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RESEARCH ARTICLE

Exploring genetic parameters and trait relationships in the F_2 population of double cross hybrid of tomato (*Solanum lycopersicum* L.)

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Abstract

An investigation was undertaken to examine the genetic parameters of tomato (*Solanum lycopersicum* L.), along with path and correlation analyses, to improve yield and quality attributes utilizing 16 quantitative and qualitative indicators in the F_2 population of a double cross hybrid (H1), comprising 250 plants. The results of the investigation revealed a high coefficient of variation (both phenotypic (PCV) and genotypic (GCV)), coupled with high heritability (>95%) in traits such as average fruit weight (SFW), number of fruits/clusters (NFC) and lycopene content (LC). The selection of these traits suggests a strong potential for genetic improvement. The correlation analysis showed a strong and significant association with yield and its contributing traits, like the weight of the single fruit (0.869), followed by the height of the plant (0.843) and the number of fruits/plant (0.793). Path analysis also showed a substantial direct effect on yield from the number of fruits/plant (0.419) and weight of single fruit (0.416). This study's selection of these traits insights valuable breeding strategies for developing tomato varieties with high yield and enhanced nutritional quality.

Keywords

correlation analysis; heritability; path analysis; *Solanum lycopersicum* L.

Introduction

The tomato (*Solanum lycopersicum* L.) is a valuable crop in the horticultural industry due to its high nutritional content, which includes essential minerals such as iron, calcium and phosphorus, along with vitamins A and C. Tomatoes are also a rich source of antioxidant lycopene, which is known to reduce the risk of cancer and heart disease (1).

A comprehensive understanding of factors influencing productivity, like genetic, environmental and management practices to enhance tomato yield. These factors collectively determine the crop's output (2). In tomato breeding, mainly for F_2 segregating population, understanding the relationship between yield and its contributing traits is essential for guiding selection processes to improve agricultural efficiency and productivity (3).

Correlation and path are essential in F_2 populations to identify key traits for enhancing breeding strategies and contribute to yield improvement. Correlation analysis helps breeders recognize the strength and direction of relationships between critical yield-contributing traits, including the average weight of the fruit, height of the plant and number of fruits per plant (NFP), all of which are critical for improving productivity. By understanding these associations, breeders can prioritize the most essential traits during selection to enhance overall productivity effectively (4).

Path analysis enhances the understanding by differentiating the direct and indirect impacts of these traits on yield. If the weight of the fruits has a significant direct impact on yield, but other characteristics exert only indirect effects, breeders might focus on fruit weight to achieve optimal yield. This analysis is particularly helpful in segregating populations, where genetic variability offers a sustainable potential for selection and genetic improvement (4). By employing these analyses, breeders can more precisely target traits that can drive both yield and quality to enhance the overall selection efficiency.

Additionally, genetic variability, like heritability (h^2), genetic advance (GA) and coefficients of variation (GCV and PCV) are essential for assessing the genetic potential for enhancing yield traits in the F_2 population. High GCV values indicate robust genetic control over traits. PCV more effectively evaluates the impact of environmental factors compared to GCV (5). Selecting traits with high heritability combined with high GCV may lead to effective genetic improvement of GCV (6). These parameters assist breeders in selecting traits with significant genetic potential, ultimately contributing to enhancing elite tomato varieties with high yield.

Integrating variability parameters with path and correlation analysis in F_2 population is crucial for tomato breeding. These approaches improve selection efficiency, resulting in the development of tomato varieties that fulfill global food demands through increased yield and nutritional quality. This study emphasizes exploring genetic parameters and trait associations in the F_2 generation of a tomato double-cross hybrid (H1) to enhance productivity through breeding.

Materials and Methods

The trial was conducted at the university orchard, Department of Vegetable Science, TNAU (Tamil Nadu Agricultural University), Coimbatore, from 2022 to 23. The experiment involved 250 F_2 tomato plants derived from the cross H4 × H5 and their parental lines (CBESL 133, CBESL142, CBESL168, CBESL169), which were assessed for yield and yield-contributing traits. The F_2 population (H1) was developed by selfing the F_1 hybrid (H4 (CBESL142×CBESL168) × H5(CBESL133×CBESL169)). Each plant was labeled to record nine quantitative traits, (PH (height of the plant (cm)), number of primary branches (NOPB), days taken to attain first flowering (DFF), 50% flowering (DFPF), number of flowers per cluster (NFLC), NFC, NFP, the weight of single fruit (SFW (g)) and yield per plant (YLD (kg)), and seven qualitative traits (LC (mg/100 g), ascorbic acid (AA (mg/100 g), β-carotene content (B (mg/100 g)), total soluble solids (TSS (°Brix)), titrable acidity (TA (%)), PT (cm) and NOL). The correlation coefficient was calculated using a standardized formula (7). Heritability (h^2), PCV and GCV and GA as a percentage of the mean (GAM) were calculated by the standardized technique (8). The direct and indirect pathways were determined by standardized techniques (9).

Results and Discussion

The present analysis offers insights into the genetic improvement and variability in the double-cross hybrid F_2 population for yield and quality traits. Heritability (h^2), genetic advance mean in percentage (GAM) and two types of coefficients of variation, PCV and GCV, are the primary metrics employed in the F_2 population of the double cross H4XH5 (H1). These statistics help breeders assess the potential for selecting and enhancing specific traits.

Genetic parameters in F_2 generation of the double cross hybrid

The PCV measures a trait's overall variability (due to genetic and environmental factors), while the GCV measures the variability solely attributable to genetic factors. High values for both indicate a more significant potential for selection and improvement of the trait. Eight parameters were found to have highest PCV and GCV *viz.,* days to first flowering (21.79, 21.66%), number of fruits per cluster (28.16, 28.05%), single fruit weight (SFW) (28.15, 28.02%), NFP (17.31, 17.15%), β-carotene content (31.26, 31.15%), PT (23.54, 23.37%), LC (32.68, 32.56%) and NOL (40.39, 40.33%) (Table 1). All traits analyzed exhibited higher PCV than GCV, but it exhibits narrow difference (10), suggesting the minimal environmental influence on these traits (11, 12).

High heritability (>95%) was exhibited by almost all the traits (Table 1). Among the traits analyzed, the highest heritability was observed for the NOL (99.7%), followed by LC (99.28%), the average weight of fruit (99.10%), number of fruits per cluster (99.28%) and plant height (PH) (97.00%). These ranges for yield traits were consistent with findings of other studies which observed high heritability coupled with high genetic mean percentage (13-16). Among quality traits, β-carotene content recorded the highest heritability at 99.26%. which was similar results of a previous study on quality traits indicating that additive genes control these traits (12). This means that simple breeding techniques can achieve phenotypic selection for improvement.

The GAM indicates the probable upgrading through selection. The NFC showed the highest GAM (57.54%), followed by the NFLC (41.33%), indicating strong selection potential for these traits (Table 1). This range of GAM aligns with previously published reports which also noted high GAs for these traits (17, 18). Single fruit weight (57.47%) and carotenoid content (63.93%) also exhibited strong potential for genetic improvement which are similar to the findings of previous studies (19, 20). Quality parameters like the NOL (82.95%) and LC (66.84%) showed high GAM, suggesting strong selection potential. Similar findings were highlighted in other studies which noted that high GAM values for quality traits indicate significant potential for improvement through selection (14, 21).

Yield traits, such as the NFC, PH, SFW and quality traits like LC, showed high heritability, variability and GA indicating strong selection potential and effective improvement potential through breeding. For quality traits with moderate or low GAM, such as titratable acidity and total soluble solids, more intense selection pressure or environmental management may be necessary. These findings provide valuable insights for crop development programs that create high-yielding, nutritionally

Table 1. Estimates of variability parameters for growth, yield and quality traits of double cross hybrid H4×H5

Traits	Mean	Range		Coefficient of variation		h^2	GAM (%)
		Minimum	Maximum	PCV (%)	GCV (%)		
PH (cm)	133.65	82.57	158.18	15.05	14.88	0.97	30.31
NOPB	12.65	7.66	18.66	17.52	17.41	0.98	35.62
DFF	25.50	14.66	37.94	21.79	21.66	0.98	44.35
DFPF	29.09	16.16	41.97	19.00	18.83	0.98	38.44
NFLC	4.83	2.18	7.67	20.39	20.23	0.98	41.33
NFC	3.46	1.53	5.75	28.16	28.05	0.99	57.54
SFW (g)	67.78	37.97	92.64	28.15	28.02	0.99	57.47
NFP	56.45	33.90	79.75	17.31	17.15	0.98	35.01
YLD (g)	4022.23	1587.18	7812.92	18.73	18.55	0.98	37.86
AA (mg/100g)	44.69	38.97	54.23	18.36	18.18	0.98	37.07
CAR (mg/100g)	11.86	6.42	15.95	31.26	31.15	0.99	63.93
PT (cm)	0.43	0.24	0.82	23.55	23.37	0.98	47.78
TSS (˚Brix)	4.61	2.44	8.58	17.00	16.83	0.97	34.32
LC (mg/100g)	12.01	4.89	16.64	32.68	32.56	0.99	66.84
TA (%)	0.43	0.16	0.69	11.19	10.87	0.94	21.75
NOL	4.38	4.00	5.00	40.39	40.33	0.99	82.95

PCV-Phenotypic coefficients of variation, GCV- Genotypic coefficients of variation,h^2- Heritability, GAM-Genetic advance at 5% selection intensity, PH-Plant height (cm), NOPB-Number of primary branches, DFF-Days to first flowering, DFPF-Days to 50% flowering, NFLC-Number of flowers per cluster, NFC-Number of fruits per cluster, SFW-Single fruit weight (g), NFP-Number of fruits per plant, YLD-Yield per plant (g), AA-Ascorbic acid (mg/100g), CAR-β-carotene content (mg/100g), PT-Pericarp thickness (cm), TSS-Total soluble solids (˚Brix), LC-Lycopene content (mg/100g), TA-Titrable acidity (%), NOL-Number of locules

rich tomato varieties (22).

Correlation analysis in yield contributing traits in F_2 generation of the double cross hybrid

The analysis of correlations between yield and related traits in the F_2 generation of the double-cross hybrid (Table 2) revealed a strong positive correlation between PH and YLD (0.843). This result aligns with previously published reports suggesting that increased PH tends to result in higher yields (23, 24). Plant height also showed positive correlations with SFW (0.869), followed by the NFC (0.793), NFLC (0.767) and quality traits such as carotene content (0.608), AA content (0.604) and LC (0.542). This suggests that PH may contribute to both the quantity and quality of fruit produced which was supported by a previous study (25).

The NOPB also demonstrated a moderately significant positive correlation with the NFLC (0.478) and the NFC (0.456). These results aligned with the findings of a previous study (24), indicating that a greater number of branches can improve flowering and fruiting.

The weight of a single fruit showed the highest correlation with YLD (0.946), indicating that larger fruits significantly contributed to maximum yield, as similarly reported in another investigation (26). Fruit weight also exhibited strong association with quality parameters, like AA (0.856), carotene content (0.698) and LC (0.565), emphasizing the role of larger fruits in both yield and quality. The NFLC strongly correlates with the NFC (0.966) and YLD (0.692). This suggests that increased flowering leads to more fruit, a finding supported by other workers (27, 28). Additionally, AA content positively correlated with carotene content (0.732) and LC (0.461), highlighting a beneficial interaction between vitamin C and other essential nutritional compounds in the fruit. Another study also reported similar trends, emphasizing the nutritional quality of high-yield plants (29).

DFF (-0.874) and DFPF (-0.881) showed a negative correlation with YLD (yield/ plant), suggesting that plants flowering earlier tend to have reduced yields. This negative association also extends to traits such as SFW (-0.852) and NFP (-0.688), indicating that delayed flowering supports higher yields. Similar findings were noted in another study which stated that delayed flowering improves fruit set and yield (30). They also reported that the number of days taken to reach first and DFPF negatively correlates with the NFLC (-0.713 and -0.711) and the number of fruits per cluster (-0.713 and -0.702), further illustrating that delayed flowering supports better reproductive success.

The height of the plant (PH), NOPB and SFW all have significant positive impacts on yield, with strong correlations to both quantity and quality attributes. These traits are essential for selecting high-yielding varieties. Conversely, traits like early flowering are negatively associated with yield, implying that delaying flowering may allow plants to remain in the vegetative phase longer, accumulating more biomass and necessary resources for fruit development. Consequently, delayed flowering is desirable in breeding programs focused on yield improvement.

Overall, traits such as PH, NOPB and SFW serve as important selection criteria in breeding for yield (19, 31). Although delayed flowering is negatively correlated with specific traits, appears to play a role in enhancing overall yield, especially in the context of larger, more nutritionally rich fruits, as supported by other studies (23, 26).

Correlation heatmap of the traits

This heatmap illustrates the association between various phenotypic and genotypic traits, as indicated by the color scale ranging from -1 (blue color in Fig. 1 indicates a strong negative correlation) to 1 (red color in Fig. 1 indicates a strong positive correlation). Strong positive correlations are observed between traits like YLD and NFLC (flowers number per cluster) (0.94), as well as between NFC (fruits number per cluster) and NFLC (0.95), which shows a close positive association between these traits. On the other hand, negative correlations exist between PH and SFW (-0.84), indicating that an increase in one trait may tend to decrease in the other. Statistically significant correlations ($p \leq 0.05$) are represented with asterisks (*), highlighting the most

Table 2. The simple correlation coefficient between yield and quality traits in F_2 generation of the double cross hybrid (H1)

	PH	NOPB	DFF	DFPF	NFLC	NFC	SFW	NFP	AA	CAR	PT	TSS	LC	TA	NOL	YLD
PH	1.000	0.441	-0.867**	-0.862**	0.767**	0.793**	0.869**	0.642*	0.604*	0.608*	0.488*	0.393	0.542*	0.463*	0.373	0.843**
NOPB		1.000	-0.482*	-0.474*	0.478*	0.456*	0.422	0.290	0.341	0.197	0.209	0.146	0.284	0.201	0.297	0.429
DFF			1.000	-0.323	-0.713*	-0.713*	-0.852**	-0.666*	-0.622*	-0.544*	-0.551*	-0.403	-0.418	-0.392	-0.367	-0.874**
DFPF				1.000	-0.711*	-0.702*	-0.856**	-0.688*	-0.608*	-0.542*	-0.568*	-0.404	-0.415	-0.394	-0.374	-0.881**
NFLC					1.000	0.966**	0.712*	0.509*	0.492*	0.433	0.367	0.285	0.455*	0.239	0.491*	0.692*
NFC						1.000	0.780**	0.429	0.617*	0.553*	0.317	0.347	0.474*	0.322	0.502*	0.720*
SFW							1.000	0.577*	0.856**	0.698*	0.486*	0.495*	0.565*	0.548*	0.495*	0.946**
NFP								1.000	0.175	0.155	0.775**	0.433	0.387	0.301	0.447*	0.803**
AA									1.000	0.732*	0.188	0.362	0.461*	0.524*	0.427	0.714*
CAR										1.000	0.192	0.344	0.428*	0.559*	0.211	0.574*
PT											1.000	0.655*	0.396	0.424	0.360	0.652*
TSS												1.000	0.533*	0.480*	0.391	0.530*
LC													1.000	0.484**	0.446**	0.538*
TA														1.000	0.253	0.524*
NOL															1.000	0.548*
YLD																1.000

** -Significant at 1 % and * - Significant at 5 % level of significance

PH- Plant height (cm), NOPB- Number of primary branches, DFF- Days to first flowering, DFPF-Days to fifty percent flowering, NFLC-Number of flowers per cluster, NFC-Number of fruits per cluster, SFW-Single fruit weight (g), NFP-Number of fruit per plant, AA- Ascorbic acid content (mg/100g), CAR- Carotenoid content (mg/100g), PT-Pericarp thickness (cm), TSS-Total soluble solids (˚brix), LC-Lycopene content (mg/100g), TA-Titratable acidity (%) , NOL-Number of locules, YLD-Yield per plant (g)

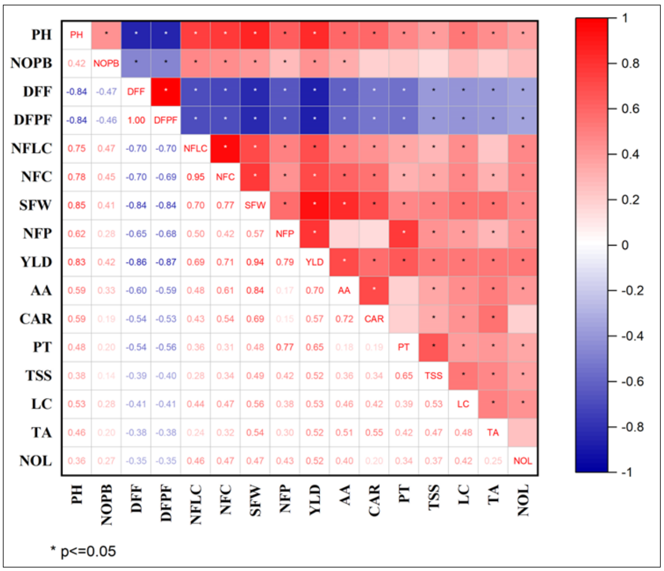

Fig. 1. Heatmap showing the correlation between yield and its contributing traits in F_2 generation of the double cross hybrid.

reliable relationships in this analysis (Fig. 1). The color bar on the right aids in interpreting correlation strength, with darker colors representing stronger relationships.

Path analysis on yield per plant in F_2 generation of the double cross hybrid

The analysis of indirect and direct effects of various characteristics on YLD, as shown in Table 3, underscores the key factors influencing tomato yield in the F_2 generation of the double cross hybrid (H1).

Direct effect on yield traits

The NFP (0.419) followed by SFW (0.416) exhibited strong direct positive effects on YLD, indicating that yield is highly influenced by both the size of the fruits and quantity. The importance of fruit number and average weight as critical contributors to yield (26). Another study also support that these traits had an extensive direct impact on yield (19).

Ascorbic acid content had a moderate direct effect on yield (0.188), indicating that plants with higher quantities of AA can still produce more yields. This correlation between nutritional quality and yield is supported by other studies (29, 32). DFPF (-0.074) and NFLC (-0.006) showed negligible negative direct effects on yield. The negative direct effects of early flowering have also been noted other studies indicating that delayed flowering may contribute to better yield outcomes (33, 34).

Plant height demonstrated a high positive indirect effect on YLD through both SFW (0.341) and NFP (0.246). This suggests that increased PH may indirectly promote fruit size and number, enhancing yield. These findings align with other studies which identified PH as a significant trait affecting yield indirectly (19, 35). Additionally, the NOPB showed a moderate positive indirect effect through SFW (0.165) and a comparatively minor effect through the number of fruits/plant (0.109). Similar conclusions were noted in another study found that more branches positively influence fruit size and yield (36). This indicates that more branches can promote better fruit set and size, contributing to yield increases.

Days to attain DFPF and DFF exhibited high negative indirect effects on yield through SFW and NFP (fruits number/plants). This highlights that delayed flowering has a substantial beneficial impact on fruit size and number, indirectly boosting yield. Similar observations were reported in other studies suggesting that delayed flowering allows more resources for fruit development, thereby increasing overall yield (26, 30).

NFC and NFLC exhibited high and moderate positive indirect effects through SFW and the number of fruits/plants (NFP). Other studies also confirmed that these traits indirectly contribute to yield by improving fruiting efficiency (23, 37).

Single fruit weight exhibited a moderate positive indirect effect through the NFP (0.232) and AA (0.152). This means that while fruit size directly influences yield; it is also

Table 3. Path analysis showing the direct and indirect effect of yield and quality traits on yield per plant in F_2 generation of the double cross hybrid (H1)

	PH	NOPB	DFF	DFPF	NFLC	NFC	SFW	NFP	AA	CAR	PT	TSS	LC	TA	NOL	YLD
PH	**0.017**	0.010	-0.010	0.059	-0.005	0.023	0.341	0.246	0.104	0.005	0.012	0.009	-0.017	0.010	0.005	0.843**
NOPB	0.007	**0.026**	-0.006	0.033	-0.003	0.013	0.165	0.109	0.060	0.002	0.005	0.003	-0.009	0.004	0.003	0.429**
DFF	-0.014	-0.011	**0.013**	-0.070	0.004	-0.021	-0.338	-0.263	-0.107	-0.005	-0.014	-0.009	0.014	-0.008	-0.005	-0.874**
DFPF	-0.014	-0.011	0.012	**-0.074**	0.004	-0.021	-0.336	-0.273	-0.107	-0.005	-0.015	-0.009	0.014	-0.008	-0.005	-0.881**
NFLC	0.012	0.012	-0.009	0.049	**-0.006**	0.029	0.286	0.202	0.085	0.004	0.010	0.006	-0.014	0.005	0.006	0.692**
NFC	0.013	0.011	-0.009	0.049	-0.006	**0.031**	0.314	0.170	0.110	0.005	0.008	0.008	-0.015	0.007	0.006	0.720**
SFW	0.014	0.010	-0.010	0.059	-0.004	0.023	**0.416**	0.232	0.152	0.006	0.013	0.011	-0.018	0.012	0.006	0.946**
NFP	0.010	0.007	-0.008	0.048	-0.003	0.012	0.230	**0.419**	0.030	0.001	0.020	0.010	-0.013	0.007	0.006	0.803**
AA	0.010	0.008	-0.007	0.042	-0.003	0.018	0.336	0.066	**0.188**	0.006	0.005	0.008	-0.015	0.011	0.005	0.714**
CAR	0.010	0.005	-0.007	0.037	-0.003	0.016	0.280	0.064	0.131	**0.009**	0.005	0.008	-0.014	0.012	0.003	0.574**
PT	0.008	0.005	-0.007	0.040	-0.002	0.009	0.196	0.312	0.034	0.002	**0.027**	0.015	-0.013	0.009	0.005	0.652**
TSS	0.006	0.004	-0.005	0.028	-0.002	0.010	0.197	0.169	0.065	0.003	0.017	**0.024**	-0.018	0.010	0.005	0.530**
LC	0.009	0.007	-0.005	0.029	-0.003	0.014	0.225	0.154	0.084	0.004	0.010	0.012	**-0.034**	0.011	0.006	0.538**
TA	0.008	0.005	-0.005	0.027	-0.001	0.009	0.221	0.122	0.093	0.005	0.011	0.011	-0.016	**0.023**	0.003	0.524**
NOL	0.006	0.006	-0.004	0.024	-0.003	0.013	0.182	0.165	0.069	0.002	0.009	0.008	-0.013	0.005	**0.014**	0.548**

Residual effect-0.151 Bold values refer to direct effects.

PH-Plant height (cm), NOPB-Number of primary branches, DFF-Days to first flowering, DFPF-Days to fifty percent flowering, NFLC-Number of flowers per cluster, NFC-Number of fruits per cluster, SFW-Single fruit weight (g), NFP-Number of fruit per plant, AA-Ascorbic acid content (mg/100g), CAR-Carotenoid content (mg/100g), PT-Pericarp thickness (cm), TSS-Total soluble solids (˚brix), LC-Lycopene content (mg/100g), TA-Titratable acidity (%), NOL-Number of locules, YLD-Yield per plant (g)

enhanced by other traits like fruit number and quality. Other studies also highlighted the role of fruit weight in maximizing yield potential (26, 33).

Ascorbic acid content had a higher positive indirect effect through SFW (0.336), suggesting that higher vitamin C content contributes to increased fruit size, boosting yield. Similar relationship also noticed between nutritional quality and yield (29, 32).

Pericarp thickness and LC displayed moderate to high positive indirect effects on yield via SFW and NFP. These traits, which enhance fruit quality and structure, support yield by improving fruit size and number. Other studies also found these traits to be critical contributors to yield, directly or indirectly (32, 38).

The path analysis reveals that total fruit number/ plant (NFP) and SFW are the most important traits directly contributing to yield in the F_2 generation. Additionally, indirect effects through traits such as NOPB, PH and PT further influence yield by promoting larger and more fruits. The observed negative indirect effects of early flowering confirm that delayed flowering is beneficial for optimizing yield. This comprehensive view of direct and indirect effects provides valuable insights for breeding programs, allowing breeders to focus on important yield-contributing traits.

Conclusion

The study highlights the strong GA, high genetic variability and heritability (>95%) in the F_2 generation of double cross hybrid (H1), indicating a significant potential for a breeding program to enhance critical traits such as average weight of the fruit, number of NFP and LC. Association analysis further highlights the crucial role of direct contributors to yield, like the height of the plant, SFW and the number of NFP, while delayed flowering emerged as a beneficial trait for yield optimization. These findings offer valuable insights for developing high-yielding, nutritionally superior tomato varieties. Future research should focus on broadening the genetic base by incorporating diverse germplasm and integrating molecular markers to enhance selection precision. Additionally, exploring the interaction between genetic traits and environmental factors could further optimize breeding strategies for improved yield and quality across varying climatic conditions.

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Authors' contributions

TS contributed to conceptualized and supervised the research design and experimental planning. RS carried out the experiment, data collection and analysis. MK contributed by imposing the experiment and NM, NS and SH helped in statistical analysis.

Compliance with ethical standards

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

Ethical issues: None

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