending on the amount of variability present (Kumar *et al.* 2020). The value between GCV and PCV obtained from this study had low difference, indicating that the vegetative traits were not highly affected by the environmental factors, and successful selection could be achieved based on the phenotypic values. These findings were corroborated by the previous studies which observed a slight value difference between GCV and PCV for vegetative traits in eggplants (Kumar *et al.* 2020; Sulaiman *et al.* 2020). Higher PCV values compared to GCV values for all vegetative and yield traits in this study also indicated the existence of environmental influence on the phenotypic traits. These small differences between PCV and GCV values proposing the governance of genetic factors. Hence, the direct selection on a phenotypic basis would be effective in plant breeding as that trait are mainly influenced by the genetic factors instead of the environmental factors. This finding shows the importance of adaptive capacity to the environment for future crop breeding program. Other researchers also previously reported the higher values of GCV, PCV and heritability for yield per plant and its related traits in *Solanum* species, conforming the results obtained in these studies (Madhukar *et al.* 2015; Yadav *et al.* 2016).

Heritability is one of the important genetic components where the proportion of phenotypic traits or total variance is inherited down to the progeny (Oladosu *et al*. 2014). A higher range of high broad-sense heritability was observed for all vegetative and yield component traits, with the highest value indicated by plant height (PH). High broad-sense heritability (h^2_B) values also ensure the success of a breeding program through the selection of most-consistent parental accessions (Sulaiman *et al.* 2020). Yield per plant and its components (number of fruits, fruit weight, fruit length and fruit girth) in this study showed a high value of broad-sense heritability and genetic advance (GA), suggesting that a direct selection for both traits may produce a significant improvement in plant vegetative and yield per plant. This finding also suggests an additive type of genes action that controls the yield and its components. Therefore, a higher GA and broad-sense heritabilityvalues, especially for yield and its components are desired by plant breeders because direct selection of these traits can be affiliated without being discomposed by the environmental effects. The results obtained are in accordance with previous studies (Kumar *et al.* 2013; Sulaiman *et al.* 2020). A lower heritability values and genetic advance were indicated by days to 50% flowering, stem diameter and number of primary branches, with the action of non-additive genes being involved in these traits (Akpan *et al.* 2016). Based on the overall genetic analysis, plant height, fruit weight, fruit length, fruit girth and yield per plant showed a higher value compared to other traits. These traits have the potential to be manipulated over other traits for an eggplant improvement program especially on yield and its components.

The cluster analysis grouped the individual eggplant accessions based on similarity and affiliation on the basis of vegetative, yield and its components. In this study, the results of clustering analysis clearly grouped the 20 eggplant accessions into four clusters, with a similarity coefficient of 0.35. The wide diversity in eggplant due to the origins and morphological traits has been previously reported by many researchers (Hanifah *et al.* 2018; Ahmed *et al.* 2019; Kaushik 2020). Among these four clusters, cluster IV was the most important cluster because this cluster was associated with the highest mean of fruit weight, fruit girth and yield per plant. According to the cluster grouping, it is suggested that a cross between group I and IV would obtain a higher heterosis and vigour progeny based on wide differences between these two groups in terms of vegetative and yield performance.

Susceptibility analysis of 20 eggplant (*Solanum* spp.) accessions against *M. incognita* infection suggested that there was a potential resistance trait within the local germplasm. Previous studies have reported that resistance was correlated with nematode reproduction, with a low nematode reproduction compared to the most susceptible genotype indicating a highly resistant response (less 10%), a moderately resistant showing intermediate levels of nematode eggs (less 50%) and susceptible accessions having more than 50% eggs per gram root (Hadisoeganda and Sasser 1982; Hussey and Janssen 2002). Contrary to eggs per gram root, the gall index was not positively correlated with higher nematode population. Our finding showed that higher gall index did not always reflect higher eggs per gram root as reported in previous study (Aydinli *et al.* 2019). From the 20 eggplant accessions, only *S. torvum* accession was not affected by RKN infestation and was designated as immune, being concordant with previous reports by other researchers (Bagnaresi *et al.* 2013; Uehara *et al.* 2017; Okorley *et al.* 2018).

Six accessions were resistant to RKN, with accession DINO 03-0200 and DINO 03-0056 showing high resistance. Previous study has shown that the resistant genotypes were able to suppress the reproduction rate of *Meloidogyne* spp. with improved growth performance in eggplant (Aydinli *et al.* 2019). These resistant plants might react to the *Meloidogyne* sp. infection through prevention or limitation of root penetration to juvenile nematodes, with physical root tissue barriers and biochemical secretions may be involved in these resistance mechanisms (Ali *et al.* 2015). Studies have shown that *M. incognita* infection can induce gall symptoms on the root system of most Malaysia eggplant accessions. Susceptible eggplant accessions have been reported with high nematode reproduction, root galling and plant growth reduction (Shah *et al.* 2018; Sarven *et al.* 2019). This susceptible plant encourages nematode feeding activities that induce gall formation on the roots of eggplant, where it will prevent further growth and elongation of the root and hence, infected plant produces scanty roots (Ali *et al.* 2015).

Conclusion

Information of the genetic performance in local eggplant germplasm is important to select future parents for eggplant variety improvement. The 20 studied eggplant (*Solanum* spp.) accessions varied in terms of their morphology, yield performance and susceptibility against *M. incognita* infection. The genetic variance of traits studied such as fruit weight, number of fruits per plant, fruit length and yield per plant can be manipulated through direct selection based on the estimation of high broad-sense heritability and genetic advance values. Based on the performance of eggplant accession individually on morphology and yield traits, MTe-01 and MTe-02 from cluster IV can be considered as the potential parents in developing new eggplant cultivars with greater yield production. Meanwhile, two accessions from cluster I (NTH 08-0024 and NTH 08-0041) and two accessions from cluster IV (DINO 03-0056 and DINO 03-0200) have the potential as resistant cultivars in *M. incognita* management, and they can be utilized for breeding programs. High-yielding and RKN-resistant accession DINO 03-0056 is also recommended to be used as parental line in eggplant breeding programs for simultaneous improvement of yield and RKN resistance.

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Author Contributions

MNA, TS and NAAS planned the experiments, MNA, NAB and FHSS performed the experiment, MNA, TS and NAAS interpreted the results, MNA, TS and NAAS made the write up and statistically analyzed the data and made illustrations.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Data Availability

The data will be made available on acceptable requests to the corresponding author.

Ethics Approval

Not applicable.

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