Citron watermelon characterisation and trait analysis in Kalahari sands

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Background: Citron watermelon, a drought-tolerant and nutrient-dense crop requiring low input, holds potential for enhancing food security under climate change conditions. However, it remains under-researched, with low productivity levels.

Aim: To agro-morphologically characterise citron watermelon accessions and identify trait relationships relevant for variety development.

Setting: The experiment was carried out at a Lupane State University Farm with Kalahari sands in Zimbabwe.

Methods: A randomised complete block design field experiment, with three replications, was conducted over two consecutive seasons.

Results: The accessions displayed wide diversity in fruit shape, skin colour and seed colour. Fruit yield ranged from 18.5 t/ha to 190.2 t/ha, exhibiting a strong positive correlation with the number of fruits per plant (R = 0.99) and individual fruit weight (R = 0.98). Path analysis confirmed that these traits exerted the highest direct effects on yield. Principal component analysis revealed that the first three components explained 89.85% of the total variation between accessions.

Conclusion: The significant variation and trait correlations observed offer opportunities for effective parental selection and early genetic gains in breeding programmes. There is scope to improve yield-determining traits, such as the number of fruits per plant and individual fruit weight, forming a strong basis for initiating a breeding programme for this crop.

Contribution: Promising accessions identified in this study can be utilised as parental lines for citron watermelon improvement.

Keywords: *Citrullus lanatus*; genotypic correlation; morphological traits; path analysis; under-utilised crop.

Introduction

Citron watermelon, *Citrullus lanatus* (Thunb.) Matsum and Nakai var *citroides*, a subspecies of the dessert watermelon, is a drought-tolerant crop that originated from tropical Africa, particularly in the Kalahari Desert (Paris 2015). A low salt, fat and cholesterol content, high mineral and phytochemical density form the basis of the nutrition and health benefits of the crop (Jumde & Gousoddin 2015; Mandizvo, Odindo & Mashilo 2021). Despite its potential to contribute to food security, citron watermelon has received little attention in terms of scientific research and utilisation compared to the sweet dessert watermelon (Mujaju & Faith 2011).

There is a growing demand for high-yielding and drought-tolerant crops, attributed to the accumulative human populace and the corresponding decrease in acreage designated for crop production as well as climate change (Levi et al. 2017). Supporting the growing and consumption of crops that have received less attention by researchers but are drought resilient, like citron watermelon, will mitigate the adverse effects of climate change (Chivenge et al. 2015). This has been the case for maize and small grains wherein drought-resistant varieties were developed to ensure food security in dry regions (Njinju et al. 2022; Simtowe et al. 2019; Yadav, Goyal & Singh 2017). Citron watermelon is a crop that is considerably drought-tolerant (Mo et al. 2015 & Mandizvo et al. 2022), making it suitable for growing in dry regions. Citron watermelon accessions cultivated and preserved by smallholder farmers may provide valuable germplasm for the development of new citron watermelon cultivars with desirable traits (Mujaju et al. 2010).

Agro-morphological traits have been widely studied in watermelon germplasm and are valuable for assessing genetic variability and guiding crop improvement efforts (Coskun & Gulsen 2024a). Stone, Boyhan and McGregor (2019), Amzeri et al. (2021), Ngwepe, Shimelis and Mashilo (2021) and Mashilo et al. (2022b) documented key phenotypic variation in several watermelon accessions for fruit shape (FS), rind colour, seed size and yield components that can be exploited in breeding activities. Similarly, Elbekkay et al. (2021) observed that morphological variability in watermelon landraces established a wide variation in several traits, especially fruit size, sweetness and rind thickness, which are critical for the development of high-yielding market-preferred cultivars. It has been documented that fruit weight and number of fruits per plant had positive significant correlations with fruit yield (Mohosina et al. 2020; Singh et al. 2022). In particular, Agah et al. (2021) showed strong relationships between the number of fruits per plant and fruit yield in cucurbits. Nyurura and Maphosa (2022) and Katuuramu, Levi and Wechter (2023) used path coefficient analysis to estimate the direct and indirect effects of individual traits on yield, demonstrating its value in unravelling the complex relationships among traits.

In the sub-Saharan region, citron watermelon has been underutilised in breeding programmes even though it is drought-tolerant and has significant potential to contribute towards food security. The present study addresses this gap by characterising 10 accessions and determining the genotypic correlation, path analysis and association of traits. The qualitative traits, such as fruit shape and fruit skin colour, and quantitative parameters, such as individual fruit weight and number of fruits per plant were characterised to explore the genetic variability in citron watermelon. The findings of the present study will be valuable in facilitating the use of citron watermelon in breeding programmes that are aimed at increasing yields, improving the role of the crop in sustainable farming in semi-arid regions.

Research methods and design

Site description

The experiment was carried out at Lupane State University Farm in Zimbabwe (18°55.889′ S; 27°48.418′ E). The location is at an elevation of 1016 m above sea level. The site is characterised by deep Kalahari sands, with a pH from 4.0 to 6.0 (Mukungurutse et al. 2018). Rainfall ranges from 350 mm/year to 500 mm/year, with temperatures ranging between 28 °C and 35 °C.

Planting material and study design

A total of 10 citron watermelon accessions obtained from the Zimbabwe National Gene Bank were used as the planting materials. The experiment was carried out in a randomised complete block design (RCBD) for two consecutive seasons, with 10 treatments and three replicates. Manual planting was conducted by placing 2–3 seeds per station with an inter-row × intra-row spacing of 2 m × 0.9 m at a sowing depth of 2 cm. Weeds were controlled manually during the experiment to reduce competition with the crop for nutrients, light and water. Pests and disease control were carried out using pesticides whenever it was necessary.

Data collection

Data were collected at the physiological maturity stage, where the number of fruits per plant, fruit width (cm) and individual fruit weight (kg) were measured from five plants per plot and averaged. Fruit weight was determined using a digital weighing balance (HESA3303, China), and fruit yield (ton/ha) was then computed by multiplying the fruit weight by the number of fruits per plant. Fruit width was determined by measuring the largest diameter of the cross-section of the tested fruits. Using a string and a ruler, the fruit length was determined by measuring the fruit (in centimetres) starting from the point where the tendril joins the blossom end (the rounded end) to the opposite end (the stem end). Fruit shape, predominant fruit skin colour (PFSC), secondary fruit skin colour pattern (SFSCP), fruit skin stripe colour (FSSC) and seed colour (SC) were determined using the International Union for the Protection of New Varieties of Plants (UOPV 2008) descriptors for the morphological characterisation of watermelon. Fruit rind thickness (millimetres) was determined by slicing the fruit in half and measuring the thickness using a digital calliper (HDCD28150, China). A kilogram of sliced flesh was turned into juice using a blender. The total soluble solids (%) were determined using a digital refractometer (ATC-1, Japan) by placing 1–2 drops of the juice on the prism. The pH of the clear juice was measured using a calibrated handheld pH meter (H198103, India) by immersing its electrode into the liquid. Finally, vitamin C was determined through a redox titration method suggested by (Kareem et al. 2020).

Data analyses

Analysis of variance (ANOVA) was conducted in the GenStat statistical package (18th edition). Significantly different means were compared using Fisher's Protected, Least Significance Difference Test (LSD) at a 5% significance level. Following Miller et al. (1958), genotypic correlation coefficients were calculated from the corresponding variance and covariance components in Microsoft Excel (version 2021). The relationships of the parameters to fruit yield (ton/ha) were determined using the correlation coefficient. Dewey and Lu's (1959) method was followed to find direct and indirect pathways using the matrix estimation. Principal component analysis (PCA) was performed using GenStat.

Ethical considerations

This study followed all ethical standards for research without direct contact with human beings or animals.

Results

Morphological variation in qualitative traits

The assessment of the morphological traits of the 10 selected citron watermelon accessions revealed considerable variability across five qualitative traits: FS, PFSC, SFSCP, FSSC and SC. The accessions showed a wide variation in FS, which included broad elliptical, pyriform, elliptical, flattened, round and oblong (Table 1). Major elliptical shapes were recorded for three accessions (185, 2766 and 378), while three others (177, 2660 and 60) showed a predominance of flat shapes in fruits, indicative of a greater degree of non-spherical FSs among the tested genotypes. Furthermore, PFSC also displayed variation; five different colours were recorded, that is, white, light green, dark green, brown and medium green. Light and dark green appeared most frequently in three accessions each, while two were brown. Marked variation featured in SFSCP, which included mixed, solid, spotted and striped patterns. The spotted pattern was the most common across four accessions (2766, 179, 378 and 60), followed by striped from three accessions (177, 2767 and 2660). Four distinctive FSSC were observed: dark green, yellow, light green and brown, with yellow being the dominant colour for five accessions (2733, 2766, 179, 2767 and 378). The variation of SC was evident because of recording five different colours, which include light brown, black, green, red and medium green, while the majority colour was green with four accessions (179, 2660, 500 and 378).

TABLE 1: Morphological variation in qualitative traits for the 10 Kalahari sands citron watermelon accessions.

Accessions	FS	PFSC	SFSCP	FSSC	SC
185	Broad elliptical	Yellow	Mixed	Dark green	Light brown
2733	Pyriform	Light green	Solid	Yellow	Light brown
2766	Elliptical	Dark green	Spotted	Yellow	Medium green
177	Flattened	Light green	Striped	Light green	Black
179	Elliptical	Dark green	Spotted	Yellow	Green
2767	Round	Dark green	Striped	Yellow	Red
2660	Flattened	Brown	Striped	Dark green	Green
500	Oblong	Brown	Solid	Light green	Green
378	Elliptical	Medium green	Spotted	Yellow	Green
60	Flattened	Light green	Spotted	Brown	Light brown

FS, fruit shape; PFSC, predominant fruit skin colour; SFSCP, secondary fruit skin colour pattern; FSSC, fruit skin stripe colour; SC, seed colour.

Variation in quantitative traits of citron watermelon accessions

Most quantitative traits of the citron watermelon accessions were significantly different ($p < 0.05$) except vitamin C, total soluble solids and pH, which were similar across accessions (Table 2). The coefficient of variation was greatest for fruit yield (40.3%) and lowest for pH (2.8%), an indication of different levels of trait stability across accessions. The number of fruits per plant ranged from 2.3 (accession 60) to 5.0 (accession 185), with an average of 3.3. Fruit length and fruit width also displayed wide variability, with the biggest fruit dimensions recorded in accession 179 (32.83 cm for fruit length and 22.13 cm for fruit width). Rind thickness displayed a wide range of variability, with a minimum of 22.8 mm for accession 185 to a maximum of 39.8 mm for accession 60. The individual fruit weight ranged from 1.45 kg (accession 60) to 8.79 kg (accession 179), with consistent variations observed in fruit yield/hectare, which ranged from 18.5 t/ha for accession 60 to 190.2 t/ha for accession 378. Among the nutritional traits, total soluble solids varied minimally from 6.3% to 6.95%, whereas vitamin C content displayed a narrow variation, ranging from 6.33 mg/100 g to 7.37 mg/100 g. The fruit pH was generally stable across accessions, with a narrow range from 5.20 to 5.27.

Genotypic correlation of selected traits of citron watermelon with fruit yield

The genotypic correlation analysis revealed significant associations between the selected quantitative traits of citron watermelon. Number of fruits per plant ($R = 0.99$), individual fruit weight ($R = 0.98$) and fruit length ($R = 0.68$) had a significant and strong positive genotypic correlation ($p < 0.01$) with fruit yield (tons/ha) (Table 3). Similarly, there were positive significant genotypic correlations between individual fruit weight and number of fruits per plant ($R = 0.97$, $p < 0.01$), fruit length and fruit width ($R = 0.78$,

TABLE 2: Variation in quantitative traits of 10 citron watermelon accessions.

Accessions	NFP	FL (cm)	FW (cm)	RT (mm)	VC	TSS (%)	FY(t/ha)	pH	IFW
185	5.000a	44.900a	41.950ab	39.800a	7.370	2.300	172.300ab	6.100a	6.180a–c
2733	2.670b	36.500bc	33.100bc	25.240cd	5.910	3.200	63.800de	5.880a	4.190bc
2766	4.000a	36.780bc	35.780a–c	36.400ab	6.200	2.900	114.400b–d	6.020a	5.077bc
177	2.670b	35.030bc	34.550a–c	31.650a–c	5.910	2.600	66.600de	5.830a–c	4.337bc
179	4.330a	49.630a	44.030a	35.420ab	6.490	2.600	159.800a–c	5.590bc	6.673ab
2767	2.670b	41.400a–c	28.600c	24.500cd	5.610	2.700	91.500cd	5.880a	6.116a–c
2660	2.670b	33.380c	27.620c	25.900cd	6.050	2.500	79.800de	5.830a–c	5.389bc
500	2.670b	32.430c	28.320c	27.160b–d	6.350	2.700	51.800de	5.850ab	3.575cd
378	4.000a	41.170a–c	34.950a–c	27.550b–d	5.910	2.600	190.200a	5.560c	8.790a
60	2.330b	31.480c	28.600c	22.280d	6.640	2.500	18.500e	5.990a	1.447d
Mean	3.300	38.300	33.750	29.640	6.240	2.800	100.900	5.850	5.180
Minimum	2.300	32.430	28.600	18.470	5.610	2.500	18.500	5.500	1.447
Maximum	5.000	49.630	44.300	48.490	7.370	3.200	190.200	6.100	8.790
MS	0.600*	103.700*	99.940*	103.790*	0.420^{ns}	0.200^{ns}	9671.000*	0.010*	2.450*
p-values	1.330	10.880	9.830	9.330	1.107	0.810	69.710	0.280	2.690
LSD	0.004	0.042	0.021	0.011	0.132	0.561	< 0.001	0.014	0.020
%CV	23.500	16.600	17.000	18.300	28.800	17.700	40.300	2.800	30.200

Note: Values with different letters in a column show significant differences ($p < 0.05$).

NFP, number of fruits per plant; FL, fruit-length-(cm); FW, fruit width (cm); RT, rind thickness (mm); VC, Vitamin C content; TSS, total soluble solids (%); FY, fruit yield (*t*/ha); %CV, Coefficient of variation; MS, mean squares; *, significant at 5% level *t*; ns, and not significant at 5% level; LSD, least significant differences; IFW, individual fruit weight.

$p < 0.01$), number of fruits per plant and fruit length (0.68, $p < 0.01$) and individual fruit weight and fruit length ($R = 0.58$, $p < 0.05$). Conversely, rind thickness displayed weak and statistically non-significant relationships across all traits, including fruit yield ($R = 0.120$, $p < 0.05$).

Path coefficient analysis on the effect of selected quantitative traits on citron watermelon fruit yield

The path coefficient analysis revealed that the number of fruits per plant (0.58), individual fruit weight (0.36) and fruit length (0.13) exhibited the greatest direct positive contribution to fruit yield (Table 4). On the other hand, rind thickness (–0.06) and fruit width (–0.04) displayed slight negative direct effects. Apart from the direct effects, significant indirect effects were also observed. Number of fruits per plant indirectly contributed to fruit yield via individual fruit weight (0.35) and fruit length (0.09), whereas individual fruit weight's indirect contribution through the number of fruits per plant was 0.56. Fruit length also showed moderate indirect effects through the number of fruits per plant (0.40) and individual fruit weight (0.21). Rind thickness and fruit width had least indirect effects and did not significantly influence fruit yield.

Principal component analysis

The PCA indicated that the first three principal components explained 89.85% of the total variation in the dataset (56.22%, 22.79% and 10.84%, respectively), and were characterised by their corresponding eigenvectors, which are greater than 1 (Table 5). In the individual character loadings, it was found that the first principal component (PC 1) was heavily influenced by the number of fruits per plant (0.430), fruit yield (0.421), fruit width (0.403) and rind thickness (0.363). The second principal component (PC 2) was positively loaded with pH (0.591) and vitamin C content (0.251), and negatively loaded with individual fruit weight (–0.414). The third principal component (PC 3) was mainly driven by total soluble solids, which had a positive contribution of 0.835.

TABLE 3: Genotypic correlation of selected quantitative traits of citron watermelon accessions on fruit yield.

Trait	IFW	NFP	FY	FL	FW	RT
IFW	1.000	-	-	-	-	-
NFP	0.962**	1.000	-	-	-	-
FY	0.975**	0.990**	1.000	-	-	-
FL	0.575*	0.679**	0.686**	1.000	-	-
FW	0.319^{ns}	0.311^{ns}	0.369^{ns}	0.775**	1.000	-
RT	0.150^{ns}	0.270^{ns}	0.194^{ns}	0.269^{ns}	-0.199^{ns}	1.000

ns, non-significant at 5% level; IFW, individual fruit weight; NFP, number of fruits per plant; FL, fruit-length-(cm); FW, fruit width (cm); RT, rind thickness-(mm); FY, fruit yield (t/ha).
*, Significance at 5% level; **, Significance at 1% level.

TABLE 4: Path coefficient analysis on the direct (bold) and indirect effects of selected quantitative traits on fruit yield in citron watermelon accessions.

Trait	IFW	NFP	RT	FL	FW	FY
IFW	**0.36**	0.56	-0.01	0.10	-0.01	0.98**
NFP	0.35	**0.58**	-0.02	0.09	-0.01	0.99**
RT	0.05	0.16	**-0.06**	0.03	0.01	0.19^{ns}
FL	0.21	0.40	-0.02	**0.13**	-0.03	0.69**
FW	0.11	0.18	0.01	0.10	**-0.04**	0.37^{ns}

Note: Bold values are direct contributions.
ns, non-significant at 5% level; IFW, individual fruit weight; NFP, number of fruits per plant; FL, fruit-length-(cm); FW, fruit width (cm); RT, rind thickness-(mm); FY, fruit yield (t/ha).
*, Significance at 5% level; **, Significance at 1% level.

Discussion

Morphological variation in qualitative traits

In the current study, we observed a wide variation in the qualitative traits of the citron watermelon germplasm found in the Zimbabwe National Gene Bank. This variability offers a scope for qualitative trait improvement in citron watermelon. The wide range of FSs from flattened to oblate indicates extensive underlying genetic variation, which is likely the result of both natural selection and farmers' preferences. Other studies also reported a similar diversity in fruit morphology, which has been useful in classifying landraces and intensively guiding selection for marketing purposes (Dou et al. 2018; Legendre et al. 2020; Maragal, Rao & Lakshmana Reddy 2019; Mujaju et al. 2010).

The mixed and spotted patterns found in certain accessions may serve a dual purpose: they can act as a natural camouflage against pests, potentially reducing damage, while also enhancing visual appeal, making them more attractive to customers in traditional markets. This interplay suggests that aesthetic traits may have both economic and protective benefits. Liu et al. (2025) suggest that variations in skin colour and patterns influence heat tolerance. Light-coloured watermelons reflect sunlight, keeping them cool, while darker ones absorb heat, making them better suited for cooler climates. Predominant skin colours such as light and dark green may suggest local adaptation because colouration could affect heat absorption and the quality of the fruit (Mashilo et al. 2022).

Moreover, the diversity in SC has some practical value for genotype identification and may have cultural value among traditional communities. The various shades of SC from black or red to green observed in this study are indicative of differences in seed coat biochemistry that could affect

TABLE 5: Principal component analysis of yield and yield-related traits in citron watermelon accessions.

Trait	PC 1	PC 2	PC 3
Number of fruits per plant	**0.430**	0.082	0.104
Fruit length	**0.391**	-0.168	0.085
Individual fruit weight	**0.321**	-0.414	-0.176
Fruit width	**0.403**	0.056	0.286
Rind thickness	**0.363**	0.245	0.298
Vitamin C content	0.223	**0.547**	-0.162
Total soluble solids	-0.174	-0.251	**0.835**
Fruit yield	**0.421**	-0.141	-0.103
pH	-0.092	**0.591**	0.216
Eigen values	5.622	2.279	1.084
Percentage variation (%)	56.220	22.790	10.840
Cumulative variation (%)	56.220	79.010	89.850

Note: Bold values are the highest contributions.
PC, principal component.

germination, dormancy or seed storage behaviour. Ngwepe et al. (2021) also reported wide variability in seed coat colours in citron watermelon. The variation observed in the qualitative traits of citron watermelon can serve as a valuable marker for selecting desirable traits in crop improvement. In watermelon, important breeding objectives include developing desirable cultivars with phenotypic traits that include an ideal FS, rind patterns and flesh colour based on market demands (Coskun & Gulsen 2024b). The morphological variation in qualitative traits covered in this study offers a basis for future advancements in the productivity of citron watermelon.

Variation in quantitative traits of citron watermelon accessions

The wide morphological diversity in citron watermelon accessions can be utilised by breeders for selection, as no single accession possesses all the superior traits. Significant differences in yield-related traits such as number of fruits per plant, individual fruit weight and fruit yield reveal the potential of accessions like 185, 179 and 378 for utilisation as parents in hybridisation. High individual fruit weight and yield in accessions 378 and 179 imply suitability for commercial production, especially where bulk and appearance are critical factors in marketability. Similar findings have been reported in other cucurbits, where morphological diversity supports breeding for both crop improvement and productivity (Abd Rabou & El-Sayd 2021; Mujaju et al. 2010; Agah et al. 2021; Stone et al. 2019; Singh et al. 2019). Thick rinds are mainly important for fruits intended for transport and storage, reducing post-harvest losses because of mechanical damage (Amzeri et al. 2021; Stone et al. 2019). These characteristics are particularly valuable in dry regions and to farmers with poor storage facilities. The narrow diversity and the lack of statistical significance in total soluble solids, vitamin C content and pH suggest that the citron watermelon accessions studied are relatively the same in these quality traits. Moreover, this also points out limited potential for selection merely based on these traits within the current gene pool, suggesting the incorporation of more diverse germplasm if quality improvement is a breeding goal. The current findings are consistent with those of Mashilo et al. (2022a), who reported no significant differences in these traits. Conclusively, the current study stresses the potential of citron watermelon for both yield and resilience in rain-fed farming systems. Additionally, the highest performing accessions can be advanced for further multi-environment trials and genetic analysis to identify stable and high-performing accessions in diverse agro-ecological zones.

Correlation of selected quantitative traits of citron watermelon on fruit yield

The findings of the correlation analysis call for attention to the critical role played by the number of fruits per plant and individual fruit weight in determining yield in citron watermelon. The positive significant correlations among fruit yield, number of fruits per plant and individual fruit weight imply that these quantitative traits share a common genetic base that can be simultaneously inherited. These results, along with those reported by Khan et al. (2016) and Maurya et al. (2019) in bitter gourd, a related crop, clearly established the genetic basis for these types of correlations and how they can be utilised in crop improvement of cucurbits. Furthermore, Khan et al. (2016) and Singh et al. (2022) pointed out that the number of fruits per plant and individual fruit weight were major yield determinants. In this study, fruit length demonstrated significant positive correlations with fruit yield, number of fruits per plant and individual fruit weight, indicating that longer fruits contribute positively to overall yield. These findings are consistent with those of Agah et al. (2021) and Singh et al. (2022), who also reported positive associations among these traits. In contrast, fruit width and rind thickness exhibited no significant correlation with fruit yield. Although fruit width was positively associated with fruit length, its weak relationship with yield-related traits suggests that it plays a more morphological than productive role. Rind thickness was largely independent of the other traits studied, indicating that it may be more relevant to post-harvest durability or consumer preferences than to yield improvement. This independence presents a strategic advantage, as traits like rind thickness can be selected or modified to meet specific market or storage requirements without compromising yield. Conclusively, the selection for traits positively correlated with yield, such as number of fruits per plant, fruit weight and fruit length, can indirectly enhance overall productivity. The statistical methods of correlating quantitative traits, including the number of fruits per plant and the weight or size of the fruits, may enable more efficient and targeted breeding processes. The positive association of traits like fruit length and fruit width support the development of high-yielding hybrids that are also aligned with market preferences.

Path coefficient analysis on the effects of selected quantitative traits on fruit yield in citron watermelon accessions

Path analysis revealed that the number of fruits per plant and individual fruit weight directly and positively contributed to the yield. Similar results were also reported by Mohosina et al. (2020), Agah et al. (2021), Singh et al. (2022) and Nyurura and Maphosa (2022), who demonstrated that individual fruit weight and number of fruits per plant were major fruit yield determinants in watermelon. The strong positive correlation between the number of fruits per plant and fruit yield, along with its highest direct path coefficient, indicates that increasing the number of fruits per plant is a key strategy for enhancing overall yield. Additionally, the significant indirect effects of individual fruit weight, mediated through the number of fruits per plant, further reinforce its association with fruit yield. This suggests that accessions producing heavier fruits also tend to bear more fruits, a synergistic relationship that enhances selection efficiency in breeding programmes.

However, rind thickness and fruit width showed insignificant and even negative direct effects on yield, implying that

selection for these traits may not positively contribute to productivity. These findings correspond with those of Ngwepe et al. (2021) and Katuuramu et al. (2023), who suggest that excessively thick rinds or wide fruits may not improve marketable yield and could instead reduce edible biomass. Furthermore, the number of fruits per plant and individual fruit weight play a crucial role in yield improvement and, hence, need to be given priority in citron watermelon breeding. While fruit length may be given secondary priority, rind thickness and fruit width may be considered in yield improvement breeding programmes. These findings provide a foundation for trait-targeted selection in breeding programmes aiming for yield improvement of citron watermelon in semi-arid environments.

Principal component analysis of the selected quantitative traits in citron watermelon

The PCA results indicated that the first three principal components accounted for 89.85% of the variation within the dataset. The high cumulative variance suggests that these three components adequately summarise the multivariate data. This aligns with other research conducted in sweet watermelon germplasm collections (Assefa et al. 2020).

The first principal component (PC1) appeared to have strong positive loadings from fruit yield, number of fruits per plant, fruit width and fruit length. These traits are indicative of plant productivity and the size of the fruit, which means PC1 captures the overall agronomic performance. Therefore, PC1 gives a reflection of accessions with high yield potential. The findings of this study are similar to those of Ngwepe, Shimelis and Mashilo (2021), who reported that fruit weight and fruit yield are the principal determinants of variability in citron watermelon. In a study conducted by Huh et al. (2014) involving dessert watermelon accessions, fruit weight, particularly from Korean and Turkish varieties, along with fruit length and fruit width, were identified as key determinants of fruit yield. Similar findings in other cucurbits, including cucumber, summer squash, and bitter gourd, underscore the importance of yield, positively correlated with fruit length and weight (Jatav et al. 2022; Pal et al. 2018; Swain et al. 2022).

The second principal component (PC2) is primarily associated with vitamin C content and pH, while individual fruit weight and total soluble solids contribute negatively. This component captures the fruit physiology and quality distinguishing accessions relating to internal fruit traits rather than external shape. These accessions with high PC2 scores would most likely appeal to health-conscious customers or the processing industry because of their better nutritional quality. The same has been observed in tomato and citrus studies where vitamin C content and pH played a central role in distinguishing superior varieties post-harvest for extended shelf life (Guo et al. 2023; Zhang et al. 2023). The third principal component (PC3) is primarily driven by total soluble solids and pH, and rind thickness to a lesser extent. The influence of these parameters suggests that this axis measures sweetness and soluble content. Total soluble solids and pH are critical traits influencing taste and marketability. Total soluble solids, a well-established indicator of flavour and sugar concentration, play a central role in determining consumer preference. Their prominence in the PC3 suggests that this variable is particularly useful for distinguishing accessions suitable for fresh consumption or processing. Previous studies have consistently identified total soluble solids as a primary factor driving consumer appeal in watermelons (Mashilo et al. 2022b; Ren et al. 2021; Zhu et al. 2017).

Therefore, the PCA conducted on the fruit trait dataset was successful in recognising the important aspects of the phenotypic variability by segregating yield-dominant traits from quality traits. These more advanced approaches could combine PCA with cluster analysis or genome-wide association studies (GWAS), attending to the complex traits in order to uncover the more complex genetics behind these traits.

Conclusion

This study observed a wide variation in both qualitative and quantitative traits of the 10 citron watermelon accessions. Successful plant breeding relies on the presence of genetic variability, which is essential for trait improvement and adaptation to different market demands. This variation is important to meet the different market preferences of the fruits. Accessions 185, 378 and 179 were identified as promising and can be utilised in breeding programmes, where the number of fruits per plant, individual fruit weight and fruit yield per plant are top priorities. The findings suggest that there is scope to improve several yield-determining traits, such as the number of fruits per plant, individual fruit weight and fruit length in citron watermelon, which is a good basis for initiating a breeding programme for this crop using the available genetic resources. These findings lay the foundation for breeding programmes aimed at enhancing yield and marketability, ensuring citron watermelon's role in sustainable agriculture and food security.

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Competing interests

The authors declare that they have no financial or personal relationships that may have inappropriately influenced them in writing this article.

Authors' contributions

L.T. was responsible for the research trial establishment, data collection, analysis and original write-up of the article. M.M. was responsible for the research idea, supervision, original write-up of the article, review and editing.

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Data availability

The data supporting the findings of this study are available within the article.

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