

Diversity in tree and fruit traits of wood apple (*Limonia acidissima* L.) genetic resources collected from south India

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Research Article

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Abstract

Wood apple (*Limonia acidissima* L.) is an undomesticated nutritionally and medicinally potential monotypic tree species of the genus *Limonia*, which belongs to the family Rutaceae. This species is remained underexploited due to a lack of awareness regarding its significance and systematic study of its diversity. The present work was carried out to recognize the elite populations for future cultivation among the studied populations of South India. Considering a wide genetic diversity in wood apples, 32 populations were assessed by the prepared set of qualitative and quantitative traits presented in this study. The tree height ranges between 7.68 to 16.69 m, canopy area was 18.78 to 36.36 m³ whereas, the weight of the fruits ranges between 118.30 to 233.42 g, the percentage composition of pulp was 53.91 to 72.93% and the percentage composition of seed was 4.02 to 9.07%. The tree with medium height with an average of 11.13 m and having average stem girth of 2.62 m showed large-sized fruits with an average weight of 233.43 g and an average percentage of 65.04% of pulp (TN-03). The obtained results were subjected to multivariate statistical analysis, using the techniques of principal component analysis and cluster analysis, and were formed into 4 clusters. The formation of different clusters shows the genetic variability and the dissimilarity among the genotypes which could guide the selection of elite genotypes to enrich the programs of genetic improvement of the wood apple. Out of 4 cluster groups, cluster 1 and cluster 2 could be used for domestication programs because they showed superior fruit-related traits by having the highest fruit, pulp, and seed weight even though they have average morphology of trees.

Introduction

Shortage of food sources due to the increasing population rate of the world permits the interest towards the undomesticated edible fruit-bearing plants. Fruits are a vital source of essential fats, amino acids, vitamins, mineral elements, and dietary fiber (Murthy and Bapat 2020). In addition to these constituents, fruits are also rich in proteins, fats, carbohydrates, and reducing and non-reducing sugars. *Limonia acidissima* is commonly called wood apple, elephant apple, monkey fruit, and curd fruit. Wood apple is a deciduous, erect, slow-growing tree up to 12 to 15 meters tall with firm bark and sharp spines (Morton 1987). It is a fruit-bearing tree native to India, which is distributed throughout the plains of India, particularly in drylands up to an elevation of 450 m (Orwa et al. 2009).

The whole plant and its parts such as leaves, roots, bark, and unripe and ripened fruits have been used as medicine to treat diseases. Various ethnopharmacological characterizations were reported in the previous literature. Extracts of plant parts including leaf, stem, bark, fruit, and seeds were used to cure several diseases (Joshi et al. 2011. Sharma et al. 2012). The leaf decoction was used to cure constipation and vomiting (Chatterjee 2000). The fruit pulp is used for relief against the cough, hiccup, tumors, asthma, leucorrhoea, diarrhea, dysentery, and wound healing activity (Ilango and Chitra 2009) and is a potential source of natural antioxidants (Ilaiyaraja et al. 2015). The preliminary phytochemical analysis resulted in the presence of phenolics, flavonoids, alkaloids, terpenoids, tannins, fats, sterols, saponins, glycosides, gum, mucilage, and fixed oils (Vijayvargia et al. 2014). Seeds are rich in protein, carbohydrate, amino acid, and mineral content (Sonawane et al. 2016).

Wood apple fruits remained underexploited and they are at the border of extinction due to the negligence by researchers and policymakers (Murthy and Dalawai 2020). Cultivation of wild and underexploited plants could offer their full potential utilization (FAO 1999). According to Govindaraj et al. (2015), genetic variability will be assessed by using various methods such as agronomical, phenotypical, biochemical, and marker studies, which could enable the breeders to select genotypes with contrasting traits. Whereas, a thorough analysis of morphological diversity provides a strong base to select the promising genotypes for the cultivation programs (Schlautman et al. 2020). Hence, an assessment of genetic diversity in wood apples is necessary to cultivate for the sustainable exploitation to produce valuable products, to meet the global needs.

Singh et al. (2016) and Dowarah et al. (2021) conducted a survey of diversity-rich areas of Gujarat and West Bengal and got a wide range of genetic diversity in the wood apple in terms of fruit's physical and chemical attributes. Even though there is an abundant diversity in wood apples in South India, there were no reports on the variability and breeding programs. Hence the present work is undertaken to assess the variability in trees and fruits among the population of wood apple in Southern India and it is also to recognize the elite population/s which will be included in cultivation and production.

Materials And Methods

Field survey

The Southern region of India including the districts of Karnataka, Andhra Pradesh, Telangana, Tamil Nadu, and Kerala was undertaken for the field survey, during the year 2019–2021 (Fig. 1; Table 1). Visited various forest zones and carried out extensive field studies to complete all the geographical areas of districts of Southern states of India. Based on the herbaria references, floristic reports, and critical observations, wild populations of wood apple were located and characterized. In this current study, only the natural forests and protected areas were used to select the wild and natural populations of wood apples. Tree and fruit morphology of a population were considered for characterization and collected the fruits for future analysis.

Table 1
Geological location of populations of wood apple collected from Southern India

Sl. No.	State	Population	Location	District	Latitude	Longitude	Elevation (m)
1)	Karnataka	KA- 01	Sandur Forest	Ballary	15°03'22.6"N	76°30'60.0"E	587
2)		KA- 02	Talya-Mavinakatte Forest	Chitradurga	13°56'13.0"N	76°14'46.3"E	769
3)		KA- 03	Gollapade Forest	Chikkaballapur	13°23'14.4"N	77°46'30.0"E	924
4)		KA- 04	Thondala Forest	Kolar	13°11'56.2"N	78°14'48.2"E	827
5)		KA- 05	Bannerghatta Forest	Bangalore urban	12°46'47.1"N	77°35'28.0"E	887
6)		KA- 06	Savanadurga Forest	Ramanagar	12°52'41.8"N	77°18'58.9"E	776
7)		KA- 07	Ballapura Forest	Tumkur	13°24'55.6"N	77°02'24.6"E	813
8)		KA- 08	Chowdlapura Forest	Tumkur	13°18'03.9"N	76°35'09.7"E	893
9)		KA- 09	Hagalawadi- Bukkapatna	Tumkur	13°32'00.3"N	76°44'43.3"E	751
10)		KA- 10	Nagapuri Forest	Hassan	13°20'48.8"N	76°17'57.6"E	856
11)		KA- 11	Bandipur Reserve Forest	Chamarajanagar	11°53'46.7"N	76°30'22.5"E	776
12)	Andhra Pradesh	AP- 01	Peddacheruvu	Kurnool	15°58'05.1"N	78°51'11.1"E	618
13)		AP- 02	Chelama-Pacherla Forest	Kurnool	15°26'38.5"N	78°42'13.9"E	339
14)		AP- 03	Chinthala (Peddachama)	Prakasam	15°56'48.3"N	78°58'28.2"E	389
15)		AP- 04	Guvvalacheruvu Forest	Cuddapah	14°16'49.1"N	78°50'27.6"E	618
16)		AP- 05	Talakona Forest	Chittoor	13°50'01.0"N	79°09'28.5"E	577
17)		AP- 06	Koundinya WLS	Chittoor	12°50'36.9"N	78°32'53.0"E	751
18)		AP- 07	Puttaparthi	Anantapur	14°13'44.4"N	77°52'27.3"E	627
19)	Telangana	TS- 01	Sathupally Forest	Khammam	17°14'18.8"N	80°46'14.2"E	153
20)		TS- 02	Muddalagudem Forest	Mulugu	18°08'33.8"N	80°13'09.1"E	183
21)		TS- 03	Sarvapuram, Pegadapalli	Mulugu	18°05'35.2"N	80°03'22.0"E	223
22)		TS- 04	Burgumpet	Bhupalapally	18°20'07.4"N	80°04'03.2"E	200
23)		TS- 05	Matwad-Otla Forest	Mahabubabad	17°46'03.2"N	80°02'27.6"E	235
24)		TS- 06	Talamalla, Dandepally	Macherial	19°01'22.9"N	79°11'52.0"E	225
25)		TS- 07	Manchippa Forest	Nizamabad	18°31'57.1"N	78°09'17.9"E	482
26)		TS- 08	Banswad, Narsapur	Kamareddy	18°22'13.7"N	77°56'08.3"E	507
27)	Tamil Nadu	TN- 01	Kilkothur- Alangayam	Vellore	12°46'50.5"N	78°58'48.1"E	402
28)		TN- 02	Jawdhu Hills- Pujarikote	Krishnagiri	11°59'46.5"N	78°38'03.9"E	365
29)		TN- 03	Poongurthi Forest	Krishnagiri	12°39'09.2"N	78°16'20.5"E	631
30)		TN- 04	Sengler- Kottapatti	Thirupattur	11°59'46.5"N	78°38'03.9"E	365
31)		TN- 05	Veppadi-Manmalai Forest	Attur	11°22'51.0"N	78°39'47.3"E	221
32)	Kerala	KL- 01	Agali- Anaikatti Forest	Palakkad	11°05'46.3"N	76°42'22.1"E	849

Collection of sample

Randomly 20 fruit-bearing trees were selected for each genotype and a distance of a minimum of 50 m was kept among the trees to select and collect the sample. 10 fruits were collected from different branches of each plant; these were pooled and transferred soon in gunny bags to the laboratory for further analysis. Fruits were collected at the matured stage, during the months of January-March. This was indicated by fruits naturally detached from a tree or dull greyish white color of rind (Murrinie et al. 2017).

Morphological characterization

Morphological characterization of wood apple trees and fruits was conducted with the help of 16 morphological traits including 1 qualitative and 15 quantitative traits. These traits were used to assess the variability among the 32 populations of wood apples were recorded (Table 2). The quantitative characteristics of the tree including tree height, bole length, and canopy height were achieved using the Ravi Altimeter instrument whereas, the girth of the stem and canopy area including east to west and north to south was achieved with the measuring tape.

Table 2
Morphological characters used to assess the variability among the populations of wood apple

Sl. No.	Trait	Description	Phenotype score
Qualitative traits			
1	Shape of fruit	Matured fruit shape	1. Round
			2. Flattened round
			3. Oblong
			4. Oval
			5. Ovate/ Triangular
Quantitative traits			
2	Tree height	Measured in meters	-
3	Bole length	Measured in meters	-
4	Girth of stem	Measured in meters	-
5	Canopy area of the tree	Measured in meters	-
6	Fruit length	Measured in cm	-
7	Fruit width	Measured in cm	-
8	Fruit circumference	Measured in cm	-
9	Fruit weight	Measured in gram	-
10	Pulp weight	Measured in gram	-
11	Seed weight	Measured in gram	-
12	Number of seeds	Average of 10 fruits	-
13	Rind weight	Measured in gram	-
14	Rind thickness	Measured in cm	-
15	% Composition of pulp	Per 100 gram fruit	-
16	% Composition of seed	Per 100 gram fruit	-

Characterization of fruits was done from three different lots of fruits; each group consisted of 10 randomly picked from each population. The rind was cracked manually and the fruit pulp with seeds was scooped out. The manually separated fruit pulp and seeds were stored for further characterization. The shape of the fruit was considered a qualitative trait, which was allotted with phenotypic scores ranging from 1 to k (k equal to a number of classes), to specify distinct degrees of expression (Table 2). Furthermore, the same phenotypic scores were used to compare the qualitative and quantitative data together. According to Beentje (2016), the shapes of fruits were recorded.

Quantitative characterization of fruits of collected populations was measured individually with the assistance of measuring instruments. The fruit, pulp, rind, and seed weight were noted using the electronic balance and expressed in grams, whereas fruit length, width, and rind thickness were noted with the help of a Vernier caliper and expressed in centimeters. The number of seeds present was counted manually and expressed in a number of seeds per fruit. Finally, the percentage composition of pulp and seeds was recorded and expressed as per 100-gram fruit.

Statistical methods

Descriptive statistics including minimum value, maximum value, average value, standard deviation, and coefficient of variation were determined for each morphological quantitative trait for each population with the help of Microsoft Excel 2016 and all the additional studies were carried out by using SPSS v20.0 (IBM SPSS Statistics, 2011). For quantitative and qualitative traits the mean values and phenotypic scores were used respectively, for other analyses. Pearson correlation matrix was analyzed to find the strength of linear association between each trait. Principal component analysis was used to identify the elite characteristics representing the populations, by using Z-scores and by standardizing original values. Lastly, all the populations were grouped by the k-means clustering method and drawn the scatter plot graph by using the scores of the first two principal components.

Results And Discussion

Distribution

Various states of south India including Andhra Pradesh, Telangana, Tamil Nadu, and Kerala possess rich biodiversity because of the significant topographic, edaphic, and climatic heterogeneity of nature. The geography of this region is diverse with two mountain ranges - Western and Eastern Ghats. The Western Ghats run parallel to the Arabian Sea which continues south until Kanyakumari. Whereas, the Eastern Ghats run parallel to the Bay of Bengal and finally join

the Western Ghats at Nilgiri mountains. Field survey depicts that, all the states except Kerala, show a rich diversity of wood apples. In total 32 genotypes were recognized during the field survey and the location, altitude, and geographical coordinates for each genotype were depicted in Table 1. Throughout the dry deciduous and semi-arid regions of Southern India, wood apple is distributed, majorly North-Western part of Tamil Nadu and Eastern Ghats of Andhra Pradesh compared to the Northern, Central, and Southern parts of Karnataka, Northern region of Telangana, and Central region of Kerala (Fig. 1). The altitude ranges of distribution were from 153 to 924 m above mean sea level, whereas, the rich distribution of wood apples observed during the field visit was at the altitude range from 200 to 577 m (Table 1).

Wood apple is native to India and distributed in dry deciduous regions of Burma, Sri Lanka, Pakistan, and Bangladesh and it is commonly grown throughout Southeast Asia and Northern Malaya (Morton 1987). In India and Sri Lanka, it is cultivated along roads and edges of fields and occasionally in orchards. In Malaysia and Indonesia, it is cultivated in villages and parks (Verheij and Coronel 1992). The tree is subtropical and it prefers dry climatic conditions for flowering and fruit set which is commonly found throughout Southern India. As we observed during the field survey, the wood apple is a dry plains moderate drought-resistant tree species, that prefers mainly a monsoon climate with distinct dry or deciduous forests. Mainly large number distribution was found in wild forests, neglected areas, and majorly on plains or hills, whereas the density will decrease as the altitude increases. The wood apple tree may grow on a variety of soil types; the decreasing order of soil with respect to growth richness is red soil, black cotton soil, sandy loamy soils, and red-black mixed soil. Furthermore, they are generally associated with species bearing spines and thorns such as species of *Balanites* Delile., *Ziziphus* Mill., *Acacia* Mill., and *Capparis* Tourn. ex L., *Albizia* Durazz., and *Diospyros* L.

North-Western regions of Tamil Nadu and Southern regions of Andhra Pradesh are the rich distribution centers of wood apple in the Southern states of India. This is because, they show the characteristics of a monsoon climate with a different dry season and have moderate rainfall (Guhathakurta et al. 2020b, 2020d). Whereas, the other surveyed regions of Eastern Karnataka, Northern Telangana, and the North-West part of Palakkad, Kerala showed lesser distribution as these regions receive lesser rainfall as compared to the average rainfall of the respective states (Guhathakurta et al. 2020a, c).

Genetical variability with respect to fruit yield and morphological traits of wood apple in West Bengal was reported by Ghosh et al. (2012). They noted that a tree of age 13 to 70 years can produce 5000 to 6000 fruits per tree. In another study, Dowarah et al. (2021) reported the importance of wood apple and fruit characterization in some diversity-rich districts of the wood apple of West Bengal. The above results depict that the climatic changes incorporated with genetic variation resulted in the creation of a great morphological diversity of fruits among the different genotypes of wood apple in Southern India.

Tree and fruit morphological characterization

Variability among the same species of plants favors the way of flexibility and allows them to be adjusting better to the environmental changes. Characterization of morphology of trees and fruits was achieved on the bases of 16 selected qualitative and qualitative traits (Table 2). Tables 3 and 4, depict that all the 32 surveyed populations exhibited notable variability among themselves. Tree growth and fruit morphological characteristics of wood apple genotypes were depicted in Table 3. The measured plant growth including tree height, stem girth, bole length, and canopy area is associated with the yield and physical quality of fruits. The plant height, stem girth, and bole length of studied populations ranged from 7.68 to 16.69 m, 0.98 to 2.62 m, and 1.47 to 3.57 m respectively (Table 3). Greater than half of the population (53.12%) showed the tree height in the range of 11.37 to 13.35 m. The maximum plant height was recorded in AP-01 (16.69 m) followed by TS-04 (15.49 m), AP-02 (14.88 m), TS-01 (14.25 m), AP-05 (13.90 m), and AP-07 (13.47 m). However, the minimum was noted in the population TS-03 (7.68 m) followed by KA-02 (9.09 m), KA-04 (10.12 m), TS-07 (10.28 m), KA-05 (10.37 m), KA-07 (10.95 m) and TS-08 (11.28 m). The maximum and minimum value of stem girth was observed in TN-03 (2.62 m) and KA-02 (0.98 m) populations respectively. From the aerial region to the first branching of the tree is considered as bole length, the maximum bole length was observed in the genotype AP-02 (3.57 m) and the minimum was in TN-03 (1.47 m). In total 37.50% of populations showed greater stem girth and bole length when compared to average stem girth (1.67 m) and bole length (2.49 m). Increased canopy area could contribute to the significant variation in fruit yield per tree. The total canopy spread is measured in m³ and is varied from 18.78 to 36.36 with population's average of 28.67. The maximum canopy area was observed in population TS-04 (36.36) followed by TN-03 (35.10), TN-01 (34.19), AP-03 (33.55), and so on, whereas the minimum was observed in TS-03 (18.78) followed by AP-06 (21.06), KA-02 (21.93). Significant variation in plant height of different populations may be due to the growth of respective genotypes in a particular environment as well as edaphic conditions. Higher stem girth and high canopy spread might also contribute to the maximum fruit quality in genotypes TN-03, AP-03, TS-01, TS-07, and TN-05 (Table 3).

Table 3

Variability in quantitative characters of tree and fruit, descriptive statistics, and the cluster group of wood apple populations collected from sou

Genotypes	Morphology of tree				Fruit characteristics										
	Height (m)	Bole length (m)	Stem girth (m)	Canopy area (m) ³	Fruit length (cm)	Fruit width (cm)	Fruit girth (cm)	Fruit weight (g)	Pulp weight (g)	Seed weight (g)	Rind weight (g)	No. of seeds	Rind Thickness (cm)	Pulp (%)	Seed (%)
KA- 01	12.28 ± 0.66	1.88 ± 0.41	1.09 ± 0.07	26.45 ± 2.63	8.42 ± 0.18	7.42 ± 0.14	23.30 ± 0.42	185.69 ± 2.44	108.65 ± 1.90	8.40 ± 0.21	68.62 ± 0.51	285.66 ± 4.40	0.42 ± 0.00	58.50 ± 0.26	4.5 ± 0.0
KA- 02	9.09 ± 0.67	1.55 ± 0.29	0.98 ± 0.07	21.93 ± 1.05	7.68 ± 0.13	6.80 ± 0.13	21.36 ± 0.56	140.04 ± 3.25	83.86 ± 1.29	7.78 ± 0.48	48.38 ± 1.53	235.33 ± 6.43	0.40 ± 0.00	59.91 ± 0.48	5.5 ± 0.2
KA- 03	12.38 ± 0.36	2.64 ± 0.42	2.11 ± 0.51	33.30 ± 1.09	6.56 ± 0.11	7.02 ± 0.07	22.33 ± 0.32	146.64 ± 1.23	79.42 ± 0.89	5.90 ± 0.17	61.31 ± 0.67	121 ± 1.15	0.41 ± 0.00	54.15 ± 0.25	4.0 ± 0.1
KA- 04	10.12 ± 0.09	2.34 ± 0.22	1.60 ± 0.02	31.23 ± 0.40	7.42 ± 0.19	7.43 ± 0.10	23.42 ± 0.29	171.49 ± 1.76	94.24 ± 1.13	9.71 ± 0.25	67.54 ± 0.44	446.66 ± 1.85	0.42 ± 0.00	54.95 ± 0.25	5.6 ± 0.0
KA- 05	10.37 ± 0.25	2.47 ± 0.26	1.45 ± 0.08	30.38 ± 0.94	7.54 ± 0.07	7.42 ± 0.05	23.32 ± 0.15	170.56 ± 1.71	91.97 ± 1.24	10.28 ± 0.40	68.31 ± 0.33	368.66 ± 3.48	0.42 ± 0.00	53.91 ± 0.25	6.0 ± 0.2
KA- 06	12.56 ± 0.48	2.26 ± 0.26	1.14 ± 0.07	32.62 ± 2.05	7.51 ± 0.03	7.63 ± 0.08	23.84 ± 0.30	160.35 ± 0.81	90.66 ± 1.35	14.55 ± 0.27	55.13 ± 1.93	459.33 ± 4.33	0.42 ± 0.00	56.54 ± 0.93	9.0 ± 0.2
KA- 07	10.95 ± 0.09	2.14 ± 0.43	1.23 ± 0.01	30.1 ± 1.61	7.20 ± 0.14	7.31 ± 0.06	23.16 ± 0.25	152.15 ± 1.85	85.38 ± 0.76	9.45 ± 0.26	57.30 ± 0.83	283.66 ± 3.84	0.37 ± 0.00	56.12 ± 0.19	6.2 ± 0.0
KA- 08	12.54 ± 0.23	2.89 ± 0.01	1.28 ± 0.02	32.21 ± 0.39	6.84 ± 0.04	7.71 ± 0.03	24.08 ± 0.11	179.83 ± 1.92	96.97 ± 1.69	13.37 ± 0.30	69.48 ± 0.40	535 ± 3.78	0.42 ± 0.00	53.91 ± 0.45	7.4 ± 0.1
KA- 09	11.37 ± 0.49	2.74 ± 0.49	1.59 ± 0.06	32.76 ± 0.26	7.00 ± 0.14	7.43 ± 0.10	23.46 ± 0.63	186.58 ± 1.32	103.03 ± 1.50	10.35 ± 0.17	73.19 ± 0.76	405.33 ± 3.84	0.41 ± 0.00	55.22 ± 0.55	5.5 ± 0.0
KA- 10	13.03 ± 0.29	3.00 ± 0.11	1.34 ± 0.04	32.10 ± 0.40	7.96 ± 0.09	7.36 ± 0.13	23.02 ± 0.38	157.47 ± 2.40	85.78 ± 2.04	11.05 ± 0.10	60.63 ± 0.64	444.33 ± 5.45	0.42 ± 0.00	54.46 ± 0.55	7.0 ± 0.0
KA- 11	12.73 ± 0.54	3.4 ± 0.46	1.88 ± 0.32	30.21 ± 2.65	7.89 ± 0.07	7.83 ± 0.40	23.23 ± 0.15	159.65 ± 2.44	89.90 ± 1.67	9.18 ± 0.21	60.57 ± 1.51	340 ± 5.50	0.44 ± 0.001	56.31 ± 0.75	5.7 ± 0.0
AP- 01	16.69 ± 1.17	2.98 ± 0.41	1.42 ± 0.14	32.97 ± 1.34	6.88 ± 0.20	7.39 ± 0.23	23.04 ± 0.70	148.53 ± 2.82	81.31 ± 1.91	10.15 ± 0.30	57.05 ± 0.81	337.33 ± 5.54	0.42 ± 0.002	54.73 ± 0.25	6.8 ± 0.1
AP- 02	14.88 ± 0.45	3.57 ± 0.22	1.44 ± 0.16	23.40 ± 0.88	7.18 ± 0.09	7.22 ± 0.28	23.44 ± 0.25	138.73 ± 0.76	87.04 ± 0.72	7.28 ± 0.14	44.41 ± 1.62	242.33 ± 6.00	0.41 ± 0.003	62.74 ± 0.85	5.2 ± 0.1
AP- 03	11.81 ± 0.97	1.87 ± 0.14	1.61 ± 0.05	33.55 ± 2.14	7.92 ± 0.01	8.37 ± 0.06	26.2 ± 0.24	175.09 ± 2.36	102.87 ± 1.46	11.10 ± 0.14	61.12 ± 1.43	354.33 ± 3.75	0.42 ± 0.004	58.75 ± 0.49	6.3 ± 0.1
AP- 04	13.28 ± 0.21	2.52 ± 0.35	1.28 ± 0.15	32.81 ± 1.52	7.06 ± 0.03	7.14 ± 0.02	22.50 ± 0.11	118.30 ± 1.38	70.19 ± 1.44	8.20 ± 0.09	39.90 ± 0.12	315.66 ± 9.70	0.41 ± 0.004	59.31 ± 0.54	6.9 ± 0.0
AP- 05	13.9 ± 0.11	2.3 ± 0.22	1.39 ± 0.08	23.00 ± 0.49	7.04 ± 0.15	7.38 ± 0.17	22.16 ± 0.52	146.01 ± 1.38	78.81 ± 0.87	10.00 ± 0.18	57.19 ± 0.40	287.66 ± 3.84	0.44 ± 0.008	53.97 ± 0.11	6.8 ± 0.1
AP- 06	12.44 ± 0.34	2.29 ± 0.20	1.6 ± 0.17	21.06 ± 0.27	7.29 ± 0.02	8.49 ± 0.07	25.02 ± 0.17	162.85 ± 1.65	87.85 ± 0.44	10.45 ± 0.16	64.54 ± 1.62	306.66 ± 5.20	0.40 ± 0.006	53.95 ± 0.49	6.4 ± 0.1
AP- 07	13.47 ± 0.18	2.16 ± 0.06	1.62 ± 0.08	23.20 ± 0.12	7.45 ± 0.40	6.71 ± 0.45	20.29 ± 1.21	152.19 ± 3.09	82.40 ± 3.53	9.99 ± 0.32	59.80 ± 0.24	345.33 ± 5.89	0.42 ± 0.02	54.09 ± 1.23	6.5 ± 0.3
TS- 01	14.25 ± 0.19	3.29 ± 0.94	2.17 ± 0.03	23.93 ± 0.22	8.27 ± 0.15	8.18 ± 0.08	24.52 ± 0.22	203.92 ± 1.59	119.44 ± 0.83	14.06 ± 0.05	69.90 ± 0.88	472 ± 7.76	0.44 ± 0.002	58.57 ± 0.10	6.8 ± 0.0

Genotypes	Morphology of tree				Fruit characteristics											
	Height (m)	Bole length (m)	Stem girth (m)	Canopy area (m) ³	Fruit length (cm)	Fruit width (cm)	Fruit girth (cm)	Fruit weight (g)	Pulp weight (g)	Seed weight (g)	Rind weight (g)	No. of seeds	Rind Thickness (cm)	Pulp (%)	Seed (%)	
TS- 02	12.57 ± 0.20	2.05 ± 0.06	1.89 ± 0.02	23.4 ± 1.03	7.61 ± 0.05	8.13 ± 0.03	24.55 ± 0.12	160.27 ± 0.75	105.22 ± 0.68	7.25 ± 0.04	48.38 ± 1.71	249.66 ± 6.96	0.40 ± 0.002	65.65 ± 0.57	4.5 ± 0.0	
TS- 03	7.68 ± 0.10	2.11 ± 0.11	1.15 ± 0.03	18.78 ± 0.35	7.12 ± 0.15	7.40 ± 0.19	22.23 ± 0.60	195.93 ± 1.14	115.82 ± 0.67	14.35 ± 0.21	65.10 ± 1.01	505.66 ± 6.33	0.38 ± 0.001	59.11 ± 0.27	7.3 ± 0.0	
TS- 04	15.49 ± 0.21	3.19 ± 0.01	2.58 ± 0.12	36.36 ± 0.21	6.39 ± 0.05	7.29 ± 0.08	21.85 ± 0.25	174.83 ± 2.66	108.13 ± 0.84	13.36 ± 0.27	55.39 ± 0.27	374 ± 7.93	0.43 ± 0.005	61.87 ± 0.96	7.6 ± 0.1	
TS- 05	12.20 ± 0.40	2.46 ± 0.04	2.01 ± 0.07	25.50 ± 1.32	7.25 ± 0.17	7.65 ± 0.04	22.95 ± 0.12	170.49 ± 0.57	96.63 ± 0.39	12.28 ± 0.29	61.36 ± 0.59	342 ± 3.21	0.44 ± 0.001	56.67 ± 0.24	7.2 ± 0.1	
TS- 06	13.01 ± 0.48	2.50 ± 0.04	1.46 ± 0.10	24.48 ± 0.76	7.81 ± 0.08	7.33 ± 0.17	21.97 ± 0.49	160.52 ± 1.14	100.47 ± 0.96	10.05 ± 0.11	51.46 ± 0.82	384.33 ± 6.35	0.39 ± 0.001	62.59 ± 0.52	6.2 ± 0.0	
TS- 07	10.28 ± 0.11	2.28 ± 0.02	2.08 ± 0.07	32.96 ± 0.21	8.99 ± 0.24	9.13 ± 0.06	27.45 ± 0.22	186.30 ± 0.48	112.40 ± 0.99	14.89 ± 0.13	56.29 ± 0.30	500.66 ± 7.68	0.41 ± 0.004	60.33 ± 0.58	7.9 ± 0.0	
TS- 08	11.19 ± 0.29	2.28 ± 0.09	2.07 ± 0.04	30.22 ± 0.18	6.80 ± 0.23	6.95 ± 0.32	20.86 ± 0.98	152.97 ± 0.31	98.85 ± 0.56	11.21 ± 0.21	41.05 ± 1.21	347.33 ± 8.41	0.43 ± 0.003	64.62 ± 0.23	7.3 ± 0.1	
TN- 01	13.35 ± 0.15	2.7 ± 0.21	1.34 ± 0.03	34.19 ± 1.24	7.31 ± 0.05	7.72 ± 0.10	23.05 ± 0.20	153.16 ± 2.68	111.63 ± 0.78	9.06 ± 0.09	34.96 ± 1.18	317 ± 14.73	0.38 ± 0.002	72.93 ± 1.45	5.9 ± 0.0	
Genotypes	Morphology of tree				Fruit characteristics											
	Height (m)	Bole length (m)	Stem girth (m)	Canopy area (m) ³	Fruit length (cm)	Fruit width (cm)	Fruit girth (cm)	Fruit weight (g)	Pulp weight (g)	Seed weight (g)	Rind weight (g)	No. of seeds	Rind Thickness (cm)	Pulp (%)	Seed (%)	
TN- 02	9.76 ± 0.09	2.37 ± 0.12	2.29 ± 0.06	27.99 ± 0.97	6.78 ± 0.10	6.97 ± 0.13	20.73 ± 0.26	130.67 ± 1.58	78.16 ± 0.83	10.96 ± 0.10	39.93 ± 1.16	340 ± 12.34	0.37 ± 0.01	59.82 ± 0.39	8.3 ± 0.1	
TN- 03	11.13 ± 0.06	1.47 ± 0.13	2.62 ± 0.25	35.10 ± 0.36	8.32 ± 0.23	9.74 ± 0.19	29.01 ± 0.43	233.42 ± 2.84	151.82 ± 2.13	9.98 ± 0.06	71.63 ± 0.74	315.33 ± 8.08	0.41 ± 0.005	65.03 ± 0.12	4.2 ± 0.0	
TN- 04	13.19 ± 0.18	3.43 ± 0.27	1.76 ± 0.04	31.12 ± 1.46	7.17 ± 0.08	6.09 ± 0.08	18.25 ± 0.23	138.06 ± 1.74	82.41 ± 0.97	7.77 ± 0.28	47.87 ± 0.55	269.66 ± 8.19	0.39 ± 0.00	59.69 ± 0.14	5.6 ± 0.1	
TN- 05	9.89 ± 0.24	2.13 ± 0.14	2.57 ± 0.20	23.60 ± 0.82	8.24 ± 0.06	8.04 ± 0.09	24.20 ± 0.36	136.13 ± 1.26	79.65 ± 0.95	11.48 ± 0.31	44.99 ± 0.65	242.66 ± 10.03	0.43 ± 0.008	58.51 ± 0.18	8.4 ± 0.2	
KL- 01	10.00 ± 0.34	2.31 ± 0.21	1.42 ± 0.26	26.71 ± 2.07	7.60 ± 0.11	7.47 ± 0.04	23.59 ± 0.15	155.80 ± 1.17	97.21 ± 1.12	10.06 ± 0.33	50.25 ± 1.13	258 ± 16.19	0.36 ± 0.01	62.39 ± 0.78	6.4 ± 0.1	
Min	7.68	1.47	0.98	18.78	6.39	6.09	18.25	118.3	70.19	5.90	34.96	121	0.36	53.91	4.0	
Max	16.69	3.57	2.62	36.36	8.99	9.74	29.01	233.42	151.82	14.89	73.19	535	0.44	72.93	9.0	
Average	12.12	2.49	1.67	28.67	7.45	7.57	23.20	162.64	95.57	10.44	56.66	344.77	0.41	58.73	6.4	
SD	1.92	0.52	0.45	4.79	0.58	0.69	2.08	23.34	16.15	2.26	10.34	92.01	0.02	4.40	1.2	
CV%	15.84	21.07	27.06	16.72	7.88	9.18	8.65	14.35	16.90	21.66	18.26	26.68	5.13	7.60	18.8	

Table 4
Variance of qualitative traits in wood apple populations collected from south India

Trait	Class	Number of populations	% of populations
Shape of fruit	Round	17	53.12
	Flattened round	7	21.87
	Oblong	6	18.75
	Oval	1	3.12
	Ovate/ Triangular	1	3.12

Wood apple is a nutritious fruit, as compared to many other edible fruits (Ratnayake et al. 2009). Fruit characteristics of surveyed populations of wood apple exhibited a wide range of variability. The fruit shape was observed as round (53.12%), flattened round (21.87%), oblong (18.75%), oval (3.12%), and triangular (3.12%). A considerable range of variability has been noticed with respect to fruit weight, length, width, and circumference, and the weight of pulp, rind, and seeds among the selected 32 populations as given in Table 3. The weight of the fruit is a remarkable trait which will be ranged from 118.30 to 233.42 g with a standard deviation of 23.34 and a coefficient of variation of 14.35%, this may be due to the weight of each component of fruit including pulp, rind, and seed weight. The maximum fruit weight was noted in population TN-03 (233.42 g) followed by TS-01 (203.92 g) and TS-03 (195.93 g), whereas, the minimum weight recorded in AP-04 (118.30 g) followed by TN-02 (130.67 g), TN-05 (136.13 g) and TN-04 (138.06 g). About 40.62% of population showed more than average fruit weight (162.64 g). The maximum fruit weight in populations TN-03, TS-01, and TS-03 may be due to the greater canopy area which facilitates the high photosynthetic rate and may lead fruits to attain maximum size. Similar results were observed by Singh et al. (2016). Fruit length and width are directly proportional to the weight of fruit, the maximum fruit length was noted in TS-07 (8.99 cm) followed by KA-01 (8.42 cm) and TN-03 (8.32 cm), whereas TS-04 (6.39 cm), followed by KA-03 (6.56 cm) and TN-02 (6.78 cm) was recorded for minimum fruit length. Similarly, the width of the fruit ranged from TN-04 (6.09 cm) to TN-03 (9.74 cm) and the circumference of the fruit ranged from TN-04 (18.25 cm) to TN-03 (29.01 cm). Likewise the literature showed the significant variability in fruit shape, fruit weight, length, width, and circumference of 25 germplasm of wood apple from Gujarat were noted by Singh et al. (2016) and Dowarah et al. (2021) reported similar results in 12 selected genotypes from West Bengal.

Wood apple fruit pulp might be eaten raw with or without the sugar and used especially for the preparation of jam, jelly, and cordials (Panda 2000). The results concern pulp weight in different populations of wood apple (Table 3) showed that the maximum pulp weight was observed in populations TN-03 (151.82 g), which was followed by TS-01 (119.44 g) and TS-03 (115.82 g), whereas the minimum pulp weight was observed in population AP-04 (70.19 g) followed by TN-02 (78.16 g) and AP-05 (78.81 g), respectively. With respect to pulp weight, significant variation was observed in the different ti populations, this may be influenced by fruit size, weight, and lesser number of seeds within the fruit. Greater pulp weight is might be an important trait for fruit to reach good market value. The seed weight of each population of wood apple was noted and depicted in Table 3. Minimum seed weight was noted in population KA-03 (5.90 g), which was at par with TS-02 (7.25 g) and AP-01 (7.28 g) followed by KA-02 (7.77 g) and (7.78 g), whereas the maximum seed weight was noted under TS-07 (14.89 g) which was at par with KA-06 (14.55 g), TS-03 (14.35 g) and is followed by KA-01 (13.37 g) and TS-04 (13.36 g). The rind is the non-edible outer covering of the wood apple fruit so the minimum rind weight is an utmost valid trait for selecting the fruit having more pulp weight. The minimum rind weight was observed in the population TN-01 (34.96 g) followed by TN-02 (39.93 g), TS-08 (41.05 g), and TS-02 (44.38 g). Whereas, the maximum rind weight was observed in KA-09 (73.19 g) followed by TN-03 (71.63 g), TS-01 (69.90 g), and KA-08 (69.48 g). With respect to the thickness of the rind, more than 68.75% of the tipopulation showed greater than average rind thickness (0.41), whereas the genotype KL-01 (0.36 mm) showed the minimum thickness, and 0.44 mm of maximum rind thickness was observed in the populations KA-10, AP-05, TS-01, and TS-05. The wood apple fruit pulp is embedded with white numerous seeds, which could be used for oil extraction (Lamani et al. 2021). The results of studied populations showed the maximum number of seeds in population KA-08, and the minimum was in population KA-03, but 43.75% of populations were recorded for more than the average (344.77) number of seeds per fruit. The percentage composition of pulp showed considerable variability among the populations which ranged from population KA-08 (53.91%) to TN-01 (72.93%) and this also impacts the weight of the pulp. For example, population KA-08 showed a fruit weight of 179.83 g and pulp weight of 96.97 g whereas the population TN-01 showed 153 g of fruit weight, nearly one-fourth of the former one, and a pulp weight of 111.63 g. This is because of the smaller size and less weight of fruit. Even though the fruits of KA-08 showed greater size and weight, the contribution of pulp to the total fruit weight is very less, when compared to TN-01. The percentage composition of seeds recorded in the population showed greater variability, whereas the maximum percentage of seeds was observed in KA-06 (9.07%) and the minimum percentage in KA-03 (4.02%). Regarding the ratio of pulp to seed weight, the maximum ratio was observed in KA-06 (16.06 g) and the minimum was observed in TN-03 (6.58 g). These results fell in with the findings of Ghosh et al. (2011), Singh et al. (2016), and Dowarah et al. (2021) in wood apple.

Coefficient of variation (CV) is a statistical measure of the relative dispersion and variability extent of a character in relation to the mean data. The following results of this study showed much variation among themselves. Among the morphological traits of the tree, stem girth showed a maximum (27.06%) coefficient of variation followed by a number of seeds (26.68%), seed weight (21.66%), bole length (21.00%), rind weight (18.26%), pulp weight and canopy area (16.72%). A similar pattern of variability was observed by Singh et al. (2016) in fruit characteristics among the population of *Limonia acidissima* from Gujarat that is the maximum critical difference was obtained in a number of seeds at 41.20% at a 95% confidence limit followed by fruit weight (30.70%) and pulp weight (19.20). Whereas, the minimum critical difference was observed in rind thickness (0.04%) followed by seed weight (0.59%), fruit length (0.84%), and fruit width (0.86%). Dowarah et al. (2021) found a similar variability pattern among the populations of *Limonia acidissima* from diversity-rich areas of West Bengal. Greater variability in morphological traits of fruit within the population of *Limonia acidissima* reflects the effects of genotype, environment, and interaction of both. The studied qualitative trait, fruit shape showed variability among the genotypes (Fig. 2). Among the population 53.12% of population were represented by a round shape, 21.87% by a flattened round, and 18.75% by oblong shapes. Oval and triangular shapes were observed only in TN-05 and

KA-11 populations respectively (Table 4). However, the study undertaken discloses the maximum diversity in the morphological traits of trees and fruits within 32 populations distributed in different geographical regions of Southern India.

Correlation between the traits

The correlation coefficient is important to know the statistical relationship between the morphological traits which could play an important role in the selection of populations for cultivation programs. To measure the strength of linear association between each trait Pearson's correlation coefficients were used and this will show the positive and negative relationships between characters, where the 'r' value of '1' indicates a complete positive correlation and '-1' indicates a complete negative correlation. Correlation analysis expressed a highly remarkable positive correlation (Table 5) between tree height and bole length ($r = 0.60$), and between tree height and rind thickness ($r = 0.42$). Stem girth showed the high positive correlation with fruit width ($r = 0.45$) and pulp weight ($r = 0.43$). Fruit length also showed positive and significant correlation with fruit width ($r = 0.59$), fruit circumference ($r = 0.58$), pulp weight ($r = 0.41$) and fruit weight ($r = 0.40$). The above correlation analysis revealed that more fruit length is directly proportional to more fruit width, circumference, and pulp weight. Fruits with more width showed a very high positive correlation with fruit circumference ($r = 0.95$), pulp weight ($r = 0.66$), and fruit weight ($r = 0.65$) which means the width of fruit increases with an increase in fruit circumference, pulp and fruit weight. Fruit circumference also showed a high positive correlation with fruit weight ($r = 0.62$), pulp weight ($r = 0.60$), and rind weight ($r = 0.40$), this reveals that the fruit circumference increases due to an increase in the weight of fruit, pulp, and rind. Among the traits studied, fruit weight is the major trait to influences yield and this may be influenced by increasing in the total constituents and has shown a high correlation with the pulp weight, rind weight, number of seeds, and seed weight (Table 5). Fruit weight showed a similar positive correlation compared to fruit width which showed a very high positive correlation, that it ($r = 0.89$) with pulp weight and possesses a commanding effect on it by considering 53.91% (KA-05) to 72.93% (TN-01) of the total weight. Fruit weight also highly correlates with rind weight ($r = 0.74$), number of seeds ($r = 0.50$) and seed weight ($r = 0.46$). Pulp weight shows positive correlation with percentage composition of pulp ($r = 0.48$) and rind weight ($r = 0.39$). Seed weight is another major trait, which influences great commercial value because of high seed oil content which showed a high positive correlation with the number of seeds ($r = 0.81$), followed by the percentage composition of seeds ($r = 0.77$) and pulp to seed ratio ($r = 0.74$). Rind weight has a positive correlation with the number of seeds ($r = 0.39$). The number of seeds showed a positive correlation with pulp to seed ratio ($r = 0.54$) and percentage composition of seeds ($r = 0.52$). Percentage composition of seed showed a very high positive correlation with pulp to seed ratio ($r = 0.94$). The above-obtained results were agreed almost exactly with the findings of Rezaei et al. (2019) on the fruits of *Prunus armeniaca*. In contrast, the rind weight showed a high negative correlation with the percentage composition of pulp ($r = -0.59$), and a negative correlation was also observed between rind thickness and percentage composition of pulp ($r = -0.35$) as well as between percentage composition of pulp and pulp to seed ratio ($r = -0.45$). The other traits of trees such as bole length and canopy area do not have a significant correlation with any of the traits. The overall studied results revealed that we can select a particular population for more bole length, fruit pulp, and seed yield. Along with this, we can also consider selecting and improving distinct populations for bole length, fruit pulp, and seed yield to reach the demands of consumers.

Table 5
Pearson's correlation matrix of morphological characters studied among wood apple populations collected from south India

	Tree height	Bole length	Stem girth	Canopy area	Fruit length	Fruit width	Fruit girth	Fruit weight	Pulp weight	Seed weight	Rind weight	No. of seeds	Rind thickness	Pulp %
Tree height	1.000	-	-	-	-	-	-	-	-	-	-	-	-	-
Bole length	0.607**	1.000	-	-	-	-	-	-	-	-	-	-	-	-
Stem girth	0.030	-0.012	1.000	-	-	-	-	-	-	-	-	-	-	-
Canopy area	0.239	0.203	0.265	1.000	-	-	-	-	-	-	-	-	-	-
Fruit length	-0.243	-0.310	0.103	-0.124	1.000	-	-	-	-	-	-	-	-	-
Fruit width	-0.114	-0.320	0.454**	0.129	0.599**	1.000	-	-	-	-	-	-	-	-
Fruit girth	-0.117	-0.322	0.320	0.199	0.583**	0.956**	1.000	-	-	-	-	-	-	-
Fruit weight	-0.154	-0.202	0.346	0.124	0.406*	0.655**	0.624**	1.000	-	-	-	-	-	-
Pulp weight	-0.140	-0.236	0.439*	0.149	0.417*	0.665**	0.600**	0.897**	1.000	-	-	-	-	-
Seed weight	-0.142	0.002	0.148	0.048	0.175	0.353*	0.273	0.469**	0.344	1.000	-	-	-	-
Rind weight	-0.064	-0.074	0.053	0.046	0.207	0.351*	0.400*	0.747**	0.393*	0.275	1.000	-	-	-
No. of seeds	-0.093	0.131	-0.106	0.147	0.171	0.242	0.210	0.503**	0.343	0.814**	0.397*	1.000	-	-
Rind thickness	0.429*	0.240	0.221	0.117	0.094	0.146	0.125	0.170	-0.009	0.218	0.336	0.184	1.000	-
Pulp %	-0.021	-0.094	0.250	0.076	0.127	0.178	0.099	0.045	0.480**	-0.124	-0.590**	-0.177	-0.359*	1.00
Seed %	-0.073	0.076	-0.003	-0.008	-0.066	-0.023	-0.099	-0.175	-0.227	0.775**	-0.236	0.527**	0.116	-0.1
Pulp to Seed	-0.042	0.093	-0.093	-0.033	-0.094	-0.058	-0.102	-0.163	-0.348	0.741**	-0.017	0.543**	0.224	-0.4
**. Correlation is significant at the 0.01 level (2-tailed).														
*. Correlation is significant at the 0.05 level (2-tailed).														

Principal component analysis (PCA)

PCA analysis was applied to know the significant variables among the studied morphological traits and the degrees of association were obtained and are presented as their Eigenvectors (Table 6). PCA results of 5 components explained 81.47% of the total variance, but the first two principal components explained 50.49% of the total variance. The first component (PC1) is the most important component which showed 29.06% of the total variance, represented by five dominant traits, and was a significantly positive correlation with fruit weight, fruit width, pulp weight, fruit circumference, and fruit length. Whereas, the traits including fruit pulp to seed ratio, the percentage composition of seeds, seed weight, and a number of seeds showed 21.09% of the total variance in PC2. All the results of variance of PC1 and PC2 are enclosed only the fruit-related characters and it confirms the suitability to select the elite ti populations. The morphological characteristics of fruits are described as the major characteristics to differentiating and selecting the populations (Khadiji-Khub and Khalili 2017). PC3 showed 13.05% of the total variance and it encloses the traits related to tree morphology such as tree height, bole length, canopy area, and rind thickness. Whereas PC4 constitutes the percentage composition of pulp, rind weight, and stem girth and it showed 10.81% of the total variance. No reports were available in wood apple for the PCA analysis, whereas, these results show a similar type of variance in *B. aegyptiaca* (Abasse et al. 2011). In the current study, the overall findings suggested that the PC1 and PC2 explained almost 50% of the variance, and hence the characters of these two PCs were more specific to assess the genotypic diversity of *Limonia acidissima*.

Table 6
Principal component analysis of morphological characters to assess the variability among wood apple populations collected from south India

	PC 1	PC 2	PC 3	PC 4	PC 5
Eigen values	4.704	3.375	2.089	1.730	1.137
Proportion of variance (%)	29.403	21.091	13.059	10.815	7.108
Cumulative variance (%)	29.403	50.494	63.553	74.368	81.478
Traits	Eigenvectors				
Fruit weight	0.908	-0.080	0.145	-0.145	-0.309
Fruit width	0.872	-0.155	-0.022	0.125	0.316
Pulp weight	0.837	-0.318	0.028	0.198	-0.326
Fruit girth	0.833	-0.184	0.009	0.019	0.297
Fruit length	0.605	-0.170	-0.234	-0.100	0.352
Pulp to Seed	0.008	0.949	-0.205	0.089	0.179
Seed %	0.025	0.864	-0.315	0.359	0.132
Seed weight	0.569	0.747	-0.167	0.199	-0.127
No of seeds	0.522	0.666	-0.029	0.018	-0.406
Tree height	-0.221	0.080	0.778	0.235	0.111
Bole length	-0.311	0.283	0.645	0.239	-0.210
Rind thickness	0.211	0.346	0.618	-0.121	0.421
Canopy area	0.162	0.017	0.459	0.392	-0.153
Pulp %	0.084	-0.530	-0.231	0.729	-0.176
Rind weight	0.599	0.125	0.339	-0.666	-0.179
Stem girth	0.425	-0.173	0.243	0.460	0.269

Cluster analysis of genotypes

The analyzed data were used to make groups that share a similar pattern of variance by applying k-means clustering and a scatter plot method; this could allow us to know about the distribution pattern of the variables. Four major clusters among the studied populations were classified using the scores of PC1 and PC2 which showed 50.49% of the total variance. (Table 7; Fig. 3). Clustering of 32 populations formed 4 clusters mainly based on the morphological traits of fruits. Table 7 also depicts the minimum value, mean value, maximum value, standard deviation, and coefficients of variation of all the traits of each cluster. The first cluster comprises 4 ti populations, whereas the second cluster comprises only one genotype. Cluster 1 is characterized by medium-sized trees and fruits with an average of 2.11 m of stem girth, 28.52 m³ of canopy area, 25.60 cm of fruit circumference, 175.36 g of fruit weight, and 103.60 g of pulp weight. This is also characterized by the high weight of seeds and the number of seeds with an average of 12.88g and 392 seeds per fruit respectively. Seeds could have high commercial importance because of the presence of 32.02% of oil (Lamani et al. 2021). Similarly, cluster 2 is characterized by large-sized trees and fruits with an average stem girth of 2.62 m, canopy area of 35.10 m³, fruit circumference of 29.02 cm, fruit weight of 233.43 g, pulp weight of 151.53 g, and also with medium seed weight and a number of seeds with an average value of 9.99 g and 315 seeds respectively. Hence populations of cluster 2 could utilize the quality of fruits that have economic importance because of the presence of good nutritional qualities (Lamani et al. 2022). The populations grouped under these two clusters are showing advantageous traits when compared with clusters 3 and 4 which are characterized by medium and small-sized trees and fruits. Clusters 3 is characterized by the smallest tree and fruit morphology with an average value of stem girth of 1.50 cm, canopy area of 27.66 m³, fruit weight of 153.61 g, pulp weight of 88.46 g, and seed weight of 9.06 g. Whereas, cluster 4 consists of medium-sized trees and fruits with an average canopy area of 30.07 m³, fruit weight of 167.21 g, pulp weight of 99.99 g, and the highest average weight of seeds of 12.17 g (Fig. 3 and Table 7). Results were obtained by Manohar and Murthy (2011) in 30 collections of *Cucumis sativus* var. *sativus* L. in the Karnataka state of Southern India, and they classified them into 7 clusters. The results of clusters 1 and 4 were superior with respect to larger fruits, larger seeds, good vegetative characters, and high pollen viability. Similarly, the Southern part of India shows a rich diversity of wood apples due to suitable weather and environmental conditions. However, due to the lack of proper survey and characterization, the wood apple genotypes in this region are still underexploited. Characterizing the morphological traits of trees and fruits is necessary for breeding and classification (Badanes et al. 1998). The current analysis represents that clusters 1 and 2 showed a great level of variation in different agronomical and pomological variables among the studied populations and are well suitable for domestication because of their high fruit and seed weight and could utilize for breeding programs especially, cluster 1 for seed quality (average of 7.42% of seed composition) and cluster 2 for pulp quality (average of 65.04% of pulp).

Table 7
Descriptive statistics for morphological characters of clusters identified among the populations of wood apple collected from south India

	Cluster 1				Cluster 2				Cluster 3				Cluster 4		
Characters	Min	Max	Avg	SD	Min	Max	Avg	SD	Min	Max	Avg	SD	Min	Max	Avg
Height (m)	9.90	14.25	11.56	1.98	-	-	11.13	-	9.09	16.69	12.47	1.85	7.68	15.50	11.80
Bole length (m)	1.88	3.29	2.40	0.62	-	-	1.47	-	1.56	3.58	2.53	0.55	2.12	3.20	2.56
Stem girth (m)	1.61	2.58	2.11	0.40	-	-	2.62	-	0.98	2.11	1.50	0.29	1.14	2.58	1.75
Canopy area (m) ³	23.61	33.55	28.52	5.48	-	-	35.10	-	21.06	33.31	27.66	4.32	18.79	36.36	30.07
Fruit length (cm)	7.93	9.00	8.36	0.45	-	-	8.33	-	6.57	8.42	7.44	0.44	6.40	7.51	7.00
Fruit width (cm)	8.04	9.14	8.44	0.49	-	-	9.74	-	6.09	8.49	7.33	0.52	6.96	7.72	7.42
Fruit girth (cm)	24.20	27.45	25.60	1.52	-	-	29.02	-	18.26	25.03	22.67	1.54	20.73	24.09	22.57
Fruit weight (g)	136.14	203.93	175.36	28.72	-	-	233.43	-	118.30	185.70	153.61	15.15	130.68	195.93	167.21
Pulp weight (g)	79.66	119.45	103.60	17.34	-	-	151.83	-	70.19	108.66	88.46	9.79	78.17	115.83	99.99
Seed weight (g)	11.10	14.90	12.88	1.88	-	-	9.99	-	5.90	11.06	9.06	1.41	9.07	14.55	12.17
Rind weight (g)	45.00	69.90	58.08	10.38	-	-	71.61	-	39.91	68.63	56.31	8.52	34.97	73.20	55.07
No. of seeds	242.67	500.67	392.42	118.22	-	-	315.33	-	121.00	446.67	306.78	78.24	317.00	535.00	402.85
Rind Thickness (cm)	0.41	0.44	0.43	0.01	-	-	0.41	-	0.36	0.45	0.41	0.02	0.37	0.44	0.41
Pulp (%)	58.51	60.33	59.04	0.87	-	-	65.04	-	53.92	65.65	57.64	3.80	53.92	72.94	60.08
Seed (%)	6.34	8.44	7.42	0.97	-	-	4.28	-	4.03	7.02	5.92	0.89	5.55	9.08	7.32
Pulp-seed ratio (%)	10.80	14.42	12.56	1.60	-	-	6.58	-	6.90	12.90	10.34	1.86	8.12	16.05	12.32

Conclusion

This is the first report on a study of agronomical and pomological traits of trees and fruits of different ti populations of wood apple in Southern states of India. The obtained results of wood apple populations showed a wide range of phenotypic variability and these results are much necessary to recognize the elite populations which could be utilized in future breeding programs. The survey of wood apple showed that the North-Western regions of Tamil Nadu and Southern regions of Andhra Pradesh are the rich distribution centres of wood apple compared to Eastern Karnataka, Northern Telangana, and the North-West part of Palakkad, Kerala, and this is because of change in climate and rainfall. Variability among the population was recorded using 16 morphological traits and selected 32 ti populations of wood apple. The traits like canopy area of the tree, fruit weight, rind weight, number of seeds, and percentage composition of pulp and seeds are many important traits to note the phenotypic variability in wood apples. Variability among all the 32 populations was assessed using multivariate statistical analysis, and this showed that the populations grouped under clusters 1 and 2 are more diverse compared to populations of clusters 3 and 4. The populations grouped under cluster 1 (AP-03, TS-01, TS-07, and TN-05) and cluster 2 (TN-03) showed elite fruit-related traits by having the highest fruit, pulp, and seed weight even though they have average morphology of tree, whereas population TN-03 is most promising one on the bases of the overall assessment. Hence, the population which showed the greater variability could be utilized for the cultivation and future breeding programs.

Declarations

Conflict of interest The authors declare no conflict of interest.

Human and animal rights The article does not contain any studies involving animal experiments.

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Figures

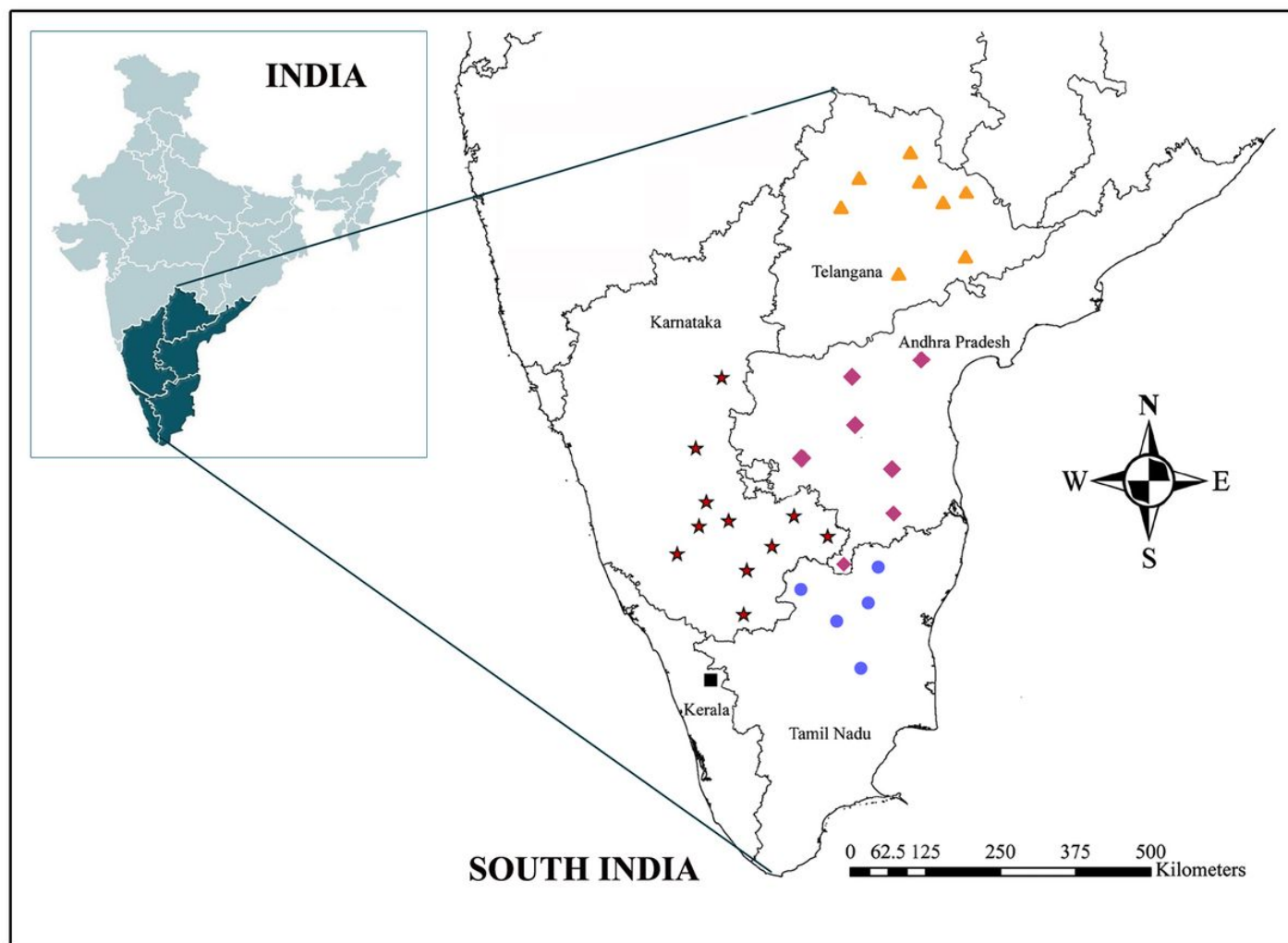


Figure 1

Map of Southern India showing the locations of populations of wood apple

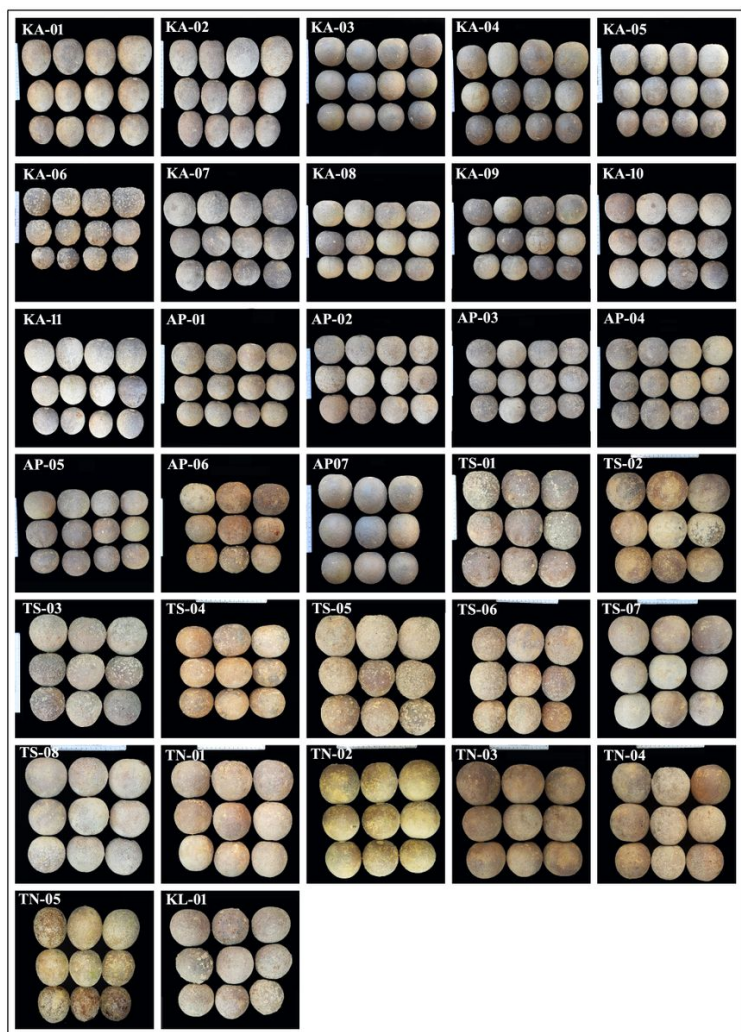


Figure 2

Morphological variability of fruits of wood apple collected from south India

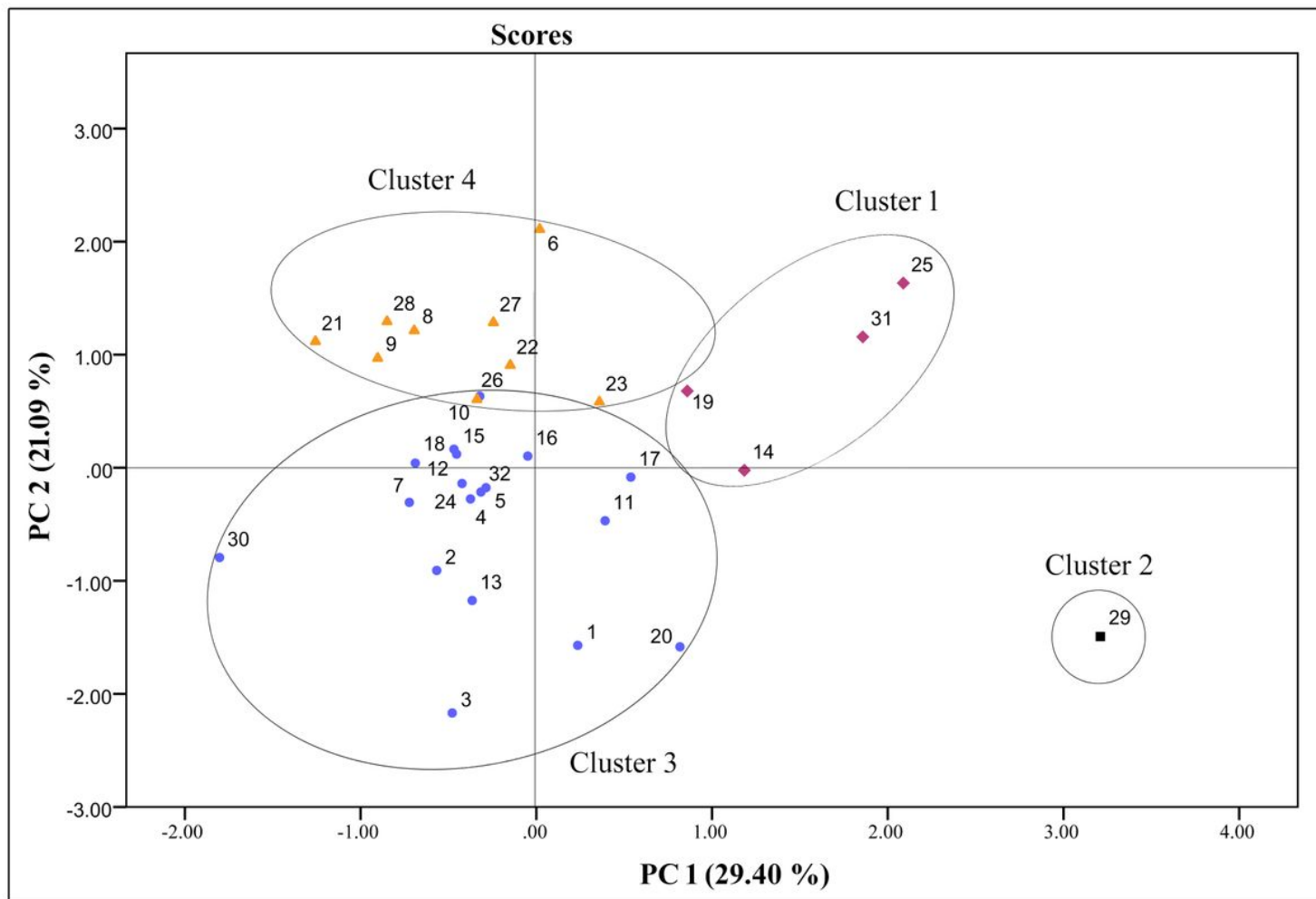


Figure 3

Cluster analysis of wood apple populaitons on the bases of scores of the first two principal components using the k-means clustering method