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RESEARCH ARTICLE

Comparative study of varietal performance and spacing on the physico-chemical attributes of cashew (*Anacardium occidentale* L.) under various planting densities

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Abstract

A field trial was carried out at the AICRP on Cashew, Bhubaneswar, Odisha, India, during the 2022-23 and 2023-24 cropping seasons to evaluate the effect of cashew varieties and planting densities on the physio-chemical attributes of cashew. Three cashew varieties *viz*., VRI-3, NRCC Selection-2 and Balabhadra were evaluated under three different planting densities (2.5 m × 2.5 m, 3.0 m × 3.0 m and 7.5 m × 7.5 m). The results revealed non-significant variations of physio-chemical attributes within the planting densities. The highest physio-chemical attributes of both cashew apple and kernel *viz*., Total Soluble Solids (TSS) (12.47 °Brix), TSS: acid (32.04), ascorbic acid (192.35 mg/100 g), total sugar (11.20 %), reducing sugar (9.30 %), non-reducing sugars (1.77 %), protein (20.74 %), carbohydrates (21.29 %), fat (43.89 %) and calcium (0.039 %) were observed in the normal densities (7.5 m × 7.5 m), while the highest titratable acidity (0.42 %) was recorded at the closer spacing (2.5 m × 2.5 m). Genetic factors were found to be the primary drivers of variation in the quality of cashew apples and kernels. Among the tested varieties, VRI-3 variety exhibited highest TSS (12.58 °Brix), total sugar (11.18 %), reducing sugar (9.25 %) and non-reducing sugars (1.78 %), but highest ascorbic acid (199.15 mg/100 g) and calcium (0.39 %) was noted in Balabhadra variety. NRCC Selection-2 demonstrated highest protein (21.25 %), carbohydrates (21.62 %) and fat (44.40 %). These findings highlight the importance of variety selection in enhancing the quality of cashew production under ultra-high-density planting systems.

Keywords: cashew; NRCC Selection-2; planting density; physio-chemical attributes

Introduction

Cashew (*Anacardium occidentale* L.) belongs to family Anacardiaceae, is considered native to tropical America (South-East Brazil) and was first introduced to India by the Portuguese in the 16th century with the primary aim of afforestation and soil conservation and due to its high production potential in waste land so it is considered as gold mine. Although cashew is primarily cultivated for its kernel, cashew apple, testa and Cashew Nut Shell Liquid (CNSL) also hold significant importance. India is the largest cashew growing country and stand as the second largest producer in the world. In India, the total cashew production stands at approximately 7.81 lakh tonnes from an area of 11.92 lakh hectares, yielding a productivity of 766 kg per hectare. In Odisha, production reaches around 1.21 lakh tonnes from 2.23 lakh hectares, with a lower productivity rate of 655 kg per hectare during 2022-23 (1).

The cashew apple is botanically a pseudo fruit developed from the pedicel. Production of cashew apple in India is estimated around 56 lakh tones per annum (2). The apple is a rich source of fermentable sugar (10.4 %) and contains a high level of vitamin C (240 mg/100 g) of edible portion which is 3 to 6 times higher than that of orange juice and about 10 times more than that pineapple juice (3, 4). It is ideal for producing preserved products such as unfermented beverages like juice, pickle, candy, squash, chutney, jam and nectar. Additionally, it is also widely utilized in making fermented products like alcoholic drinks, including *fenni* (5). The juice of cashew apple has innumerable medicinal property and is used to cure Scurvy, Diarrhea, Uterine Complaints, Dropsy, Cholera and Rheumatism (6).

Cashew is mainly cultivated for its delicious and nutritious kernels. This is an important dollar earning crop whereby it stands as the third highest foreign exchange earner among all agricultural products and contributed significantly to Indian economy (7). India accounted for 15 % export of cashew to different parts of world with total valuation US$ 339.21 million during April 2023 to March 2024 (Ministry of Commerce and Industry, APEDA Agri. Exchange 2024). The kernel is an excellent source of nutrition, containing a unique composition of protein (21 %), carbohydrates (22 %), fat (47 %), vitamins and minerals (8). This makes its nutritional profile comparable to that of milk and eggs. Notably, approximately 82 % of its total fat content consists of unsaturated fatty acids, which help maintain or lower blood cholesterol levels. Additionally, cashews offer a naturally sweet flavor without contributing excessive calories (9).

Fruit quality is a critical aspect of horticultural production, as it directly influences consumer preference, market value, postharvest shelf life and nutritional benefits. High-quality fruits possess desirable traits such as attractive appearance, appropriate size and shape, sweetness, firmness, color, aroma and resistance to mechanical damage and spoilage. From a commercial perspective, superior fruit quality enhances competitiveness in both domestic and international markets, which is essential for increasing profitability and reducing postharvest losses (10). Furthermore, fruits with higher levels of vitamins, antioxidants and phytochemicals contribute significantly to human health and nutrition, aligning with the global demand for healthy diets (11).

Planting density, defined as the number of plants per unit area, plays a crucial role in optimizing resource use efficiency and ultimately influences both yield and fruit quality in horticultural crops. An ideal planting density enhances the crop canopy's capacity to intercept sunlight, absorb water and utilize nutrients efficiently, thereby promoting balanced vegetative and reproductive growth (13). Higher plant densities often result in increased overall productivity per hectare; however, they may compromise certain fruit quality parameters such as size, color and sweetness. Conversely, lower planting densities typically promote the development of larger fruits, which are more desirable in fresh markets due to their superior appearance and market value (14). Fruit quality traits such as firmness, color, aroma and nutritional content are directly influenced by environmental factors, particularly light interception. In dense or aging orchards, canopy overcrowding leads to poor light penetration, especially to the inner and lower parts of the canopy which negatively affects photosynthesis and results in inferior fruit quality (15). Studies on apple cultivars like 'Sinap Orlovskij' and 'Spartan' have shown that planting density has a cultivar-specific effect on fruit size and quality, with 'Spartan' producing smaller fruits under high-density systems, while 'Sinap Orlovskij' remained less affected by spacing (12). Similarly, in tree crops like mango and cashew, reduced light availability due to improper spacing or lack of canopy management has been associated with lower fruit quality (16). Over time, high-density systems can experience yield and quality decline due to excessive branch overlapping, poor light distribution and increased humidity, which encourages pest and disease incidence (17). Hence, strategic pruning becomes vital to regulate canopy structure, improve microclimatic conditions and sustain both productivity and fruit quality. Many researchers observed in their previous study by increasing plant density quality of fruits deteriorate (12, 16). Recognizing the complex interactions between genotype, planting density and canopy management, recent studies have focused on evaluating varietal responses of cashew (*Anacardium occidentale* L.) under varied planting densities to determine their impact on physico-chemical attributes of fruits.

Materials and Methods

Experimental site

A field experiment was carried out at the All India Coordinate Research Project on Cashew, Odisha University of Agriculture and Technology (OUAT), Bhubaneswar, India, during the 2022-23 and 2023-24 cropping seasons located at 20.27° N latitude and 85.84° E longitude, with an average elevation of 45 m above mean sea level. The climate of the experimental site was warm and humid, with hot and dry summers. The meteorological information gathered between 2022 and 2024 at the Meteorological department, OUAT, Bhubaneswar during the meteorological observational period is shown in Fig. 1 and 2.

Experimental layout and treatment details

The experiment was laid out in split plot design with three planting density of S_1: (2.5 × 2.5 m^2), S_2: (3 × 3 m^2) and S_3: (7.5 × 7.5 m^2) as main plots and three varieties such as V_1: VRI-3, V_2: NRCC selection-2 and V_3: Balabhadra as subplot and were replicated thrice (Table 1). The grafted cashew plants of varieties (Table 2) were planted during 2020. Uniform cultural practices were implemented across all treatments following the recommended standard cultivation practices. However, specific pruning methods were employed to manage plant growth based on the planting density. In the ultra-high-density planting system, severe pruning (heading back) was conducted to control plant height effectively. In contrast, light pruning was applied in the normal density planting system, where crisscross and overcrowded branches were removed during the month of June to ensure better canopy management.

Data gathering procedure

The process involved tagging one panicle in each cardinal direction (North, South, East and West) on the trees chosen for the experiment. False fruits and nuts produced from tagged panicles were then used to record data on physiological parameters of cashew apple and quality attributes of cashew apple and kernel.

Table 1. Treatment details

Main plots (spacings)	Symbols	Sub plots (varieties)	Symbols
2.5 m × 2.5 m	S_1	VRI-3	V_1
3.0 m × 3.0 m	S_2	NRCC Selection-2	V_2
7.5 m × 7.5 m	S_3	Balabhadra	V_3
Treatment combinations			
$T_1 = S_1 V_1$	$T_4 = S_2 V_1$		$T_7 = S_3 V_1$
$T_2 = S_1 V_2$	$T_5 = S_2 V_2$		$T_8 = S_3 V_2$
$T_3 = S_1 V_3$	$T_6 = S_2 V_3$		$T_9 = S_3 V_3$

Table 2. Characteristics of cashew varieties

Parameters	VRI-3	NRCC selection-2	Balabhadra
Released from	RRS, TNAU (1990)	DCR, Puttur, Karnataka (1989)	AICRP on Cashew, OUAT, BBSR (2008)
Breeding method	Selection (No. 1602)	Selection (2/9 Dicherla)	Hybrid (Bhubaneswar-1 × BBP-8)
Branching habit	Intensive	Extensive	Intensive
Flowering time	November-December	November-January	November-December
Apple color	Red	Pink	Yellow
Avg. nut weight	7.1 g	7.4 g	9.2 g
Shelling percentage	29.1	30	30
Grade	W-240 grade	W-210 grade	W-210 grade

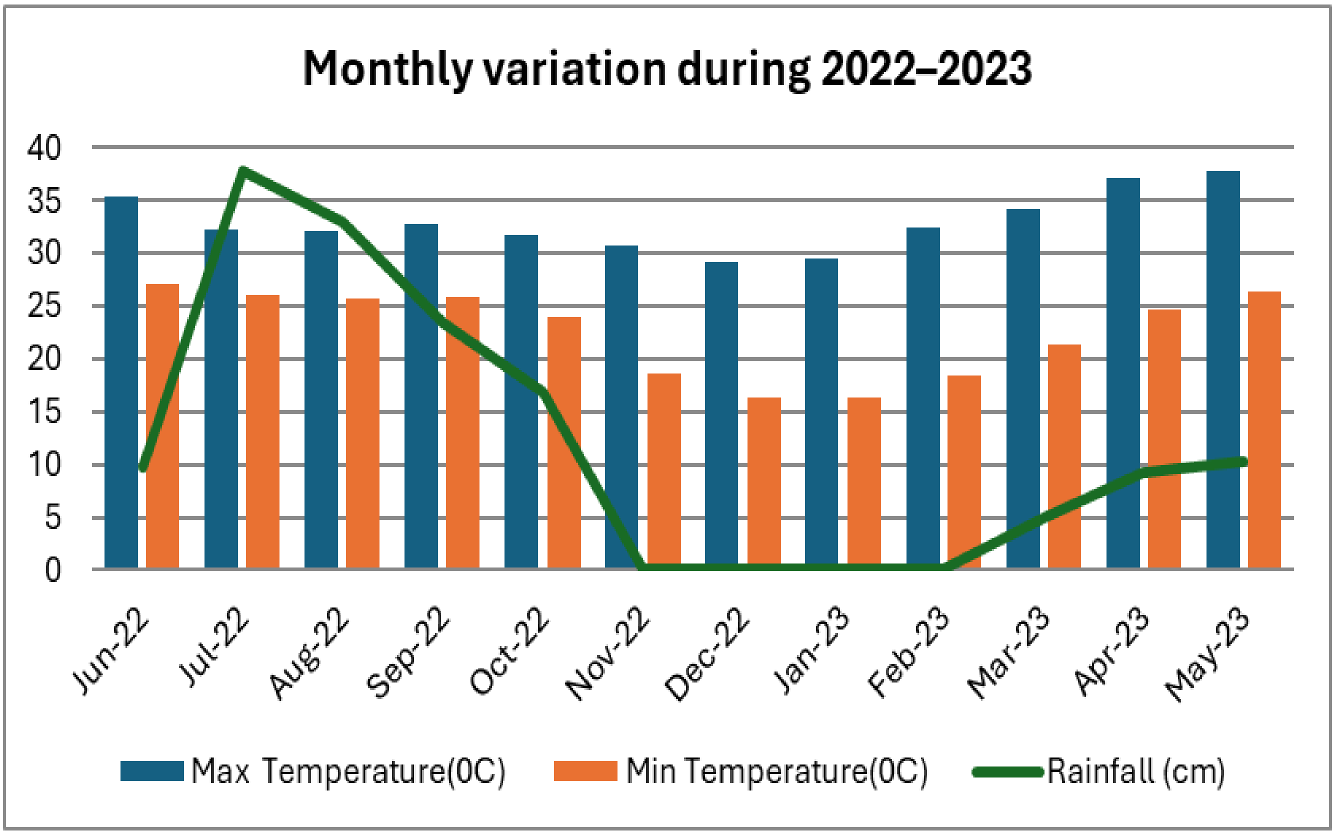

Fig. 1. Monthly variation in temperature and rainfall during 2022-2023.

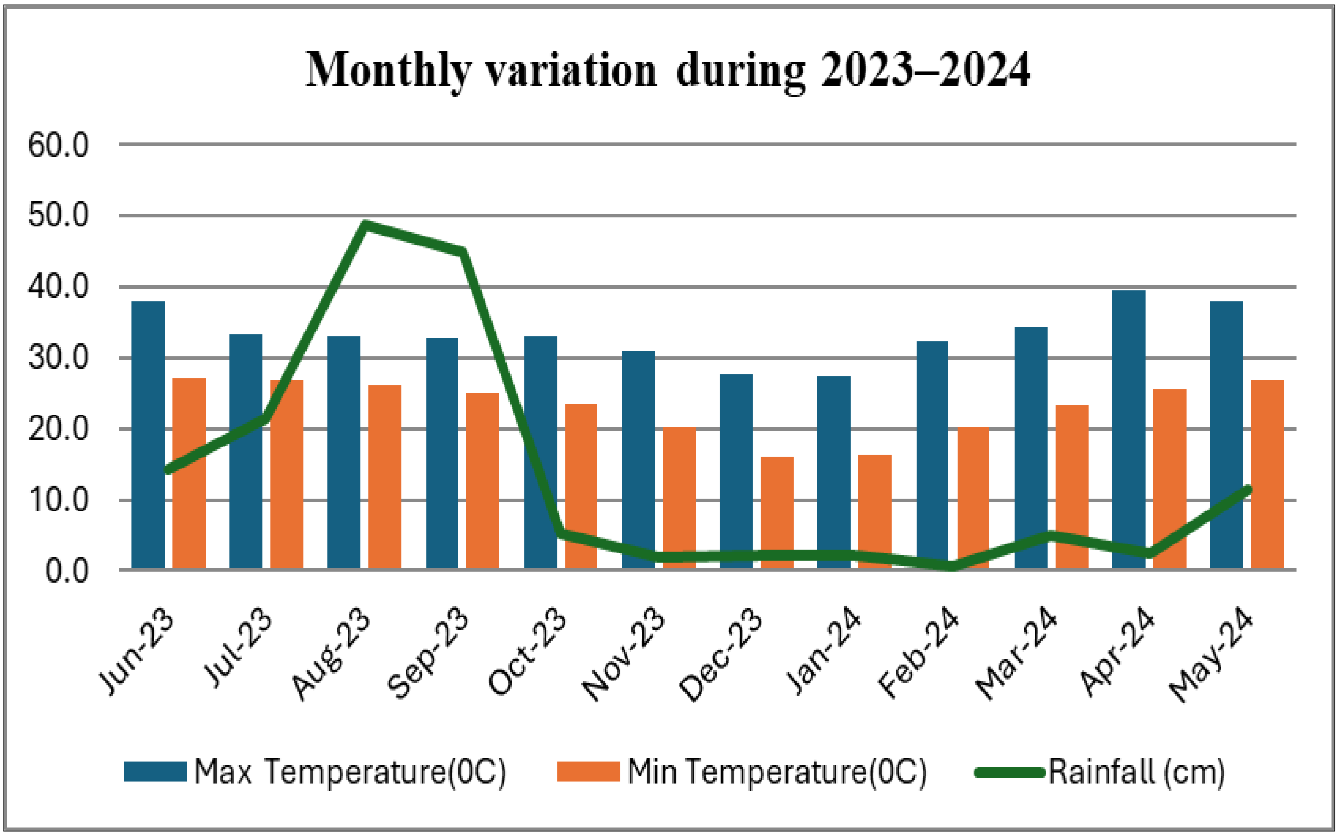

Fig. 2. Monthly variation in temperature and rainfall during 2023-2024.

Data collection process

To gather biometric data, six plants per treatment in each replication were selected. Observations were made on various physical parameters traits, along with biochemical properties of the cashew apple and kernels. The average values from the six plants in each treatment were subjected to statistical analysis.

Trait measurement

Cashew apples and nuts were harvested at full maturity and their quality attributes were analyzed in the laboratory. Observations were recorded for various quality parameters of both cashew apple and kernel, including Total Soluble Solids (TSS) (°Brix), acidity (%), TSS: Acid, ascorbic acid (mg/100 g), total sugar, non-reducing sugar, reducing sugar, carbohydrates (%), protein (%), fat (%), calcium (mg/100 g) and phosphorus (mg/100 g). Physical parameters, including apple length (cm), weight (g) and breadth (cm) were measured using ten ripened cashew apples per treatment at different stages of the apple production season-initial, mid and final.

Physical parameters of cashew apple

To assess the physical characteristics of cashew apples, ten apples were randomly selected from each treatment. Their lengths were measured using a digital Vernier caliper and the average was calculated and expressed in centimeters. Similarly, the width of each apple was measured at both the wider and narrower parts using the digital Vernier caliper and the mean width was recorded in centimeters. After separating the nuts, the apples were weighed using a digital weighing balance to determine their individual weights. The average apple weight was then calculated and expressed in grams.

Quality attributes of cashew apple

The TSS (°Brix) of fruit juice were analyzed using a digital refractometer. Titrable acidity (%) was analyzed by titrating the juice extract with 0.1N NaOH, following the standard procedure outlined in previous studies (18). TSS/acid ratio was calculated by using following formula: TSS/Titrable acidity. Total, non-reducing and reducing sugar content was estimated using the method described by researcher (19). Ascorbic acid content was estimated using the 2,6-dichlorophenol indophenol titration method (20).

Quality attributes of kernel

Protein content of cashew kernel was estimated by Lowry method (21), while carbohydrate content was determined using the protocol of Hodge and Hofreiter (22). Calcium content was analyzed as per the procedure described by Jackson (23). Fat content was analyzed using the procedure outlined by Sadasivam and Manickam (24).

Statistical analysis

The experimental values were analyzed statistically by using split plot design (SPD) with two factors and three replications. The data was analyzed statistically by using MS excel (25). The person correlation coefficient was calculated by using KAUGRAPES software (26).

Results and Discussion

Physical parameters of cashew apple

The apple characters such as cashew apple weight (g), cashew apple length (cm) and cashew apple width (cm) were not influenced by varieties and spacing interactions. The data illustrated in Table 3 indicated significant influence of planting density on physical parameters of cashew apple. The widest spacing (S_3: 7.5 m × 7.5 m) yielded the highest apple weight (61.15 g), apple length (5.65 cm) and apple width (4.24 cm). In contrast, the closest spacing (S_1: 2.5 m × 2.5 m) resulted in the lowest values for apple weight (56.10 g), apple length (5.40 cm) and apple width (3.85 cm). Notable increase in apple weight in different plant density might be due to higher accumulation of carbohydrate because of higher photosynthetic activity and reduced competition for nutrients and better light penetration in wider planting systems as compared to ultra-high and high-density plantings (29-31). The least values of apple characters were noticed in ultra density planting system compared to other wider space planting. It is mainly because of more number of panicles per unit canopy area which leads to competition for nutrients among fruits within the panicle (27). Similar findings

Table 3. Effect of spacing and varieties on physical attributes of cashew apple

Treatments	Apple weight (g)	Apple length (cm)	Apple width (cm)
Main plot			
S_1:2.5 m × 2.5 m	56.10	5.40	3.85
S_2: 3 m × 3 m	57.98	5.51	4.00
S_3: 7.5 m × 7.5m	61.15	5.65	4.24
SE(m) ±	1.431	0.077	0.098
CD @ 5 %	NS	NS	NS
Sub plot			
V_1: VRI 3	48.17	4.71	3.96
V_2: NRCC Sel.2	66.82	5.48	4.41
V_3: Balabhadra	60.24	6.36	3.72
SE(m) ±	0.694	0.045	0.033
CD (P = 0.05)	2.264	0.149	0.107
Interaction			
S_1V_1	46.50	4.62	3.81
S_1V_2	64.82	5.32	4.26
S_1V_3	56.98	6.26	3.50
S_2V_1	47.68	4.70	3.93
S_2V_2	66.57	5.48	4.39
S_2V_3	59.69	6.34	3.67
S_3V_1	50.33	4.82	4.15
S_3V_2	69.06	5.64	4.59
S_3V_3	64.07	6.49	3.98
SE(m) ±	1.203	0.079	0.057
CD (P = 0.05)	NS	NS	NS

were noted in fruit crops (33, 49, 50). Notable differences were also observed among the three cashew varieties grown under varying spacing treatments. The NRCC Selection-2 variety (V_2) exhibited the highest apple weight (66.82 g) and apple width (4.41 cm), while the Balabhadra variety (V_3) recorded the greatest apple length (6.36 cm). Conversely, the VRI-3 variety (V_1) had the lowest apple weight (48.17 g), whereas the Balabhadra variety (V_3) showed the smallest apple width (3.72 cm). Variation in cashew apple characters in genotypes was primarily driven by genetic factors, rather than the interaction between genotype and spacing. Similar observations were recorded in cashew (27, 28), Loquat (49), Mango (51, 52).

Apple quality parameters

The interaction between varieties and spacing showed no significant effect on apple quality parameters, including TSS, titratable acidity, TSS: acid ratio, ascorbic acid, total sugar, reducing sugar and non-reducing sugar across three cashew varieties and spacing treatments (Table 4). The planting density did not significantly affect the quality parameters of cashew apple. The maximum TSS (12.47 °Brix), TSS: acid ratio (32.04), ascorbic acid (192.35 mg/100g), total sugar (11.20 %), reducing sugar (9.30 %) and non-reducing sugar (1.77 %) were recorded in the spacing of (S_3) 7.5 m × 7.5 m, while the minimum was observed in the spacing of (S_1) 2.5 m × 2.5 m. The maximum titratable acidity (0.41 %) was recorded in the spacing of (S_1) 2.5 m × 2.5 m, the minimum was observed in the spacing of (S_3) 7.5 m × 7.5 m. Maintaining an optimal tree planting density enhances light interception, thereby improving photosynthetic efficiency and increasing net photosynthesis. However, excessively high planting densities can lead to a decline in fruit quality, as supported by previous studies (32-34). In this study, trees cultivated at a density of 178 trees ha^{-1} exhibited higher photosynthetic activity, which likely contributed to better fruit quality. Insufficient light penetration in dense plantations likely restricted carbohydrate accumulation, negatively affecting fruit sweetness (33, 34-37). Canopy height varies with planting density and in high-density orchards, pruning was often necessary to maintain optimal canopy structure. However, excessive pruning and training practices can influence the biochemical composition of fruits (38, 39). Among the three varieties, the VRI-3 variety recorded the highest TSS (12.58 °Brix), titratable acidity (0.42 %), total sugar (11.18 %), reducing sugar (9.25 %) and non-reducing sugar (1.78 %). Meanwhile, the maximum TSS: acid ratio (33.35) was observed in NRCC Selection-2, while Balabhadra had the highest ascorbic acid content (199.15 mg/100 g). The variation in cashew apple quality in different genotypes was primarily governed by genetic factors. Studies have shown notable differences in cashew apple quality among various genotypes, highlighting the significant role of inheritance in shaping the commercial and nutritional attributes of the fruit. The findings were consistent with the previous study (8, 40-42).

Kernel quality parameters

The interaction between variety and spacing had no significant effect on the quality parameters of cashew kernel under the UHD system (Table 5). The study found no significant influence of planting density on the quality parameters of cashew kernel. The widest spacing (S_3: 7.5 m × 7.5 m) resulted in the highest values for protein (20.74 %), carbohydrates (21.29 %), fat (43.89 %) and calcium (0.039 %), whereas the closest spacing (S_1: 2.5 m × 2.5 m) recorded the lowest values for these parameters. More quality attributes in wider spacing may be due to receiving better light penetration, enhancing photosynthetic activity (29-31). Previous studies have also reported that higher planting densities tend to reduce fruit quality, leading to lower concentrations of soluble solids, sucrose, sorbitol, fructose, glucose and organic acids such as citric and malic acids (34, 43, 44). Significant variations were noted among the three cashew varieties cultivated under different spacing treatments. The NRCC selection-2 variety (V_2) exhibited the highest protein (21.25 %), carbohydrates (21.62 %) and fat (44.40 %) content, while the Balabhadra variety (V_3) had the highest calcium content (0.039 %). Conversely, the lowest protein (19.64 %) and fat (39.69 %) content were observed in the VRI-3 variety (V_1), whereas Balabhadra (V_3) recorded the lowest carbohydrate content (20.82 %). The NRCC Selection-2 variety

Table 4. Effect of spacing and varieties on biochemical attributes of cashew apple

Treatments	TSS (°brix)	Acidity (%)	TSS:acid ratio	Ascorbic acid (mg/100g)	Total Sugar (%)	Reducing sugar (%)	Non reducing sugar (%)
				Main plot			
S_1:2.5 m × 2.5 m	12.11	0.41	29.90	183.16	10.93	9.08	1.71
S_2: 3 m × 3 m	12.21	0.40	30.82	186.65	11.06	9.20	1.73
S_3: 7.5 m × 7.5 m	12.47	0.39	32.04	192.35	11.20	9.30	1.77
SE(m) ±	0.112	0.006	0.674	2.757	0.084	0.068	0.021
CD @ 5 %	NS	NS	NS	NS	NS	NS	NS
				Sub plot			
V_1: VRI 3	12.58	0.42	30.09	174.72	11.18	9.25	1.78
V_2: NRCC Sel.2	12.39	0.37	33.35	188.29	11.07	9.20	1.73
V_3: Balabhadra	11.82	0.40	29.31	199.15	10.96	9.13	1.70
SE(m) ±	0.037	0.004	1.095	2.016	0.028	0.020	2.016
CD (P = 0.05)	0.108	0.013	3.197	5.885	0.083	0.059	5.885
				Interaction			
S_1V_1	12.37	0.43	28.85	167.34	11.05	9.16	1.75
S_1V_2	12.21	0.38	32.02	187.56	10.94	9.10	1.71
S_1V_3	11.75	0.41	28.82	194.59	10.80	8.99	1.68
S_2V_1	12.48	0.42	29.61	175.56	11.17	9.25	1.77
S_2V_2	12.36	0.37	33.42	187.03	11.07	9.20	1.73
S_2V_3	11.80	0.40	29.41	197.36	10.96	9.14	1.69
S_3V_1	12.88	0.41	31.81	181.27	11.31	9.35	1.82
S_3V_2	12.61	0.37	34.59	190.29	11.19	9.30	1.76
S_3V_3	11.91	0.40	29.71	205.49	11.11	9.25	1.73
SE(m) ±	0.074	0.009	1.592	4.032	0.057	0.040	0.022
CD (P = 0.05)	NS	NS	NS	NS	NS	NS	NS

Table 5. Effect of spacing and varieties on biochemical attributes of cashew kernel

Treatments	Protein (%)	Carbohydrates (%)	Fat (%)	Calcium (%)
		Main plot		
S_1: 2.5 m × 2.5 m	20.29	20.97	43.44	0.036
S_2: 3 m × 3 m	20.43	21.05	43.58	0.037
S_3: 7.5 m × 7.5 m	20.74	21.29	43.89	0.039
SE(m) ±	0.138	0.104	0.168	0.001
CD @ 5 %	NS	NS	NS	NS
		Sub plot		
V_1: VRI 3	19.64	20.87	42.79	0.038
V_2: NRCC Sel.2	21.25	21.62	44.40	0.035
V_3: Balabhadra	20.57	20.82	43.72	0.039
SE(m) ±	0.113	0.072	0.045	0.001
CD (P = 0.05)	0.328	0.212	0.131	0.003
		Interaction		
S_1V_1	19.43	20.78	42.58	0.036
S_1V_2	21.14	21.43	44.29	0.033
S_1V_3	20.30	20.69	43.45	0.038
S_2V_1	19.54	20.80	42.69	0.039
S_2V_2	21.22	21.59	44.37	0.035
S_2V_3	20.54	20.76	43.69	0.039
S_3V_1	19.97	21.04	43.12	0.041
S_3V_2	21.39	21.83	44.54	0.037
S_3V_3	20.86	21.00	44.01	0.041
SE(m) ±	0.225	0.145	0.193	0.001
CD (P = 0.05)	NS	NS	NS	NS

(V_2) exhibited the lowest calcium content (0.035 %). The variation in the quality of cashew kernels was primarily influenced by genetic factors, which determine quality attributes such as protein, fat and carbohydrate content. Different cashew genotypes exhibit distinct physiological and metabolic characteristics, contributing to variations in kernel quality. Previous studies had consistently highlighted the role of genetic diversity in kernel biochemical composition. Researchers observed significant differences in cashew kernel quality across different cultivars and breeding lines, indicating that inheritance plays a crucial role in determining the commercial and nutritional value of the kernels (40-42, 45-48).

Correlation study between genotypes and spacing on physio-chemical attributes of cashew

A Pearson correlation coefficient analysis was carried out to study the relationship between apple physico-chemical parameters under various planting densities and varieties for pooled data (Fig. 3). Apple physical attributes exhibited positive correlation with protein, carbohydrates, fats and calcium and found negatively correlated with TSS, total sugar, reducing and non-reducing sugar and titratable acidity (P < 0.5). Apple biochemical parameter like TSS was found positively associated with characters such as apple weight, apple width, TSS: acid, total sugar, carbohydrate, reducing and non-reducing sugar

Traits	AW	AL	AW	TSS	TA	TSS/A	AA	TS	RS	NRS	P	CHO	F	Ca
AW	1.0000													
AL	0.6157	1.0000												
AW	0.5499	-0.2628	1.0000											
TSS	-0.2415	-0.7934	0.6539	1.0000										
TA	-0.9302	-0.3331	-0.7459	-0.0557	1.0000									
TSS/A	0.6402	-0.1249	0.9467	0.5708	-0.8454	1.0000								
AA	0.6986	0.9486	-0.0592	-0.6280	-0.4572	0.0481	1.0000							
TS	-0.1791	-0.5019	0.5648	0.8383	0.0025	0.4284	-0.3013	1.0000						
RS	-0.0457	-0.3685	0.6022	0.7639	-0.0990	0.4725	-0.1617	0.9856	1.0000					
NRS	-0.4020	-0.7028	0.4574	0.9205	0.1855	0.3278	-0.5258	0.9397	0.8709	1.0000				
P	0.9924	0.5471	0.6110	-0.1560	-0.9584	0.7052	0.6538	-0.1291	-0.0044	-0.3350	1.0000			
CHO	0.7447	-0.0422	0.9470	0.4335	-0.8924	0.9643	0.1092	0.2989	0.3587	0.1777	0.7917	1.0000		
F	0.9924	0.5471	0.6110	-0.1560	-0.9584	0.7052	0.6538	-0.1291	-0.0044	-0.3350	1.0000	0.7917	1.0000	
Ca	-0.0412	0.5139	-0.3041	-0.1843	0.2192	-0.2447	0.5253	0.2610	0.3279	0.1211	-0.0854	-0.3407	-0.0854	1.0000

Fig. 3. Correlation study of the interaction between genotypes and spacing on physio-chemical attributes of cashew. AW: apple weight; AL: apple length; AWi: apple width; TSS: total soluble solids; TA: titratable acidity; TSS/TA: TSS acid ratio; AA: ascorbic acid; TS: total sugar; RS: reducing sugar; NRS: non-reducing sugar; P: protein; CHO: carbohydrates; F: fat; Ca: calcium.

content whereas negatively associated with protein, fat, calcium and ascorbic acid content. Ascorbic acid content is one of the important biochemical parameters of cashew apple and it was found positively associated with apple weight, apple length, TSS: acid, protein, carbohydrate, fat and calcium whereas negatively correlated with TSS and titratable acidity. Protein, carbohydrate and fat content of cashew apple observed positive correlation with apple physical parameters, TSS, TTS: acid and ascorbic acid content however, negatively associated with calcium content of cashew apple.

Conclusion

The study revealed that genetic factors significantly influenced the physio-chemical attributes of cashew apples and kernels, while planting density had a non-significant effect. The highest physico-chemical attributes were observed at a planting density of 7.5 m × 7.5 m, while the lowest were recorded at 2.5 m × 2.5 m spacing. Among the varieties, VRI-3 showed superior sugar-related traits, Balabhadra had the highest ascorbic acid and calcium content and NRCC Selection-2 recorded the highest protein, carbohydrate and fat content. For long-term sustainability and improved quality, the development of dwarf cashew varieties could further optimize and promote the adoption of ultra-high-density planting systems in cashew cultivation.

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Authors' contributions

All the authors contributed to the above work, starting from designing the experiment, collecting data, assisting with statistical analysis, interpretation of results and manuscript preparation. CKR and PKP conceptualized the research; CKR, PKP and KS designed the experiments; PKP, KS and CJ contributed experimental materials; CKR, PKP, KS and RKN executed the field and laboratory experiments and data collection; CKR, SCS, SS and CJ assisted in data analysis and technical guidance; CKR, PKP and KS prepared the manuscript; CJ, BRN and KKM contributed to manuscript modifications and coordination. All the authors read and approved the final manuscript.

Compliance with ethical standards

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

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