



RESEARCH ARTICLE

Genetic variability, trait association and multivariate analysis for yield improvement in bottle gourd (*Lagenaria siceraria* (Molina) Standl.)

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Abstract

The present study evaluated 30 diverse bottle gourd genotypes during rabi 2023–24 at Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh. The trial was laid out in a randomised block design (RBD) with 3 replications and the observations were analysed using analysis of variance, genetic variability, correlation and path coefficient to assess genetic diversity and trait interrelationships influencing yield. Highly significant differences among genotypes for all studied traits revealed substantial inherent variability, providing a strong basis for selection. The genotypes, 2021/BOGVAR-8 and 2021/BOGVAR-6, exhibited superior performance with earliness, desirable fruit traits and high yield potential. The standard checks, Pusa Naveen and Kashi Kirti, also showed a good yield pattern and were used as standards. The first two principal components explained a large percentage of the variation, with yield being related to fruit length (FL), fruit girth (FG), average fruit weight (AFW), number of fruits per plant (NFPP) and branching behaviour. Earliness traits were negatively correlated with yield, indicating a trade-off between early maturity and productivity. Genetic parameter estimates showed high heritability (h^2) with large genetic gain (GA) for important traits contributing to yield, suggesting that the additive effects of genes were predominant. Correlation matrix and path coefficient analysis also revealed that the number of branches per plant (NBPP), fruit weight (FW) and fruit size traits were major determinants of yield with both direct and indirect effects. The integrated application of multivariate and genetic analyses enabled efficient identification of elite genotypes and key yield-associated traits. The identified superior genotypes may be further exploited in hybridisation and selection programmes for yield enhancement.

Keywords: bottle gourd; genetic variability; yield improvement

Introduction

Bottle gourd (*Lagenaria siceraria* (Molina) Standl.) is an important tropical and subtropical cucurbit crop with high nutritional, medicinal and economic value (1). In India, it is an essential part of diversified vegetable farming as it is adaptable, has a short duration and can be grown throughout the year. Recent national agricultural data highlight its growing footprint, with India recording approximately 251000 ha under bottle gourd cultivation, yielding about 4.27 million metric tonnes annually (2). Although bottle gourd is widely cultivated, it has a relatively low productivity, mainly due to the lack of high yielding, early maturing and genetically stable cultivars (3). While contemporary research trends in other major cucurbits have progressed rapidly into advanced multi-omic and high-quality telomere-to-telomere (T2T) genomic assemblies, genetic improvement programs for bottle gourd remain heavily bottlenecked. There is a prominent research gap regarding standardised phenotypic characterisation and a clear mapping of the inheritance of complex agronomic traits (4). This lack of a robust genetic roadmap hampers targeted ideotype breeding. Addressing this serious limitation requires a thorough and urgent investigation into the genetic basis of yield and its component traits to accelerate the development of next-generation, high-performing cultivars.

Bottle gourd yield is a complex polygenic characteristic which is influenced by several interrelated characters such as flowering behaviour, fruit size, fruit number and vegetative growth (5, 6). The efficiency of selection for such traits is closely related to the size of the genetic variability and the relative importance of additive and non-additive gene effects (7). Estimates of genotypic coefficient of variation (GCV) and phenotypic coefficients of variation (PCV), heritability (h^2) and genetic advance (GA) provide critical insights into the nature of variability and the potential response to selection (8). In addition, correlation analysis clarifies the direction and intensity of the relationship between traits and path coefficient analysis can decompose the relationship into direct and indirect effects, which can help to identify the traits that play a key role in yield (9). Assessment of genetic divergence among genotypes is important for identifying diverse parents capable of producing superior recombinants. Cluster analysis classifies genotypes into distinct groups and aids in selecting diverse parents for hybridisation programmes (10).

Although several studies have examined variability in bottle gourd, comprehensive integration of multivariate analysis, trait association and yield component analysis across diverse breeding lines remains limited. The present study was conducted with the objective of (i) quantifying genetic variability for yield and

related traits; (ii) evaluating trait associations through correlation and path coefficient analyses; (iii) assessing genetic divergence for identification of diverse parental lines; and (iv) identifying superior genotypes for yield and earliness. The findings provide a scientific basis for selection and hybridisation programmes and help in developing bottle gourd varieties with high yield and early maturity.

Materials and Methods

Experimental site and agro-climatic conditions

This experiment was carried out during the rabi season of (2023–24) at the Horticultural Research- cum- Instructional Farm of Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh, India. The experimental material comprised 30 bottle gourd genotypes, including advanced breeding lines, local collections and standard check varieties. The genotypes included lines from the 2018, 2019 and 2021 breeding series along with the standard checks Pusa Naveen, Kashi Kirti, Narendra Prabha and Narendra Pooja-3.

Field layout and experimental design

The field evaluation was established utilising a randomised block design (RBD). The entire layout was divided into 3 distinct replications to minimise experimental error and accommodate soil heterogeneity gradients across the site. Each plot covered an area of 27 m² with a spacing of 3.0 m between rows and 0.75 m between plants. Standard cultivation practices recommended for bottle gourd were followed to raise a healthy crop. Observations were recorded on five randomly selected plants from each plot for traits related to growth, flowering and yield.

Agronomic practices and crop management

A comprehensive nutritional programme was adopted based on regional packages of practices for cucurbitaceous crops in Chhattisgarh. Well-decomposed farm yard manure (FYM) was applied uniformly at the rate of 15 tonnes/ha during preparatory tillage as a basal organic matrix. The inorganic chemical fertiliser schedule comprised a total dose of 100 : 60 : 60 kg/ha of N : P₂O₅ : K₂O, applied in split doses. Given that the trial was conducted during the dry rabi season, irrigation water application was closely regulated. Irrigation was carried out immediately after sowing to ensure uniform moisture availability for optimal germination. Subsequent irrigations were given at regular intervals of 8–10 days. Poly mulching was done to suppress weed growth. Manual weeding was recommended and carried out across all treatments at 20-day intervals, starting from the day of planting. No plant protection interventions were carried out.

Phenotypic observations and data collection

Observations were recorded systematically from selected plants in each plot across distinct developmental phases. Floral and phenological traits such as days to first male flower (DTFMF), days to first female flower (DTFFF), node number of first male flower (NNFM) and node number of first female flower (NNFF) were recorded. Days to 50 % flowering (DT50F) were recorded when half of the plot reached flowering. Days to first fruit set (DTFFS), days to first fruit harvest (DFFH) and the growth and yield-related parameters, viz., number of branches per plant (NBPP), were counted manually; vine length (VL, cm) and fruit length (FL, cm) were measured using a ruler and the fruit girth (FG, cm) was recorded using a Vernier caliper. Average fruit weight (AFW, g), number of fruits per plant (NFPP), total duration of crop (DOC)

from sowing to harvest (days) and total fruit yield (q/ha) were recorded based on plot area and total harvested weight using the following formula:

Statistical and biometrical analysis

$$\text{Fruit yield (q/ha)} = \frac{\text{Weight of fruit (kg/plot)}}{\text{Net plot area (sq. m)}} \times \frac{1000}{100}$$

The significance of differences between the experimental treatments was calculated using the standard analysis of variance (ANOVA) technique. To evaluate the potential for targeted selection, essential genetic parameters such as GCV, PCV, broad-sense h² and GA were calculated following established biometrical protocols (11, 12). Furthermore, correlation analysis was performed to examine associations among traits (13) and path coefficient analysis was performed to decompose the correlation into direct and indirect effects of traits on yield (6, 14). R software was used for plotting graphs.

Results and Discussion

Genotypic performance for yield and component traits

The mean performance of the genotypes was highly significant in all the traits studied (Table 1), showing a high degree of variability in flowering, growth and yield-related characters. The breeding line 2021/BOGVAR-6 exhibited the earliest flowering of male flowers (26.87 days) and breeding line 2021/BOGVAR-8 exhibited the earliest flowering of female flowers (29.08 days) and lower NNFF (13.57). The standard variety Pusa Naveen had comparatively delayed male flowering (38.79 days) and female flowering (49.13 days), indicating the breeding lines from 2021 had valuable genetic potential for early flowering. Also, 2021/BOGVAR-8 resulted in shorter vines (105.20 cm) and shorter crop duration (134.93 days) but significantly increased early flowering and faster fruit set (35.35 days), which means better reproductive efficiency with moderate vegetative development. Considerable variation was also observed for plant architecture and fruit traits. The cultivar Pusa Naveen had the maximum primary branches per plant (11.14), indicating strong vegetative growth. The AFW was observed with a wide range of variation and a mean of 673.43 g among all the traits. The genotype 2021/BOGVAR-8 showed the highest AFW with 1389.08 g, which indicated its superior sink strength and it also had a higher NFPP (11.54), indicating efficient partitioning of assimilates towards fruit development. The same genotype also resulted in desirable fruit size, as FL (39.61 cm) and FG (50.01 cm) were found to be in the better range of Pusa Naveen, making it a promising genotype for fruit improvement programmes. Similar variability for FL, fruit size and yield has also been reported in melon and other cucurbit crops, emphasising the importance of these characters in genotype selection and hybrid development. The study highlights that the genotypes 2021/BOGVAR-8 and 2021/BOGVAR-6 suggest successful accumulation of favourable alleles governing earliness and yield traits. Its phenological characteristics, such as the parameter, days to flowering and maturity, are also highly correlated with yield and can be effectively selected (15). The other two genotypes, 2021/BOGVAR-5 and 2021/BOGVAR-7, had good yields because their fruit quality was good, while the yields of the other two genotypes, 2021/BOGVAR-2 and 2019/BOGVAR-4, were poor. Fruit length, fruit size and yield of melon genotypes were highly variable,

Table 1. Mean performance of genotypes for yield and component traits

Genotypes	DTFMF	DTFFF	NNFM	NNFF	DT50F	DTFFS	DTFFH	FL	FG	AFW	NFFP	NBPP	DOC	VL	YQ
2018/BOGVAR-1	37.61	47.22	15.75	18.19	44.33	48.14	52.63	22.27	20.03	475.09	6.99	4.27	145.29	134.32	182.43
2018/BOGVAR-2	34.95	43.75	14.61	16.92	41.14	44.87	49.04	20.91	18.54	488.38	6.52	3.97	136.47	125.41	169.77
2018/BOGVAR-3	40.27	50.69	16.89	19.46	47.52	51.41	56.22	23.63	21.52	517.62	7.46	4.57	154.11	143.23	195.09
2018/BOGVAR-4	32.72	39.11	14.33	16.56	40.25	44.52	47.43	25.05	13.77	438.08	6.87	4.01	135.27	126.24	169.49
2018/BOGVAR-5	37.70	45.31	16.57	19.04	46.49	51.00	54.37	28.29	15.99	473.45	7.85	4.63	152.75	144.16	194.77
2018/BOGVAR-6	35.21	42.21	15.45	17.80	43.37	47.76	50.90	26.67	14.88	447.02	7.36	4.32	144.01	135.20	182.13
2018/BOGVAR-7	35.08	43.27	14.65	16.89	40.63	44.24	49.87	14.30	28.29	594.46	5.67	3.56	136.59	130.13	170.97
2019/BOGVAR-1	37.75	46.70	15.80	18.16	43.78	47.46	53.52	15.23	30.57	577.49	6.07	3.83	145.42	139.37	183.71
2019/BOGVAR-2	40.42	50.13	16.95	19.43	46.93	50.68	57.17	16.16	32.85	624.87	6.47	4.10	154.25	148.61	196.46
2019/BOGVAR-3	40.20	50.44	16.56	18.72	44.57	49.41	53.12	18.14	18.43	493.42	7.61	4.62	155.69	146.41	183.13
2019/BOGVAR-4	34.88	43.54	14.32	16.28	38.59	43.13	46.34	16.06	16.20	459.84	6.65	4.00	137.87	128.21	159.36
2019/BOGVAR-5	37.54	46.99	15.44	17.50	41.58	46.27	49.73	17.43	17.15	483.42	7.13	4.31	146.78	137.31	171.25
2019/BOGVAR-6	36.59	44.42	14.73	18.11	43.31	48.05	51.26	17.95	23.33	546.83	6.13	4.42	145.03	134.81	192.14
2019/BOGVAR-7	34.00	41.16	13.66	16.85	40.19	44.79	47.76	16.86	21.59	520.94	5.72	4.11	136.23	125.87	178.80
2019/BOGVAR-8	39.18	47.68	15.80	19.37	46.43	51.31	54.76	19.04	25.07	564.05	6.54	4.73	153.83	143.75	205.47
2019/BOGVAR-9	33.30	42.29	13.19	16.82	40.60	46.16	48.73	20.28	21.23	507.00	6.94	4.06	136.62	124.78	181.73
Local-1	38.38	48.99	15.25	19.34	46.90	52.88	55.87	22.92	24.65	549.83	7.94	4.68	154.28	142.50	208.83
2021/BOGVAR-1	35.84	45.64	14.22	18.08	43.75	49.52	52.30	21.60	22.94	522.17	7.44	4.37	145.45	133.64	195.28
2021/BOGVAR-2	35.18	42.81	12.96	16.02	37.56	41.50	44.52	15.74	15.55	450.48	6.80	3.50	136.03	125.79	160.22
2021/BOGVAR-3	29.15	36.82	9.47	17.02	37.28	42.78	53.14	24.18	44.19	1029.14	9.84	7.70	128.01	163.18	227.78
2021/BOGVAR-4	35.90	43.68	13.22	16.35	38.33	42.35	45.43	16.06	15.87	469.22	6.94	3.57	138.81	128.36	163.49
2021/BOGVAR-5	33.90	37.58	12.95	19.37	38.77	44.07	54.06	22.17	35.94	909.23	9.66	7.11	140.65	156.83	222.74
2021/BOGVAR-6	26.87	34.48	9.70	16.61	35.20	42.11	50.75	27.52	45.31	1145.83	9.98	8.59	116.84	164.27	259.22
2021/BOGVAR-7	29.65	37.61	9.47	17.11	38.00	42.77	53.77	22.96	38.74	941.96	8.87	6.81	134.93	160.62	223.19
2021/BOGVAR-8	26.90	29.08	8.20	13.57	30.09	35.35	44.22	39.61	50.01	1389.08	11.54	8.63	105.20	163.95	278.89
2021/BOGVAR-9	36.28	38.10	14.87	18.91	41.96	47.37	56.09	14.77	34.96	811.10	8.89	6.19	145.54	143.11	218.04
Pusa Naveen	25.72	30.88	11.65	12.50	31.69	37.76	45.36	38.79	49.13	1159.98	11.51	11.14	120.76	172.93	306.52
Kashi Kirti	28.86	31.61	12.30	17.60	35.07	39.03	47.63	37.00	40.18	1024.67	11.19	10.54	128.13	162.24	304.52
Narendra Prabha	37.98	40.22	15.55	22.93	41.85	45.37	66.21	25.50	33.56	643.32	10.62	9.48	138.36	152.53	289.82
Narendra Pooja-3	31.74	36.54	13.31	17.39	37.24	39.42	53.88	29.69	38.88	945.04	11.09	10.04	147.48	156.17	297.00
Mean	34.66	41.96	13.93	17.63	40.78	45.38	51.54	22.56	27.65	673.43	8.01	5.66	139.89	143.13	209.07
SE (m)	1.36	1.53	0.55	0.67	1.49	1.71	1.78	0.91	1.02	26.85	0.29	0.22	4.63	5.01	7.15
CD 5 %	3.85	4.33	1.55	1.90	4.23	4.84	5.03	2.58	2.90	76.02	0.82	0.61	13.10	14.17	20.25
CV (%)	6.80	6.32	6.82	6.59	6.35	6.53	5.97	6.99	6.41	6.91	6.25	6.60	5.73	6.06	5.93

1.DTFMF: Days to first male flower, 2.DTFFF: Days to first female flower, 3.NNFM: Node number of first male flower, 4.NNFF: Node number of first female flower, 5.DT50F: Days to 50 % flowering, 6.DTFFS: Days to first fruit set, 7.DFFH: Days to first fruit harvest, 8.FL: Fruit length, 9.FG: Fruit girth, 10.AFW: Average fruit weight, 11.NFFP: Number of fruits per plant, 12.NBPP: Number of branches per plant (90 days), 13.DOC: Duration of crop (Sowing to harvest), 14.VL: Vine length (cm), 15.YQ: Yield per plot (q/ha).

highlighting the significance of these traits in genotype selection and development of hybrids (16). The results are bolstered by the superior performance of the standard checks used, Pusa Naveen and Kashi Kirti. Yield and its component traits exhibit considerable variation and can be used as good selection indices, especially when traits such as fruit weight (FW) and number have a direct contribution to yield (17) (Fig. 1).

Genotypic variation and analysis of variance

Analysis of variance showed that all the traits analysed were highly significant of the differences among the genotypes (Table 2). The mean squares of treatments were significant, thereby showing that there was a high genetic variability. The DTFMF appearance, DTFFF, NNFM, NNFF, DT50 % flowering, DTFFS and DTFFH were significantly different among the genotypes for phenological traits. This indicates a variability of flowering habit and fruit formation. There were highly significant treatment differences for FL (cm), FG (cm) and AFW (g), indicating high variation among the fruits in terms of their morphology and size. Other yield-contributing traits like NFPP, NBPP at 90 days, VL (cm) and yield/plot (YQ, q/ha) also presented significant differences and indicated the selection of superior genotypes. The growth cycle or crop duration in days and maturity period were significantly affected by the genotype, showing the crop duration variability. The large range for YQ and the large average FW range indicated that these traits accounted for much of the difference in yield among genotypes. The observed variability suggests good potential for selection and genetic improvement in bottle gourd. This variability is necessary to good selection and crop improvement (18). An extensive range of variations existing for various quantitative traits has also been reported in bottle gourd by various workers (15, 16, 19, 20)

Genetic variability, heritability and genetic advance

The range of the estimated genetic parameters indicated a considerable variability between these yield components (Fig. 2), which are a suitable basis for efficient selection. The PCV was slightly larger than the GCV for all traits, suggesting a relatively low environmental effect and that the observed variation is mostly under genetic control. The FL, FG, AFW, NFPP, NBPP (90 days) and YQ showed high GCV and PCV values (> 20 %), indicating high variability among the plants for these economically important traits. The FG, AFW and branching behaviour were exceptional in having high h^2 (95 % or higher) and high genetic advance (GA) as percent of the mean (79 % or higher), suggesting that most of the

genes for these traits are additive and that direct selection for these traits would be very effective in yield improvement. The DTFMF, DTFFF, NNFM, NNFF and DT50F showed moderate variability (10–20 %). Heritability for these traits was also high (70 % or more) and GA was moderate to high, suggesting that they are genetically highly controllable and have moderate to high potential for selection gain, but progress may be relatively slower than highly variable traits. Low variability (< 10 %) was found for DTFFS, DTFFH, DOC and VL. Though the GCV and PCV were relatively low, moderate to high h^2 (64–70 %) and comparatively low GA indicated the existence of non-additive gene effect(s) and/or relatively high environmental effect(s) which constrained the efficiency of simple phenotypic selection. The YQ was highly heritable (92.87 %) and highly genetically advanced (42.45 %) with significant variability, suggesting that yield improvement could be made successfully in this crop by selecting on the many component traits which are highly associated with yield, including fruit size and fruit number. In conclusion, high variability, high h^2 and high GA for important yield-contributing traits suggest that they can serve as good selection indices for the development of high-yielding bottle gourd varieties. The observed trend of PCV being slightly higher than GCV suggests that the environment had a lesser effect and more genetic control. The small difference between PCV and GCV for all traits in bottle gourd indicated the high genetic control of the expression of these traits and their reliability for selection (21). High GCV and PCV for yield and its component traits (fruit size, fruit number, branches and yield) suggest a considerable amount of variability. There is high variability for fruit yield, no. of fruits, VL and branching characteristics, which highlights the significance of selection in bottle gourd improvement (22). High h^2 and GA for some traits (such as FG, FW and branches) indicate that additive gene action predominates. The h^2 values for fruit yield, AFW, NFPP and branching traits were high, accompanied by high GA, suggesting that these traits could be improved by direct selection (23). Yield of fruit is positively correlated with the number of fruit, branches and AFW, which also correlates with your finding that these are important yield-determining traits (24). Moderate variation in the flowering traits and low variation in maturity traits is consistent with the observations made in bottle gourd. These findings support direct selection for major yield-contributing traits in bottle gourd breeding (25).

Table 2. Analysis of variance (ANOVA) for growth, flowering, yield and yield-related traits of bottle gourd (*Lagenaria siceraria*) genotypes

Character	Source of variation		
	Replication	Treatment	Error
	Df = 2	Df = 29	Df = 58
Days to first male flower	28.42	50.99**	5.57
Days to first female flower	32.40	81.87**	17.28
Node number of first male flower	11.05	12.29**	2.55
Node number of first female flower	6.08	10.61**	1.35
Days to 50 % flowering	10.60	4.50**	4.25
Days to first fruit Set	44.62	37.82**	17.61
Days to first fruit harvest	111.50	21.82**	28.09
Fruit length	104.38	91.12**	25.30
Fruit girth	121.42	319.75**	23.86
Average fruit weight	203784.45	347943.01**	56423.23
No. of fruits per plant	3.06	8.87**	0.77
No. of branches per plant (90 days)	5.71	14.08**	1.15
Duration of crop (sowing to harvest)	577.36	238.37**	141.79
Vine length (cm)	740.63	438.03**	141.19
Yield per plot (q/ha)	2462.67	5271.17**	519.91

Df: degrees of freedom.



1



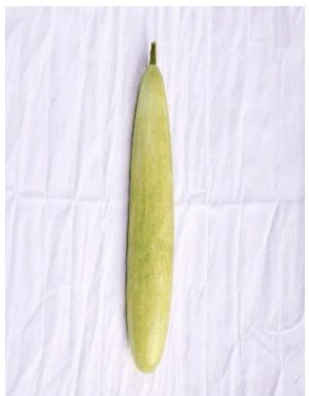
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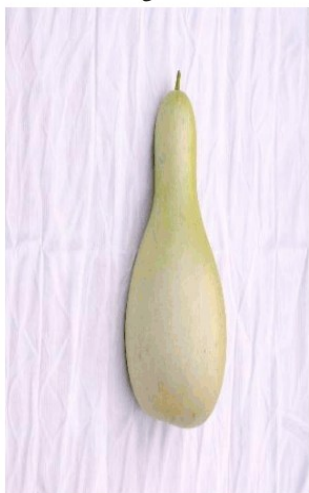
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8



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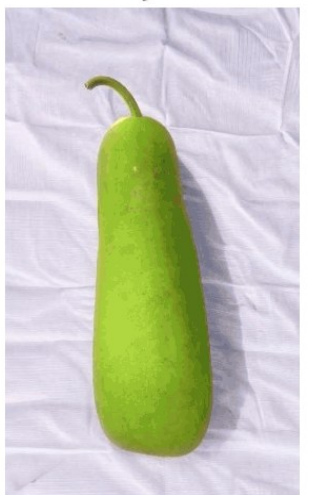
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11



12



13



14



15



16

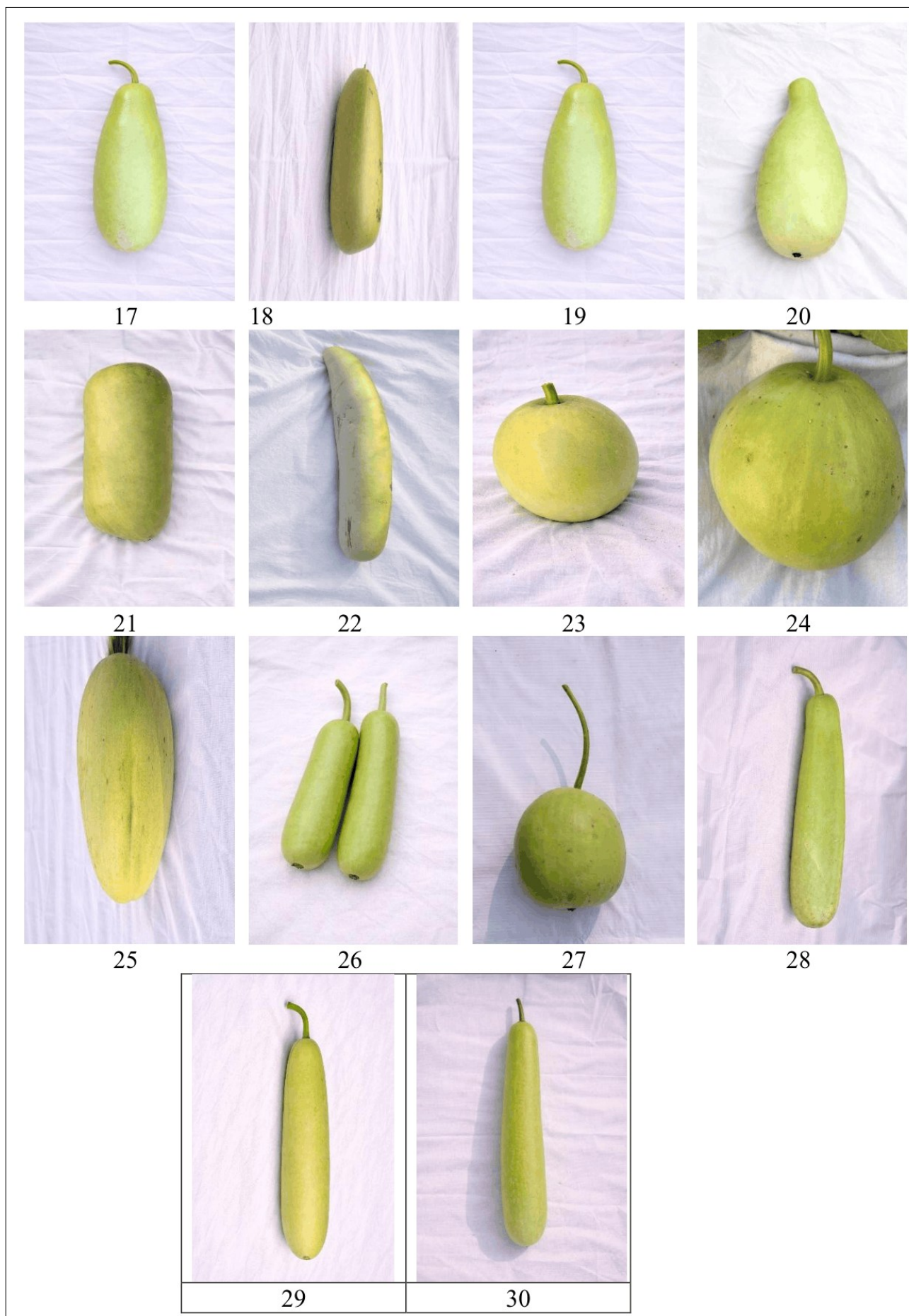


Fig. 1. Bottle gourd (*Lagenaria siceraria*) genotypes evaluated in the present study. 1. 2018/BOGVAR-1; 2. 2018/BOGVAR-2; 3. 2018/BOGVAR-3; 4. 2018/BOGVAR-4; 5. 2018/BOGVAR-5; 6. 2018/BOGVAR-6; 7. 2018/BOGVAR-7; 8. 2019/BOGVAR-1; 9. 2019/BOGVAR-2; 10. 2019/BOGVAR-3; 11. 2019/BOGVAR-4; 12. 2019/BOGVAR-5; 13. 2019/BOGVAR-6; 14. 2019/BOGVAR-7; 15. 2019/BOGVAR-8; 16. 2019/BOGVAR-9; 17. Local-1; 18. 2021/BOGVAR-1; 19. 2021/BOGVAR-2; 20. 2021/BOGVAR-3; 21. 2021/BOGVAR-4; 22. 2021/BOGVAR-5; 23. 2021/BOGVAR-6; 24. 2021/BOGVAR-7; 25. 2021/BOGVAR-8; 26. 2021/BOGVAR-9; 27. Pusa Naveen; 28. Kashi Kirti; 29. Narendra Prabha; 30. Narendra Pooja-3.

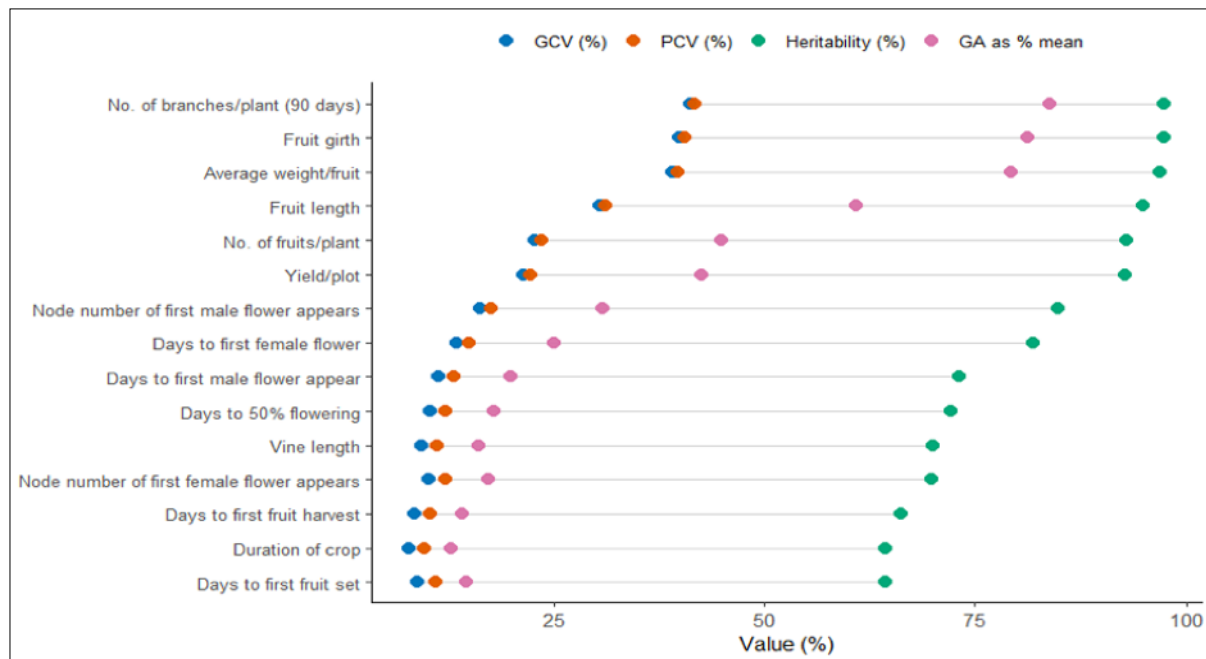


Fig. 2. Genetic parameters of variability for yield and its component characters.

Genotypic and phenotypic correlation coefficient matrix between yield and its component characters

Correlation analysis between the genotypic and phenotypic data revealed that YQ showed a significant positive correlation with NFPP, AFW, FG, FL, DTFFH and DOC, suggesting that these traits are the most important components of yield (Table 3). The negative association of yield with DTFMF, DTFFF, NNFM, DT50F, NBPP and DTFFS underscores the importance of earliness to maximise productivity. Earliness-related characters had a positive correlation with each other, while yield-related and fruit-related

characters had negative and positive correlations, respectively, with each other, indicating their involvement in yield. There was a positive correlation between DOC and flowering and fruiting characteristics, while most yield components were negatively correlated, especially at the genotypic level. Generally, genotypic correlations were more positive than phenotypic correlations, suggesting that the genetic aspects play a major role in determining these associations. The overall results showed that the NFPP, AFW, FG and FL were positively and highly correlated to yield, indicating that these are important factors affecting yield.

Table 3. Genotypic and phenotypic correlation coefficient matrix between yield and its component characters

Character		DTFMF	DTFFF	NNFM	NNFF	DT50F	DTFFS	DFFH	FL	FG	AFW	NFPP	NBPP	DOC	VL	YQ
DTFMF	G	1.000	0.920**	0.907**	0.677**	0.901**	0.831**	0.437**	-0.752**	-0.747**	-0.850**	-0.754**	-0.749**	0.880**	-0.743**	-0.683**
	P	1.000	0.929**	0.913**	0.762**	0.922**	0.873**	0.596**	-0.521**	-0.561**	-0.714**	-0.495**	-0.563**	0.904**	-0.263*	-0.438**
DTFFF	G		1.000	0.809**	0.493**	0.895**	0.861**	0.278**	-0.756**	-0.773**	-0.867**	-0.850**	-0.840**	0.845**	-0.753**	-0.790**
	P		1.000	0.840**	0.606**	0.912**	0.879**	0.450**	-0.578**	-0.631**	-0.767**	-0.634**	-0.691**	0.866**	-0.342**	-0.582**
NNFM	G			1.000	0.597**	0.858**	0.781**	0.388**	-0.539**	-0.711**	-0.817**	-0.651**	-0.598**	0.864**	-0.661**	-0.533**
	P			1.000	0.672**	0.876**	0.808**	0.513**	-0.403**	-0.593**	-0.738**	-0.481**	-0.490**	0.868**	-0.303**	-0.377**
NNFF	G				1.000	0.703**	0.648**	0.869**	-0.430**	-0.292**	-0.436**	-0.240*	-0.207	0.641**	-0.252*	-0.150
	P				1.000	0.788**	0.761**	0.909**	-0.234*	-0.164	-0.352**	-0.054	-0.093	0.756**	0.119	0.018
DT50F	G					1.000	0.974**	0.531**	-0.635**	-0.677**	-0.797**	-0.739**	-0.713**	0.895**	-0.650**	-0.633**
	P					1.000	0.979**	0.672**	-0.414**	-0.493**	-0.659**	-0.470**	-0.523**	0.924**	-0.178	-0.385**
DTFFS	G						1.000	0.493**	-0.628**	-0.643**	-0.751**	-0.729**	-0.715**	0.823**	-0.624**	-0.642**
	P						1.000	0.667**	-0.365**	-0.425**	-0.585**	-0.411**	-0.482**	0.885**	-0.098	-0.346**
DFFH	G							1.000	-0.217*	0.073	-0.115	0.037	0.083	0.455**	0.099	0.145
	P							1.000	-0.048	0.144	-0.081	0.180	0.152	0.644**	0.384**	0.264*
FL	G								1.000	0.570**	0.694**	0.808**	0.779**	-0.668**	0.692**	0.787**
	P								1.000	0.581**	0.675**	0.817**	0.784**	-0.395**	0.684**	0.798**
FG	G									1.000	0.960**	0.790**	0.836**	-0.684**	0.912**	0.840**
	P									1.000	0.941**	0.792**	0.840**	-0.456**	0.836**	0.841**
AFW	G										1.000	0.860**	0.855**	-0.783**	0.931**	0.836**
	P										1.000	0.827**	0.839**	-0.608**	0.784**	0.804**
NFPP	G											1.000	0.956**	-0.653**	0.873**	0.924**
	P											1.000	0.951**	-0.351**	0.848**	0.929**
NBPP	G												1.000	-0.621**	0.898**	0.977**
	P												1.000	-0.405**	0.825**	0.972**
DOC	G													1.000	-0.621**	-0.575**
	P													1.000	-0.093	-0.291**
VL	G														1.000	0.869**
	P														1.000	0.845**
YQ	G															1.000
	P															1.000

1.DTFMF: days to first male flower; 2.DTFFF: days to first female flower; 3.NNFM: node number of first male flower; 4.NNFF: node number of first female flower; 5.DT50F: days to 50 % flowering; 6. DTFFS: days to first fruit set; 7.DFFH: days to first fruit harvest; 8. FL: fruit length; 9.FG: fruit girth; 10.AFW: average fruit weight; 11.NFPP: number of fruits per plant; 12.NBPP: number of branches per plant (90 days); 13.DOC: duration of crop (sowing to harvest); 14.VL: vine length (cm); 15.YQ: yield per plot (q/ha).

The number of fruits, branches and FW were found to be positively correlated with the fruit yield, indicating their importance as selection traits (24). Negative correlation between yield and earliness traits suggests a trade-off between rapid maturity and productivity. Phenological traits are interrelated and can have inverse correlations with yield under specific conditions (26). The genotypic correlations are stronger than the phenotypic correlations, suggesting a high genetic component to these relationships and a low environmental component. Genotypic correlations are generally higher, indicating the true genetic relationship among the traits (26).

Path analysis

To gain insight into the nature of these associations, the genotypic correlation was divided into direct effects and indirect effects (Fig. 3) and analysed using path coefficient analysis. The residual was very small (0.01), indicating that the variation in yield was well explained by the characters used in the analysis. Results showed that the NBPP had the greatest positive direct effect on yield, followed by FW and DOC, indicating that these factors played a major role in determining yield. The FL was also a positive contributor with a moderate direct effect. The two positive strong correlation parameters, NFPP and VL, had a negative direct effect on yield, implying that these are important indirect factors in terms of other traits with a positive effect on yield, such as NBPP and fruit-related characters. Likewise, the earliness characteristics were negatively correlated with yield, though they were minor in direct effects, indicating that they are mostly indirect. The indirect effects further highlighted that the number of branches per plant played a central role, contributing positively to yield through AFW, FL and FG, as well as NFPP. There was also a high association between FG and AFW, which also confirmed the yield improvement. Earliness traits, on the other hand, had a negative contribution due to the negative effects on fruit and branching traits. As per correlation and path analysis, the fruit size traits, NFPP and branching behaviour are the key traits that control the yield of bottle gourd, with earliness being an important supportive trait. Therefore, the selection procedure should be based on genotype combinations that flower early, produce a high number of fruits, have superior fruit size and possess a high-yielding

branching pattern. These relationships in terms of direct and indirect effects. The result revealed that NBPP, AFW and DOC had the most dominant direct positive effect on the yield; hence, they are the most important factors. The weight of fruit, fruit number and branching characteristics had significant direct and indirect effects on yield (23). The NFPP and VL were interesting traits as they had high positive intra-dependencies but a negative direct effect on yield, meaning that these traits exerted an indirect effect through other traits. Similar observations have been reported in bottle gourd, where yield was influenced by indirect effects of several characters, including node number to staminate and pistillate flower anthesis, days to first pistillate/staminate flower anthesis and VL (26). Branching behaviour, fruit size and fruit number emerged as key determinants of yield improvement in bottle gourd.

Multivariate structure of trait variation

The variability among the genotypes was effectively partitioned by principal component analysis (PCA); PC1 accounted for 66.9 % of the total variation and PC2 accounted for 20.6 % of the total variation. The sum of the two explained 87.5 % of the total variability, which was a good representation of the genotype–trait associations (Fig. 4). The trait loading pattern showed that PC1 was mainly controlled by the traits of yield and its related traits. The correlation between YQ and FL, FG, AFW, NFPP, NBPP and VL was shown to be close and therefore have narrow angles among these vectors, indicating strong positive associations among these traits. Of these, NBPP and NFPP were located closest to yield, indicating their main contribution to the determination of yield. The AFW and FG also made a significant contribution, emphasising the role of fruit size and reproductive efficiency. Earliness-related traits, viz., DTFMF, DTFFF, DT50F and DFFH, however, were in the opposite direction of PC1, showing a strong negative relationship with yield and its component traits. This antagonistic relationship would be expected to be an intrinsic characteristic of the current set of genotypes regarding earliness and productivity. Other traits (e.g., NNFM, NNFF and DOC) were placed away from yield vectors, indicating less or indirect influence on yield.

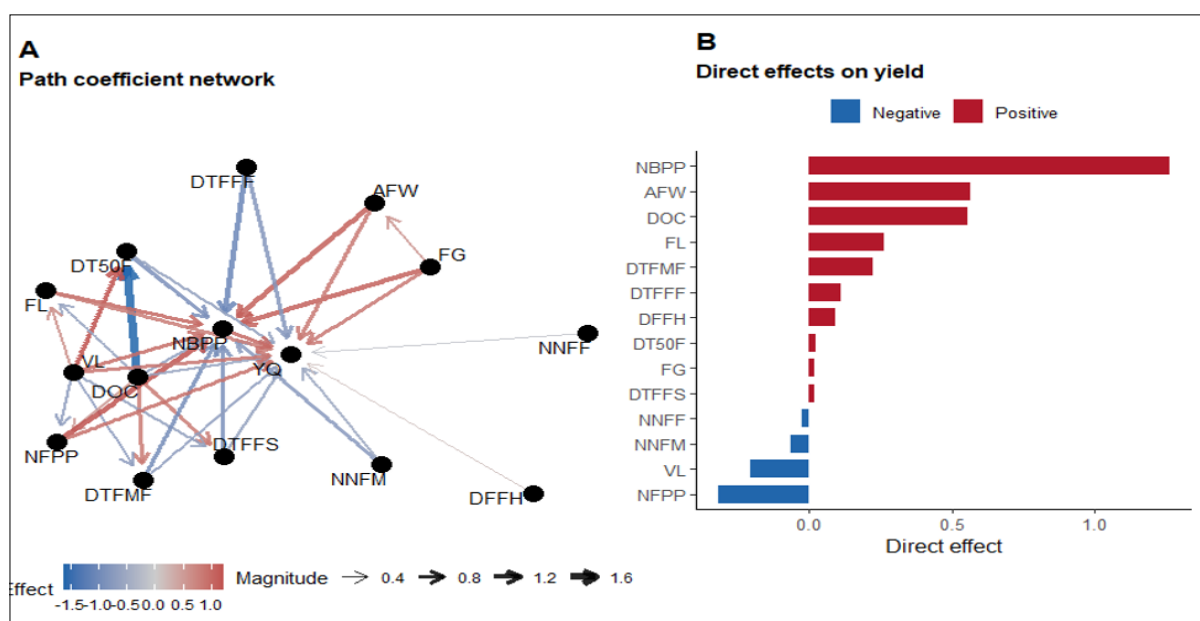


Fig. 3. Direct and indirect effects of component character on yield and its components. DTFMF: days to first male flower; DTFFF: days to first female flower; NNFM: node number of first male flower; NNFF: node number of first female flower; DT50F: days to 50 % flowering; DTFFS: days to first fruit set; DFFH: days to first fruit harvest; FL: fruit length; FG: fruit girth; AFW: average fruit weight; NFPP: number of fruits per plant; NBPP: number of branches per plant (90 days); DOC: duration of crop (sowing to harvest); VL: vine length (cm); YQ: yield per plot (q/ha).

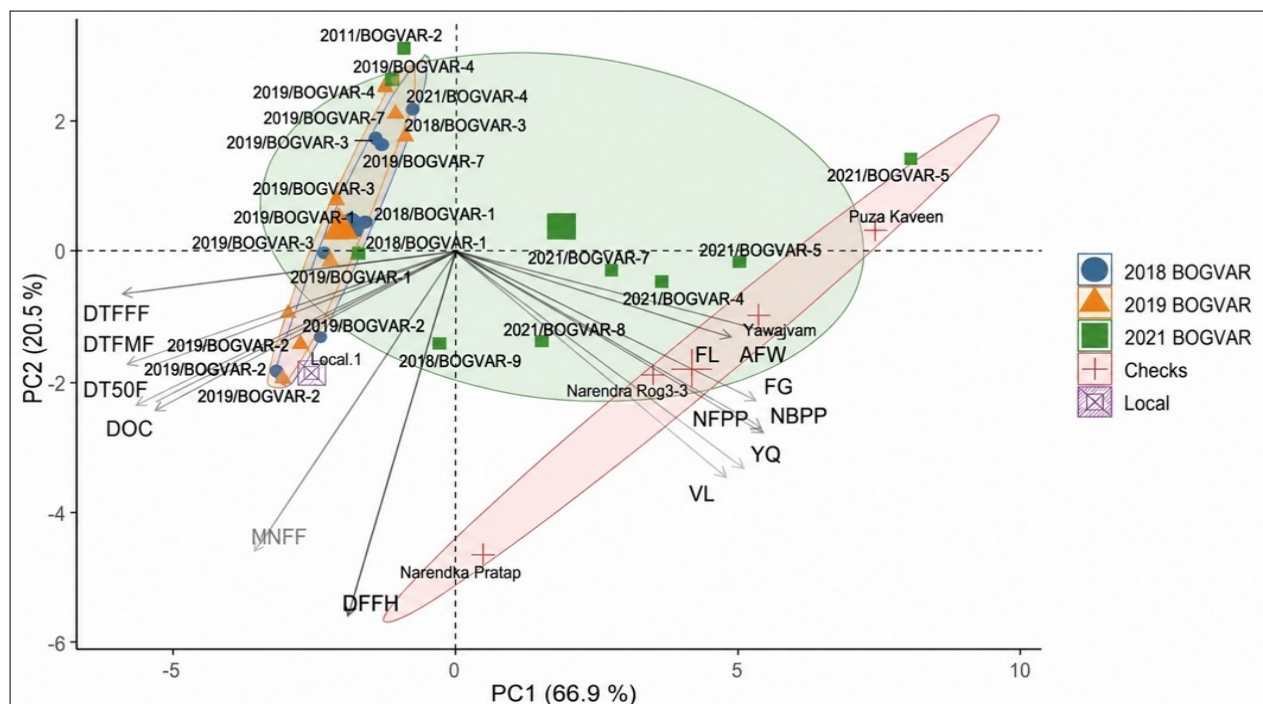


Fig. 4. Principal component analysis (PCA) biplot of mean performance for yield and component traits. DTFFM: days to first male flower; DTFFF: days to first female flower; NNFM: node number of first male flower; NNFF: node number of first female flower; DT50F: days to 50 % flowering; DTFFS: days to first fruit set; DFFH: days to first fruit harvest; FL: fruit length; FG: fruit girth; AFW: average fruit weight; NFPP: number of fruits per plant; NBPP: number of branches per plant (90 days); DOC: duration of crop (sowing to harvest); VL: vine length (cm); YQ: yield per plot (q/ha).

The vertical dispersion of the genotypes in PC2 was predominantly due to maturity-related characters, especially DFFH and NNFF. This suggests that the inter-genotypic variation in maturity and reproductive positioning further separated the genotypes from the yield-related variation explained by PC1. The distribution of genotypes on the biplot clearly gave the information on the performance of the genotypes. The check varieties Pusa Naveen and Kashi Kirti were found on the positive side of PC1 and were found to be close to yield and fruit traits, indicating their performance and justifying them as benchmarks. Narenda Pooja-3 also grouped together around these vectors, indicating relatively high productivity. The experimental lines with the highest scores on the positive side of PC1 were 2021/BOGVAR-8, suggesting the greatest association with yield and fruit-related traits. 2021/BOGVAR-6 and 2021/BOGVAR-3 were also of good quality with good positions, further proving them to be elite. Conversely, most of the genotypes of both the 2018 series and 2019 series were grouped on the negative side of PC1, corresponding to early maturing traits and had less yield potential. These series are closely clustered, indicating low variability within each series. The local genotype had a performance near the centre, indicating moderate performance and not being associated with any of the traits for improved yield or earliness. It is interesting to note that the variable spread of the 2021 BOGVAR genotypes along both the principal components shows an increased genetic variability and better combination of traits than previous breeding lines, confirming the success of recent selection programmes. The PCA shows that the NBPP, NFPP, FL, FG and AFW have the greatest influence on yield in bottle gourd, while the earliness traits show a negative correlation with the yield. It is evident from the different positioning of different genotypes like 2021/BOGVAR-8, 2021/BOGVAR-6 and Pusa Naveen that they have superior standing and could find potential application in breeding programmes for yield and productivity improvement.

The high cumulative variation explained by the first two PCs reflects strong trait interrelationships among the evaluated genotypes in crop studies, with high percentages of the variation accounted for by the first few PCs corresponding to high correlations between yield and its component traits. Similar findings have been reported previously (17). Strong loading of fruit and yield traits on PC1 suggests their major contribution to genetic divergence. These traits are closely linked to yield and thus are prime determinants of productivity. Fruit number, FW and yield traits are highly variable and directly related to yield improvement (27). Similarly, yield and the component traits are highly correlated and are strongly influenced by genetic factors and therefore suitable indicators for selection (19). The negative correlation between earliness traits (days to flowering and fruit set) and yield indicates a trade-off between early maturity and yield. In soybean, phenological characteristics have been reported to strongly influence yield, although negative associations have sometimes been observed (28). The PC2 was enriched with maturity component variation (DFFH and NNFF) and thus was used to further differentiate the genotypes. Highly promising genotypes like 2021/BOGVAR-8, 2021/BOGVAR-6 and 2021/BOGVAR-3 were clearly identified in the biplot, which was strongly related to yield-increasing traits. The placement of Pusa Naveen and Kashi Kirti on these vectors confirms their excellent performance and their suitability as reference vectors. Older genotypes were grouped apart from yield components, suggesting low productivity and low variability. In melon, these observations suggest that the more spread out the PCA is, the more variability there is and the more leeway there is for selection and hybrid development.

Conclusion

The study revealed substantial genetic variability among bottle gourd genotypes for yield and related traits, indicating strong potential for genetic improvement. Variability, principal

component analysis (PCA), correlation and path coefficient analyses identified fruit size traits, number of fruits per plant (NFPP) and branching behaviour as major contributors to yield, whereas earliness traits exhibited a negative association with productivity. Remarkable performances of the standard cultivars viz. Pusa Naveen and Kashi Kirti and the identification of superior genotypes viz. 2021/BOGVAR-8 and 2021/BOGVAR-6 suggest the availability of promising genetic resources for future breeding programmes. Fruit girth (FG), average fruit weight (AFW), number of branches per plant (NBPP) and yield are associated with high variability, high heritability (h^2) and high genetic advance (GA), which indicates a high effectiveness of direct selection for these traits. The results have been a good base for parent selection and desired traits for the development of better bottle gourd cultivars with high yield, early maturing and agronomically efficient cultivars. The integrated application of multivariate and genetic analyses enabled efficient identification of elite genotypes and key yield-associated traits. The identified superior genotypes may be further exploited in hybridisation and selection programmes for yield enhancement.

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Authors' contributions

DS provided the materials and contributed to the research and data interpretation. JT provided support, invaluable guidance and continual encouragement. PG and BV participated in the design of the study and performed the statistical analysis. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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