Journal of Applied and Natural Science
17(3), 1081 - 1091 (2025)
ISSN : 0974-9411 (Print), 2231-5209 (Online)
journals.ansfoundation.org

Research Article

Morphological and physico-chemical profiling of Sapota genotypes

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Article Info
https://doi.org/10.31018/jans.v17i3.6384
Received: April 23, 2025
Revised: July 28, 2025
Accepted: August 10, 2025

How to Cite
Meem, H. Z. *et al.* (2025). Morphological and physico-chemical profiling of Sapota genotypes. *Journal of Applied and Natural Science*, 17(3), 1081 - 1091.https://doi.org/10.31018/jans.v17i3.6384

Abstract
Sapota (*Manilkara zapota*), a tropical evergreen fruit tree, holds substantial economic and nutritional importance in many regions, particularly in South and Southeast Asia. Its fruits are rich in sugars, vitamins, and minerals, making it a valuable addition to both local diets and commercial markets. The present study aimed to evaluate and characterize nineteen local Sapota germplasm conserved at the Germplasm Center of Patuakhali Science and Technology University (PSTU), Bangladesh. The assessment was carried out using key morphological features and physico-chemical attributes of the ripe Sapota fruits to identify superior genotypes for breeding and cultivation. Parameters such as fruit weight, dimensions, yield, total soluble solids (TSS), titratable acidity, pH, and vitamin C content were meticulously recorded. Among the evaluated genotypes, Germplasm-3 emerged as notable for its superior fruit weight (83.62 g), length (5.22 cm), and width (4.95 cm), indicating its potential for high consumer acceptance. Germplasm-7 excelled in productivity, bearing the highest number of fruits (110) and yield (8.17 kg/germplasm). In terms of fruit quality, Germplasm-9 exhibited the highest TSS (25.85%), indicating greater sweetness, while Germplasm-5 showed promising nutritional content with the highest vitamin C (17 mg/100g) and pH (6.67). The highest titratable acidity (0.23%) was shared by Germplasm-8, -9, and -15. These results provide critical insights into the variability among local Sapota germplasm, facilitating targeted selection for genetic improvement. Germplasm-3, -7, and -9, in particular, offer considerable promise for future breeding programs aimed at enhancing fruit quality, yield potential, and commercial value in Sapota cultivation systems.

Keywords: Sapota genotypes, Morphological characterization, Physico-chemical traits, Germplasm evaluation, Fruit quality assessment

INTRODUCTION

Sapota [*Manilkara zapota* (L.) van Royen] is an economically important species of the Sapotaceae family native to tropical America. As a rainforest tree known as the "Chicle tree", it has a long history of human use (Simpson and Ogorzaly, 1995). It has been used for many purposes including latex, fruit, and timber. It is a commercially important cultivated fruit in several countries including Bangladesh. As a fairly slow-growing, medium-sized (15-30 m), long-lived evergreen tree, Sapota is also valued as an ornamental tree and used in tropical landscapes due to its rounded crowns and glossy leaves (Peiris, 2007). Sapota fruit is a climacteric fruit, which contains various significant nutrients such as polyphenols, sugar, carotenoids, antioxidants, vitamins, minerals, and ascorbic acid. Worldwide, Sapota fruit is one of the most highly consumed fruits due to its nutritional properties (Poongavanam *et al.,* 2023). The traditional uses, nutritional composition, and pharmacological activities of Sapota, emphasizing its potential as a source of bioactive compounds for health applications (Shui *et al.,* 2020). It's mainly consumed in a fresh state as a table fruit in many countries where it is produced (Kute and Shete, 1995). The pulp of Sapota when ripe is soft, granular and very sweet. Sapota is an energy-rich fruit with high total soluble solids (20-22%) and serves as a good source of digestible sugar, containing appreciable amounts of protein, fat, fibre, and minerals like calcium, phosphorus, and iron (Shanmugavelu and Srinivasan, 1973). A large area of Bangladesh is being brought under this crops every year. The popularity of this crop is increasing among the farmers due to its high production per unit area, continuous fruiting and thereby income throughout the year, low cost of production, liking to Bangladeshi palate, and very little incidence of diseases and pests. Besides, the tree is quite hardy and grows well in a wide range of climatic conditions. It is well adapted to different types of soils, salinity, and water stress to a great extent (Peiris, 2007).

Despite having much importance, the fruit crop faces several problems, such as no specific characterization, few improved varieties, and no systematic production practices in Bangladesh. Moreover, local people most often neglect this fruit, so it is confined only to the homestead and is not being commercially cultivated. Literature reveals that in Bangladesh, only a few research works relating to morpho-physical-chemical studies of different local Sapota accessions have been undertaken. Moreover, little research in the diversity of Sapota for the evaluation of superior genotypes has been documented. Besides, there is a lack in crop improvement for this important underutilized fruit crop in Bangladesh. Attempts should be made to evaluate the Sapota germplasm for different traits to make recommendations for cultivation in different areas.

Among the above-mentioned problems, the present study was thought to focus on the characterization of different Sapota germplasm. Characterization is an important aspect for documentation of the performance of the studied cultivars which subsequently will help to introduce, select, and improve existing Sapota germplasm (Islam *et al.,* 2016). The morphological characterization of Sapota provides insights into its physical and chemical properties, which are crucial for varietal identification and crop improvement programs (Nag *et al.,* 2024). So, characterization is an important aspect for documentation of the performance of the studied cultivars, which subsequently will help to introduce, select and improve existing Sapota varieties (Islam *et al.,* 2016). Therefore, the present study aimed to undertake a systematic investigation to find suitable germplasm with higher production, better size, and high nutritional quality of fruits.

MATERIALS AND METHODS

Experimental design and site

Nineteen local germplasms of Sapota viz. Germplasm-1 to Germplasm-19 available at Patuakhali Science and Technology University (PSTU) Germplasm Center, Patuakhali, Bangladesh were selected as the experimental materials. The field experiment followed a Randomized Complete Block Design (RCBD) with four replications and the laboratory experiment was carried out using a Completely Randomized Design (CRD) that was repeated four times from May 2020 to April 2021. All the selected germplasm was seven-year-old grafted trees that started first flowering and fruiting at the age of four years. Data related to leaf, flower, and fruit characteristics of Sapota were collected. Randomly, one branch was selected for data collection in each direction. The fruits were harvested at the mature but unripe stage and then brought to the Postharvest Laboratory, where they were kept in ambient conditions (temperature 28 °C and Relative Humidity 80-90%) for ripening to study their physico-chemical properties. Laboratory experiments were conducted at the Plant Biotechnology Laboratory and the Postharvest Laboratory of the Department of Horticulture, PSTU.

Data collection

Morphological parameters

The length and width of the leaves were measured using a slide caliper, and the mean values were initially recorded in millimeters (mm). The final measurements were then converted and expressed in centimeters (cm). The shape and apex of the leaf were determined by visual observation. The color of the leaf was determined by using the 'ON Color Measure' application

(Islam *et al.,* 2016).

The number of sepals and stamen per flower was estimated by dissecting the flowers. The length and width of petals were measured by a slide caliper and the mean value in mm was determined (Islam *et al.,* 2016).

Fully matured fruits were harvested to determine their weight and other measurements. The fruit weight was recorded in grams using an electric balance (DJ-220 A, Japan) with a sensitivity of ten grams. The shape of the fruit was determined by visual observation. The color of fruit pulp was determined by using the 'ON Color Measure' application. The length and width of the fruits were measured using a slide caliper, and the mean values were initially recorded in millimeters (mm). The final measurements were then converted and expressed in centimeters (cm). The number of seeds per fruit was counted from fully ripe fruits. Number of fruits in each germplasm was counted. Yield per germplasm was determined by taking the weight of all the fruits of germplasm with an electric balance (DJ-220 A, Japan) sensitive to ten grams and it was expressed as kg/ germplasm (Islam *et al.,* 2016).

Cluster Analysis and Dendrogram Construction

A hierarchical clustering analysis was performed to assess the genetic diversity among the nineteen Sapota germplasm based on their morphological and physico-chemical attributes.

Physico-chemical properties of fruits

Titratable acidity (TA)

Titratable acidity (TA) was estimated using the method outlined by Ranganna (1977) with slight modifications. A sample of ten grams of pulp tissue was blended with 40 mL of distilled water. The blending was performed using a kitchen blender for two minutes. The homogenate was subsequently filtered through Whatman No. 2 filter paper. An aliquot of 5 mL from the filtrate was poured to a 100 mL conical flask. After that, as an indicator two drops of 1% phenolphthalein solution were added. The sample was titrated with 0.1 M sodium hydroxide (NaOH) until a pink color persisted for 15 seconds. The volume of titrant used was noted and the result was computed as the percentage of citric acid using the following formula:

Citric acid (%) = Titre (mL) x Vol. made up (50 mL) x NaOH normality (0.1 M) x Citric acid eq. weight (64 g) x 100/ Weight of sample taken (10 g) x Volume of sample for titrate (5 mL) x 1000 ……(1)

Total soluble solids (TSS)

The residual filtrate from the TA analysis was employed for total soluble solids TSS determination by using a digital refractometer (BOECO, Germany). The refractometer was calibrated through distilled water to obtain a 0% reading before sample analysis. A few drops (1-2) of the filtrate were applied to the prism surface of the refractometer to measure the TSS percentage. The recorded value was adjusted by multiplying it with the dilution factor to determine the actual % TSS of the fruit pulp. As temperature fluctuations can influence the reading, each measurement was adjusted to a standard temperature of 20°C by applying an adjustment of 0.28% to find the percent total soluble solids at 26 ± 1° C.

Ascorbic acid (Vitamin-C)

Five grams of fresh fruit pulp were weighed and combined with 35 mL of 3% metaphosphoric acid solution. Then homogenized the mixture with a kitchen blender. Following homogenization and proper filtration the aliquot was centrifuged at 2000 rpm for five minutes. The resulting supernatant was poured to a 50 mL volumetric flask and the final volume was made up using 3% metaphosphoric acid. A ten ml of aliquot was taken in a conical flask and mixed with a recommended dye. The formula below was used for calculating ascorbic acid content of the samples:

Ascorbic acid (mg 100 g^{-1})= Titre (mL) x Vol. made up (50 mL) x dye factor x 100/ Aliquot used for estimation (5 mL) x Sample weight (10 g) …..(2)

pH

For pH determination, the remaining filtrate from the of the fruit pulp of TA analysis was utilized. A glass electrode pH meter (GLP 21, Crison, Barcelona, EEC) was used to take the reading for pH calculation. Initial calibration of pH meter was done by using a buffer solution of pH 4.0, followed by pH 7.0. After proper calibration, the glass electrode was immersed in the filtrate, and a steady pH reading was noted. To maintain precision, the electrode was cleaned with distilled water and wiped using soft tissue after each use.

Fruit firmness

A digital firmness tester (Model GY – 802) was used to quantify the firmness of fully ripened Sapota fruits. The device featured a 3 mm diameter cylindrical probe that was pressed vertically within the fruit pulp. Firmness measurement readings were recorded in the Newtons (N) unit.

Fruit moisture content

The traditional hot air oven method was employed to measure the moisture content in the ripe fruit samples. Sapota fruits were sliced into portions weighing around ten to fifteen grams and transferred to pre-weighed moisture containers. These samples were then kept in a hot air oven at 105°C ± 1°C for 24 hours to dry. The moisture content was calculated based on the weight difference before and after drying. The following equation determined the moisture content:

$$\text{Moisture content (\%)} = \frac{W_2 - W_3 \times 100}{W_2 - W_1} \quad \ldots\ldots(3)$$

Where,

W_1 = hollow container weight (g)

W_2 = container with sample weight (g)

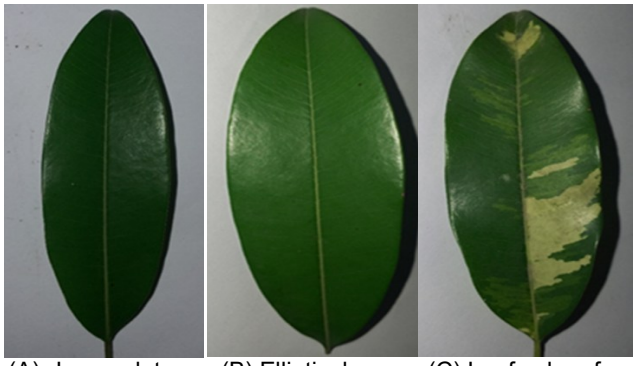
W_3 = container with sample weight after 24 hours (g)

Statistical analysis

The collected data were statistically analyzed using Analysis of Variance (ANOVA) with the MSTAT−C computer package program. Duncan's Multiple Range Test (DMRT) and Least Significant Difference (LSD) were applied to compare the means of different parameters.

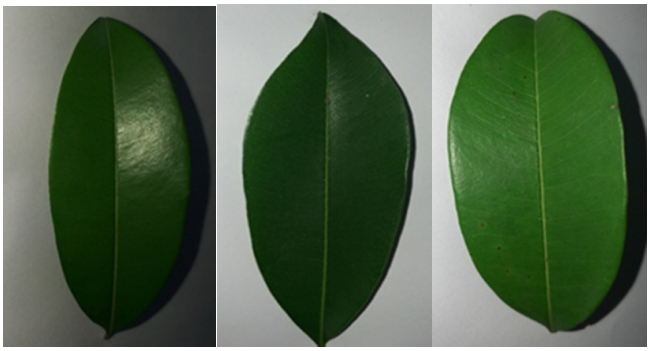
RESULTS

Significant differences among the germplasm were observed with respect of morphological and physico-chemical properties. The highest leaf length (12.8 cm) was found in Germplasm-17 and the lowest leaf length (9.8 cm) was in Germplasm-18 (Table 1). The germplasm for highest leaf width were Germplasm-17 (4.97 cm) followed by Germplasm-1 (4.60 cm) and Germplasm-8 (4.42 cm) which were statistically similar and the lowest leaf width (3.25 cm) was found in Germplasm-3 (Table 1). Among the 19 studied germplasm, Germplasm-1, Germplasm-2, Germplasm-3, Germplasm-4, Germplasm-5, Germplasm-6, Germplasm-9, Germplasm-11, Germplasm-13, Germplasm-18 had elliptical leaf while Germplasm-7, Germplasm-8, Germplasm-10, Germplasm-12, Germplasm-14, Germplasm-15, Germplasm-16, Germplasm-17, Germplasm-19 had lanceolate shape (Fig. 1). Leaf color ranged from light green, green and deep green among the accessions with the exception to green with yellow patch, which was observed in Germplasm-12. Light green color was observed for the leaves of Germplasm-1, Germplasm-2, Germplasm-3, Germplasm-4, Germplasm-7 and Germplasm-8. Green colored leaf was observed in Germplasm-5, Germplasm-6 and Germplasm-14. Dark green colored leaf was observed in Germplasm-9, Germplasm-10, Germplasm-11, Germplasm-13, Germplasm-15, Germplasm-16, Germplasm-17, Germplasm-18 and Germplasm-19. Leaf apex varied considerably (Fig. 2) among the accessions. Germplasm-1, Germplasm-2, Germplasm-6, Germplasm-7, Germplasm-13 and Germplasm-18 were observed to have retuse (slightly notched at the tip) leaf apex while Germplasm-3, Germplasm-4, Germplasm-5, Germplasm-8, Germplasm-9, Germplasm-10, Germplasm-11, Germplasm-12, Germplasm-14, Germplasm-15, Germplasm-16 and Germplasm-19 were found to have acute leaf apex. Only Germplasm-17 had acuminate leaf apex (Fig. 2).



(A) Lanceolate (B) Elliptical (C) Leaf color of Germplasm-12

Fig. 1. *Leaf shapes (A & B) observed in nineteen germplasms of Sapota and yellow patched green leaf in Germplasm-12 (C)*



(A) Acute (B) Acuminate (C) Retuse

Fig. 2. *Leaf apex (A, B & C) observed in nineteen germplasms of Sapota*

The highest length of petal was recorded for Germplasm-18 (11.22 mm) followed by Germplasm-7 (10.98 mm), which were statistically similar and the lowest length (9.75 mm) was recorded in Germplasm-3. The highest width of petal (21 mm) was recorded in Germplasm-7 and the lowest width (19.37 mm) was in Germplasm-3 (Table 1). All the germplasm was statistically similar with respect to petal width. The numbers of sepal were 6 and 8 as observed in this study (Fig. 3). Germplasm-1, Germplasm-2, Germplasm-3, Germplasm-4, Germplasm-6, Germplasm-7, Germplasm-8, Germplasm-10, Germplasm-12, Germplasm-13, Germplasm-14, Germplasm-16, Germplasm-17, Germplasm-18 and Germplasm-19 had 6 sepals/flower, while Germplasm-5, Germplasm-9, Germplasm-11 and Germplasm-15 had 8 sepals/flower. The numbers of stamen was six and seven, as observed in the study (Fig. 4). Germplasm-1, Germplasm-2, Germplasm-3, Germplasm-4, Germplasm-5, Germplasm-6, Germplasm-7, Germplasm-10, Germplasm-13, Germplasm-16, Germplasm-17, Germplasm-18 and Germplasm-19 had six stamens/flower, while Germplasm-8, Germplasm-9, Germplasm-11, Germplasm-12, Germplasm-14 and Germplasm-15 had seven stamens/flower.

Table 1. *Morphological characteristics of nineteen germplasms of Sapota*

Germplasm	Leaf length (cm)	Leaf width (cm)	Petal length (mm)	Petal width (mm)	Fruit length (cm)	Fruit width (cm)
Germplasm-1	10.68bc	4.60ab	10.10abc	20.12a	4.40bcd	4.17bcde
Germplasm-2	10.50bc	3.55def	9.90bc	19.50a	4.45bcd	4.10bcde
Germplasm-3	11.13b	3.25f	9.75c	19.37a	5.22a	4.95a
Germplasm-4	10.73bc	3.62def	10.38abc	19.90a	4.57bcd	4.15bcde
Germplasm-5	10.63bc	4.12bcd	10.33abc	19.62a	4.40bcd	4.17bcde
Germplasm-6	10.27bc	3.57def	9.92bc	19.50a	4.12d	3.87e
Germplasm-7	10.52bc	3.77def	10.98ab	21.00a	4.15d	3.87e
Germplasm-8	10.48bc	4.42abc	10.38abc	19.62a	4.42bcd	4.12bcde
Germplasm-9	10.38bc	3.30ef	10.65abc	20.50a	4.25cd	3.97de
Germplasm-10	10.43bc	3.57def	10.35abc	20.37a	4.70abcd	4.35bcde
Germplasm-11	10.55bc	3.72def	10.60abc	20.15a	4.82abc	4.52abc
Germplasm-12	10.55bc	3.77def	10.18abc	20.17a	4.35bcd	4.00cde
Germplasm-13	10.20bc	3.72def	10.78abc	20.40a	4.47bcd	4.12bcde
Germplasm-14	10.40bc	3.40ef	10.18abc	19.65a	4.82abc	4.55ab
Germplasm-15	10.52bc	3.35ef	10.60abc	20.12a	4.65bcd	4.32bcde
Germplasm-16	10.95bc	3.95cde	10.90abc	19.90a	4.60bcd	4.27bcde
Germplasm-17	12.80a	4.97a	10.27abc	20.02a	4.57bcd	4.20bcde
Germplasm-18	9.80c	3.30ef	11.22a	19.80a	4.87ab	4.50abcd
Germplasm-19	9.90c	3.37ef	10.48abc	19.80a	4.47bcd	4.20bcde
LSD (0.05)	0.99	0.55	0.99	--	0.49	0.44
CV (%)	6.62	10.34	6.77	--	7.75	7.40
Level of sig.	*	*	*	NS	*	*

Common letters within the same column do not differ significantly at a 5% level of significance as analyzed by DMRT; * Significant (p≤5%); LSD = Least Significant Difference; CV = Coefficient of variation, NS = Not Significant

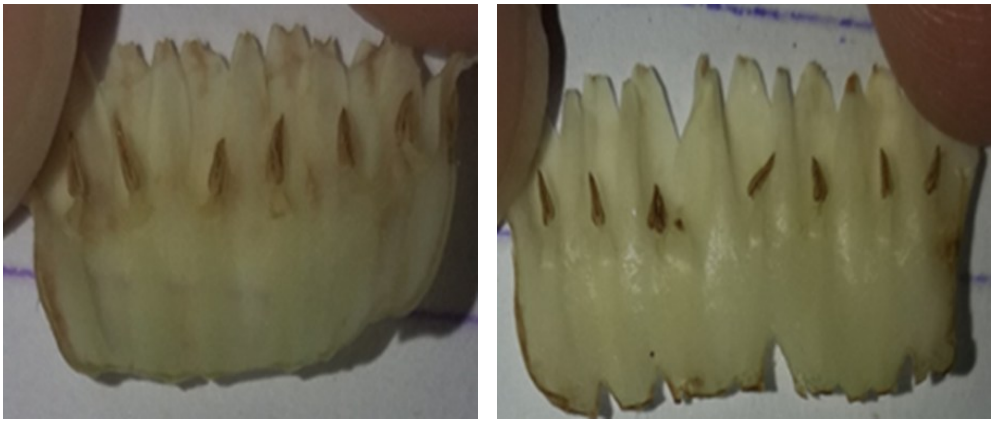
Table 2. Quantitative parameters of nineteen germplasms of Sapota

Germplasm	Individual fruit weight (g)	Number of fruits/ germplasm	Yield/germplasm (kg)
Germplasm-1	78.72b	20.00i	1.60m
Germplasm-2	73.25c	38.00f	2.77g
Germplasm-3	83.62a	30.00gh	2.45ij
Germplasm-4	71.32cd	36.00fg	2.55hi
Germplasm-5	71.95cd	30.00gh	2.25k
Germplasm-6	68.72d	45.00e	3.15f
Germplasm-7	74.42c	110.00a	8.17a
Germplasm-8	72.92c	30.00gh	2.25k
Germplasm-9	74.62c	88.00b	6.52b
Germplasm-10	70.57cd	32.00fg	2.25k
Germplasm-11	72.25cd	33.00fg	2.42ij
Germplasm-12	70.57cd	36.00fg	2.50i
Germplasm-13	74.45c	50.00de	3.67e
Germplasm-14	72.72cd	37.00f	2.75g
Germplasm-15	72.52cd	54.00cd	3.92d
Germplasm-16	72.97c	58.00c	4.22c
Germplasm-17	71.37cd	38.00f	2.65gh
Germplasm-18	72.75cd	32.00fg	2.35jk
Germplasm-19	72.40cd	25.00hi	1.85l
LSD (0.05)	3.49	5.63	0.12
CV (%)	3.37	9.18	2.75
Level of sig.	*	*	*

Common letters within the same column do not differ significantly at a 5% level of significance as analyzed by DMRT; * Significant (p≤5%); LSD = Least Significant Difference; CV = Coefficient of variation

(A) 6 sepals (B) 8 sepals

Fig. 3. *Number of sepals/flower (A & B) observed in nineteen germplasms of Sapota*



(A) 6 stamens (B) 7 stamens

Fig. 4. *Number of stamens/flower (A & B) observed in nineteen germplasms of Sapota*

The highest fruit weight (83.62 g) was found in Germplasm-3 and the lowest (68.72 g) was in Germplasm-6 (Table 2). The largest fruit (5.22 cm) was recorded in Germplasm-3 followed by Germplasm-18 (4.87 cm) and Germplasm-14 (4.82 cm), which were statistically similar and the smallest fruit (4.12 cm) was recorded in Germplasm-6. The highest fruit width (4.95 cm) was found in Germplasm-3, followed by Germplasm-14 (4.55 cm) and Germplasm-11 (4.52 cm), which were statistically similar, and the lowest fruit width (3.87 cm) was found in Germplasm-6 and Germplasm-7 (Table 1). Significant variation was found in respect of fruit shape among the germplasm (Fig. 5). Among them, Germplasm-1, Germplasm-6, Germplasm -7, Germplasm-8, Germplasm-10, Germplasm-11, Germplasm-12, Germplasm-15, Germplasm-16, Germplasm-18 and Germplasm-19 had round shaped fruits. Oval shaped fruits were found in Germplasm-2, Germplasm-3, Germplasm-4, Germplasm-5, Germplasm-9, Germplasm-13, Germplasm-14 and Germplasm-17. The fruit pulp color ranged from light brown, brown and dark brown (Fig. 6). Germplasm-3, Germplasm-7, and Germplasm-18 had light brown colored pulp, Germplasm-1, Germplasm-2, Germplasm-4, Germplasm-5, Germplasm-6, Germplasm-9, Germplasm-16 and Germplasm-19 had brown colored pulp, while Germplasm-8, Germplasm-10, Germplasm-11, Germplasm-12, Germplasm-13, Germplasm-14, Germplasm-15 and Germplasm-17 had dark brown colored pulp. The number of seeds varied from two to five. Germplasm-5, Germplasm-11, Germplasm-13 and Germplasm-16 had two seeds/fruit, Germplasm-1, Germplasm-3, Germplasm-4, Germplasm-7, Germplasm-8 and Germplasm-17 had three seeds/fruit, Germplasm-2, Germplasm-6, Germplasm-10, Germplasm-12, Germplasm-14, Germplasm-18 and Germplasm-19 had 4 seeds/fruit, Germplasm-9 and Germplasm-15 had 5 seeds/fruit. Germplasm-7 had the highest number of fruits/germplasm (110) and Germplasm-1 had the lowest number of fruits/ germplasm (20) (Table 2). Accordingly, significant variation was found concerning yield/germplasm. The highest yield (8.17 kg/germplasm) was obtained from Germplasm-7 and the lowest yield (1.6 kg/germplasm) was from Germplasm-1.

The highest titratable acidity (0.23%) was determined in Germplasm-8, Germplasm-9, and Germplasm-15 followed by Germplasm-1 (0.20%) and Germplasm-17 (0.20%) which were statistically similar and the lowest (0.10%) was in Germplasm-4, Germplasm-5,

Table 3. Physico-chemical properties of nineteen germplasms of Sapota fruit

Germplasm	TA (%)	TSS (%)	Vitamin-C (mg/100g)	pH	Firmness (N)	Moisture content (%)
Germplasm-1	0.20ab	23.77cd	11.02fg	5.77ef	2.00f	71.80h
Germplasm-2	0.15c	22.67fg	13.07de	6.27d	2.45d	71.05j
Germplasm-3	0.15c	23.52e	13.00de	6.22d	2.45d	73.60c
Germplasm-4	0.10c	21.55i	10.00g	5.70f	3.00c	72.80de
Germplasm-5	0.10c	22.77f	17.00a	6.67a	2.25e	73.50c
Germplasm-6	0.15bc	24.80b	16.00ab	5.37g	1.50g	71.90gh
Germplasm-7	0.10c	20.55j	11.00fg	5.42g	2.00f	74.20b
Germplasm-8	0.23a	21.70h	15.05bc	6.52b	3.45b	72.40ef
Germplasm-9	0.23a	25.85a	14.03cd	5.70f	3.00c	71.50hi
Germplasm-10	0.15bc	23.72d	10.00g	6.40c	1.50g	75.10a
Germplasm-11	0.15bc	22.60g	12.00ef	6.60ab	2.00f	72.40ef
Germplasm-12	0.10c	23.85c	15.04bc	6.52b	2.45d	72.70def
Germplasm-13	0.15c	23.55e	15.00bc	6.42c	3.00c	75.30a
Germplasm-14	0.10c	21.65hi	15.01bc	5.82e	4.00a	72.30fg
Germplasm-15	0.23a	24.85b	13.05de	6.20d	2.00f	74.20b
Germplasm-16	0.15bc	20.55j	12.02ef	5.72f	2.00f	72.90d
Germplasm-17	0.20ab	23.85c	11.00fg	5.82e	2.45d	71.10ij
Germplasm-18	0.10c	21.75h	14.06cd	6.20d	3.00c	72.50def
Germplasm-19	0.15bc	22.65g	15.01bc	5.02h	2.00f	74.50b
LSD (0.05)	0.04	0.10	1.15	0.07	0.17	0.41
CV (%)	6.48	0.32	6.16	0.98	5.13	0.40
Level of sig.	*	*	*	*	*	*

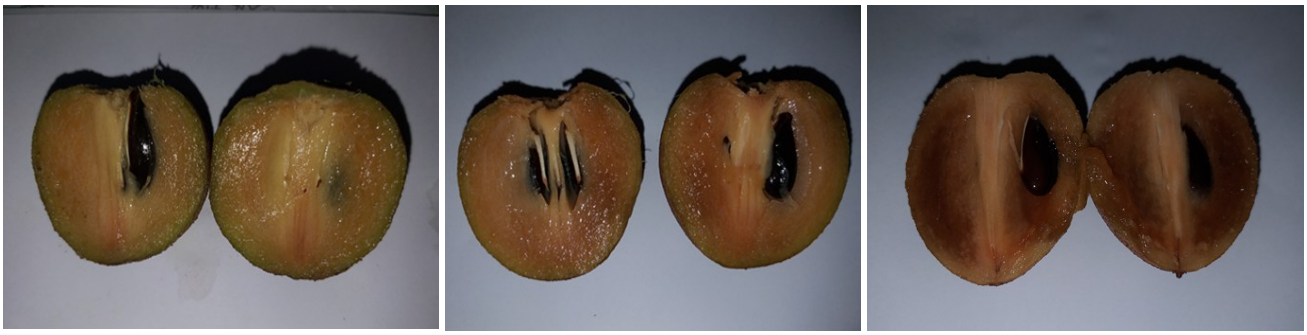
Common letters within the same column do not differ significantly at a 5% level of significance as analyzed by DMRT; TA=Titratable Acidity; TSS=Total Soluble Solids; * Significant (p≤5%); LSD = Least Significant Difference; CV = Coefficient of variation

Germplasm-7, Germplasm-12, Germplasm-14, and Germplasm-18. The maximum total soluble solids (25.85%) was recorded in Germplasm-9 and the minimum (20.55%) was in Germplasm-7, and Germplasm-16. The maximum value of Vitamin-C (17 mg/100 g) was noted in Germplasm-5, followed by Germplasm-6 (16 mg/100 g) which was statistically similar to Germplasm-5 and the minimum (10 mg/100 g) was in Germplasm-4, Germplasm-10. The maximum pH (6.67) was determined in Germplasm-5 followed by Germplasm-11 (6.60) which was statistically similar to Germplasm-5 and the minimum (5.02) was in Germplasm-19. The maximum fruit firmness (4 N) was recorded in Germplasm-14 and the minimum (1.5 N) was in Germplasm-6, Germplasm-10. The maximum value of moisture content (75.30%) was determined in Germplasm-13 followed by Germplasm-10 (75.10%) which were statistically similar and the minimum (71.05%) was in Germplasm-2 (Table 3).

By using morphological and biochemical data, a similarity tree among the assessed Sapota genotypes was obtained (Fig. 7). There were two major clusters i.e., cluster A and cluster B. Cluster A was divided into two main sub-clusters (A1 and A2). The A1 sub-cluster comprises 3 genotypes namely, Germplasm-1, Germplasm-17, and Germplasm-3. Moreover, the bigger sub-cluster A2 was composed of thirteen genotypes and divided into two sub-sub clusters. The first sub-sub cluster comprises eleven genotypes namely, Germplasm-2, Germplasm-12, Germplasm-8, Germplasm-5, Germplasm-11, Germplasm-10, Germplasm-13, Germplasm-4, Germplasm-16, Germplasm-14, and Germplasm-18. Besides, the remaining two genotypes (Germplasm-6 and Germplasm-19) of sub-cluster A2 were categorized under the second sub-sub cluster. Furthermore, cluster B comprises three genotypes namely, Germplasm-7, Germplasm-9, and Germplasm-15. However, the clustering of the assessed genotypes is dependent on the similarity of different traits among the genotypes. Besides, the genotypes within a cluster indicate maximum similarity for several parameters among themselves. Therefore, the categorization of genotypes helped to find out the degree of similarity and dissimilarity among the genotypes.

(A) Round (B) Oval

Fig. 5. *Fruit shapes (A & B) observed in nineteen germplasms of Sapota*



(A) Light brown (B) Brown (C) Dark Brown

Fig. 6. *Fruit pulp color (A, B & C) observed in nineteen germplasms of Sapota*

DISCUSSION

The present study characterized nineteen sapota germplasm based on morphological and physico-chemical attributes. The findings revealed significant variability across almost all studied parameters, except petal width, indicating a broad genetic base among the genotypes. This morphological diversity suggests the potential for these traits to serve as reliable descriptors for identifying and classifying sapota genotypes. These results are consistent with earlier findings by Ramadoss and Arivazhagan (2016), who reported substantial variation in plant, leaf, and fruit traits of sapota. Similar diversity has been highlighted by Islam et al. (2016), Shirol et al. (2009), Suhasini *et al.* (2011), and Bhalekar and Chalak (2016), further validating the observed trends. Recent studies continue to emphasize the significance of morphological diversity in sapota for cultivar differentiation and trait selection. For instance, Kumar *et al.* (2021) reported extensive variability in fruit size, shape, and skin texture across regional germplasm collections, underlining the importance of conserving and utilizing local genetic resources in breeding programs. Likewise, Saraswathy *et al.* (2010) highlighted that morphological descriptors, such as leaf morphology and fruit characteristics, remain integral to cultivar identification. Mondal *et al.* (2023) evaluated morphological variation among sapota cultivars in West Bengal and reported significant inter-genotypic differences in traits such as fruit weight, skin texture, and pulp color. Sapota was likely initially propagated through seedlings, resulting in high genetic variability due to heterozygosity, and was later vegetatively propagated based on regional preferences, with additional diversity possibly arising from multiple introductions from its center of origin (Kundapura *et al.,* 2023). A study conducted in Bangladesh utilized Random Amplified Polymorphic DNA (RAPD) markers to assess the genetic diversity among eight sapota germplasm. The research revealed significant polymorphism, indicating a broad genetic base that can be exploited for breeding programs and conservation strategies (Meem *et al.,* 2020). Similarly, a genetic diversity study using RAPD markers conducted on sixteen sapota cultivars re-

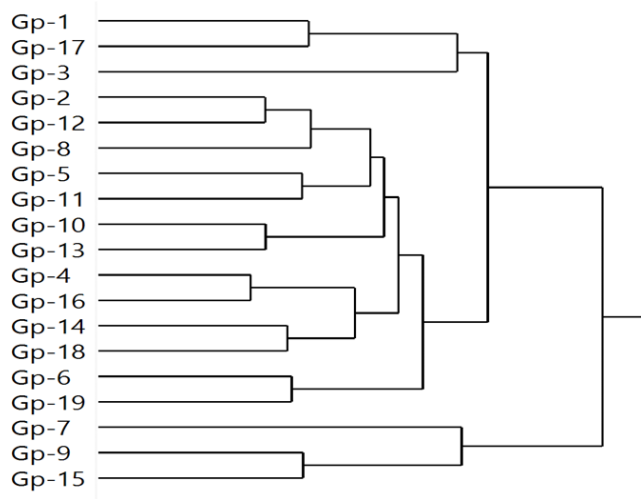


Fig. 7. *Dendrogram of nineteen Sapota germplasms (Gp*)

vealed wide variation in growth and yield traits, which may be attributed to genotypic differences (Kumar et al., 2015).

In terms of physico-chemical parameters, significant variation was observed across all measured attributes, including titratable acidity (TA), total soluble solids (TSS), vitamin C content, fruit firmness, moisture content, and pH. Titratable acidity, a critical determinant of fruit flavor and maturity, was expressed in terms of citric acid, the primary organic acid in sapota (Lee *et al.,* 2013). As seen in the present study, a progressive decline in acidity with advancing fruit maturity is consistent with previous observations (Pawar *et al.* 2011; Brito & Narain, 2002). Such variation in TA among germplasm is also supported by Suhasini *et al.* (2011), Kulkarni *et al.* (2007), and more recently by Poongavanam *et al.* (2023), who highlighted the role of edible coatings in maintaining postharvest acid content. The climacteric fruit sapota has a short shelf life due to its high respiration rate and ethylene production, leading to weight loss and quality deterioration (Renu *et al.,* 2022).

Total soluble solids (TSS), which reflect the sugar content and are crucial for consumer acceptability, varied significantly among the germplasm. This is consistent with the observations of Redd *et al.* (1986) and Abdul-Karim *et al.* (1987), who noted that TSS is strongly influenced by both the genotype and environmental conditions. Recent work by Rathva *et al.* (2024) demonstrated a direct correlation between TSS and genotype-specific responses to agro-climatic zones, supporting our findings of wide inter-genotypic variation in TSS values. Mondal *et al.* (2023) similarly reported high TSS variability among regional cultivars. Moreover, the use of organic amendments such as vermicompost has been shown to positively impact fruit quality, including TSS, as demonstrated in the 'Kalipatti' cultivar by Chaudhary *et al.* (2024).

Ascorbic acid (vitamin C) content also varied notably, with higher concentrations observed in less mature fruits, consistent with previous findings (Pawar *et al.,* 2011; Brito and Narain, 2002). This trait is particularly important given the increasing consumer demand for nutritionally rich fruit. Recent research by Phillips *et al.* (2021) confirms the significance of vitamin C variability across sapota accessions and its role as a functional quality marker in genotype selection. Recent research by Poongavanam *et al.* (2023) confirms the significance of vitamin C variability across sapota accessions and its role as a functional quality marker in genotype selection. Bala *et al.* (2017) observed that specific gravity, ascorbic acid and total phenols decreased, whereas cumulative loss in weight and malondialdehyde content increased with increasing storage period.

Fruit firmness, an essential attribute influencing postharvest handling and shelf life, decreased with fruit ripening, in line with the studies of Jarimopas and Kitthawee (2007). In addition, moisture content and pH values were found to differ significantly among the Sapota germplasm, affirming the role of genetic and environmental interactions. Jadhav *et al.* (2018) and Poongavanam *et al.* (2023) support the significance of these traits in postharvest quality and storage potential.

Interestingly, recent biochemical studies have shown that sapota peels and seeds also contain substantial levels of phenolics and flavonoids, with significant antioxidant properties (Beniwal *et al.,* 2024). This highlights sapota's broader nutritional and economic potential beyond its pulp, and points to new avenues for value-added utilization. The variation in fruit physio-chemical properties and yield parameters across different germplasms confirms the differences among them, which may be due to the highly heterozygous nature of the investigated genotypes (Bhoumick *et al.,* 2023).

The current research offers a detailed morphological and biochemical profiling of local sapota germplasm, which remains relatively under-documented in Bangladesh. While prior studies have focused on sapota's nutritional or postharvest aspects, this work integrates these with genetic and morphological diversity analysis. The use of cluster analysis and dendrogram-based diversity evaluation further enhanced the discrimination of superior genotypes, which can be prioritized in breeding programs targeting yield improvement, quality enhancement, and climate adaptability. Given the increasing challenges posed by climate change and biotic stresses, identifying diverse and resilient genotypes is imperative. The present research findings can contribute valuable insights for developing improved sapota cultivars adapted to the diverse agro-climatic zones of Bangladesh and the broader South Asian region.

Conclusion

In summary, the comprehensive characterization of nineteen local Sapota germplasms revealed significant variability in both morphological and physico-chemical traits. Genotypes Germplasm-3, Germplasm-7, and Germplasm-9 emerged as superior candidates with enhanced fruit size, yield, and nutritional quality, indicating their strong potential for breeding and commercial cultivation. The dendrogram analysis further confirmed the existence of distinct genetic clusters, emphasizing the rich genetic diversity within the evaluated accessions. These findings bridge an important knowledge gap in the characterization of this underutilized fruit crop in Bangladesh and lay a solid foundation for future crop improvement initiatives. Moving forward, it is recommended that future studies incorporate molecular marker-assisted analyses to validate and further

elucidate the genetic relationships among Sapota genotypes. Additionally, multi-location trials and postharvest evaluations are necessary to ascertain the adaptability and storage characteristics of the promising genotypes under varying agro-climatic conditions.

ACKNOWLEDGEMENTS

The authors are highly grateful for the funding support provided by the Ministry of Science and Technology, Bangladesh, as a National Science and Technology Fellowship.

Conflict of interest

The authors declare that they have no conflict of interest.

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