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RESEARCH ARTICLE

Physical fruit growth dynamics in guava (*Psidium guajava* L.) genotypes

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Abstract

Guava (*Psidium guajava* L.) is a widely cultivated tropical fruit crop valued for its nutritional richness, adaptability and economic importance. This study aimed to investigate the developmental progression of key fruit traits across eleven diverse guava genotypes during the winter season. Fruits were sampled at five growth stages, i.e. 35, 65, 75, 85 days after flowering (DAF) and at physiological maturity (PM) and were evaluated for fruit weight, length, width, seed core diameter and pulp thickness. Significant variation ($p \leq 0.05$) was observed among genotypes and across stages for all traits, with the highest values occurring at the PM stage. Genotypes such as Sasni and VNR Bihi recorded the highest values for various fruit physical traits, making them good material for breeding programs focused on fruit size and pulp content. Principal Component Analysis (PCA) revealed that the first three components accounted for 79.46 % of the total variability among genotypes. PC1 (48.97 %) was primarily associated with fruit weight, diameter and seed core diameter at later stages. PC2 (16.15 %) reflected variation in pulp thickness and seed core diameter at mid stages, while PC3 (14.34 %) captured additional differences in fruit length andpulp thickness at maturity. This study provides insights into stage-wise fruit development, enabling future researchers to identify the most appropriate growth stages for recording key fruit traits. These insights will support precise phenotyping and strengthen selection decisions inguava breeding and improvement programs.

Keywords: fruit growth stages; fruit physical traits; guava fruit development; physiological maturity; principal component analysis

Introduction

Guava (*Psidium guajava* L.) is a tropical and subtropical fruit crop belonging to the family Myrtaceae, which comprises approximately 150 genera and 5650 species (1). It is native to tropical America, covering the area from Mexico to Peru and has a diploid chromosome number of 2n = 2x = 22 (2). The crop was introduced to India in the early seventeenth century (3). In India, guava ranks as the 4th most important fruit crop after mango, banana and citrus. It is often called the Apple of the Tropics and the Poor Mans' Apple because it is affordable, available throughout the year and can grow in many different climates (4, 5). Along with its economic value, guava is also known for its high nutritional content and medicinal benefits (6, 7).

Various parts of the guava plant, including the leaves, bark and fruit, possess important medicinal properties such as antimicrobial, anti-inflammatory and antidiabetic effects, which contribute to its use in both traditional and modern medicine (8). Although guava holds a prominent place in fruit production, its genetic potential remains largely underutilised, with many promising genotypes yet to be fully explored for traits like yield, quality and stress tolerance (9). Understanding the changes in fruit traits across different stages of development is essential for selecting genotypes with better consumer acceptability and suitability for processing industries (10). Along with the mature stage, the changes occurring among the various developmental stages of fruits are of great value to researchers, as this helps them decide the most suitable stage for fruit sampling.

Although guava is widely cultivated and consumed, systematic studies on the dynamic changes in fruit growth traits across multiple developmental stages remain limited. Understanding such variation is critical for identifying promising genotypes with superior fruit quality attributes and for guiding selection in breeding programs. This study, therefore, fills an important gap by providing stage-wise insights that contribute to

the efficient characterisation and utilisation of guava genetic resources.

Materials and Methods

Planting Material

The experiment was carried out using eleven diverse guava (*Psidium guajava* L.) genotypes, namely Arka Kiran (AK), Allahabad Safeda (AS), Black guava (BG), Hisar Safeda (HS), Hisar Surkha (HSU), Hisar Surkha Variant (HSV), Punjab Pink (PP), Pant Prabhat (PPT), Shweta (SH), VNR Bihi (VNR) and Sasni during July, 2024-January, 2025. These genotypes were grown under uniform cultural practices in a well-maintained orchard during the course of the investigation. The plants were planted at a spacing of 6 x 3 m and were maintained under the recommended package of practices throughout the study period. The selected genotypes showed a wide range of fruit traits and genetic variation. They were studied at five stages of fruit growth: 35, 65, 75 and 85 days after flowering (DAF) (Fig. 1) and at physiological maturity (PM). These stages were decided in light of the work entitled "Physical and biochemical changes in guava (*Psidium guajava* L.) during various stages of fruit growth and development" by keeping in mind the suitability and applicability with respect to our study material (11). The PM stage was identified when the skin colour started changing from light green to yellow or yellowish green and the fruit became softer (12). This change in skin colour from deep green to yellowish green

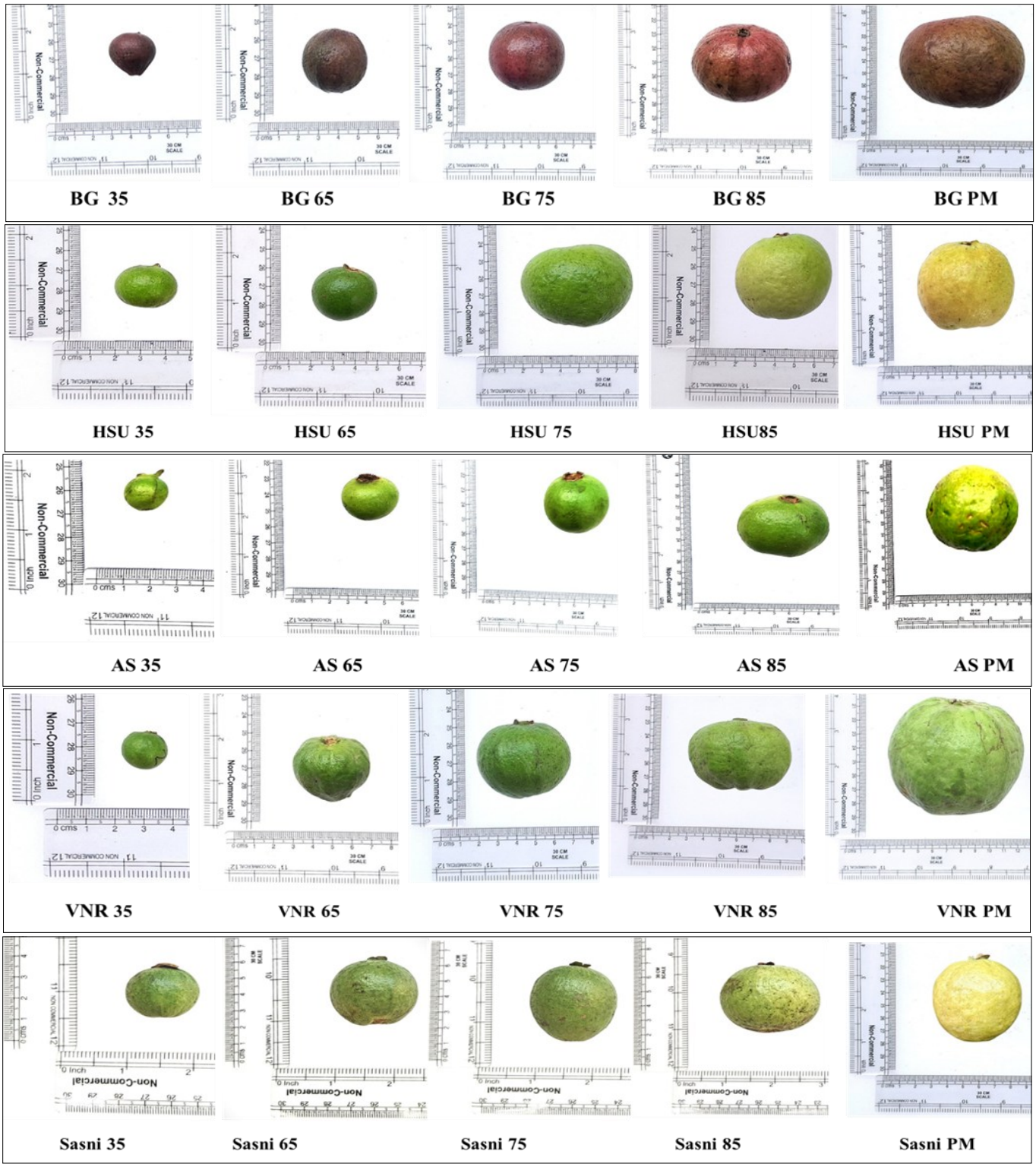

Fig. 1. Five growth stages of guava fruits in five guava genotypes.

happens because of the loss of chlorophyll and is an important sign to decide harvest maturity in guava (13).

Experimental site

The guava genotypes used in this study were maintained in the germplasm block at Todapur orchard, Division of Fruits and Horticultural Technology, ICAR–IARI, New Delhi, India (228 m above sea level; 28°38'07" N, 77°09'50" E). The site is characterised by alluvial soil with a clay loam texture, low organic matter and a subtropical climate.

Fruit sampling

The healthy fruits from different guava genotypes were selected at five developmental stages: 35, 65, 75 and 85 DAF and at PM. Each fruit was tagged using aluminium labels indicating the genotype and stage and enclosed in plastic net bags. Samples were harvested at the respective stages as described earlier and transported to the Post Graduate Laboratory, Division of Fruits and Horticultural Technology, ICAR–IARI, New Delhi. The fruits were washed, air-dried, labelled and prepared for subsequent fruit analyses as outlined below.

Assessment of fruit traits

The fruit weight was measured using an electronic weighing balance (Aczet CY 223C precision balance) and presented in grams (g). The fruit length was recorded from the base of the fruit to the apex end using vernier callipers (Mitutoyo 500-754-10) and the mean was expressed in millimetres (mm). Fruit breadth was recorded at the broadest part of the fruit using vernier callipers (Mitutoyo 500-754-10) and the mean was expressed in mm. The seed core diameter was determined on longitudinally halved fruits using vernier callipers (Mitutoyo 500-754-10) and the average value was recorded in mm. Pulp thickness was obtained by subtracting the seed core diameter from the fruit width and divided by two, both measured with vernier callipers (Mitutoyo 500-754-10). The mean value was expressed in mm.

Statistical analysis

A one-way ANOVA was carried out to determine significant differences among genotypes for various fruit physical traits in three replicates, having one fruit in each replication, using the PROG GLM procedure in SAS software (version 9.4; SAS Institute, Cary, NC, USA). Tukeys' Honest Significant Difference (HSD) test was employed to detect pairwise differences between genotypes. Additionally, the Least Significant Difference (LSD) or Critical Difference (CD) was calculated for each trait. Whenever necessary, a square root transformation of the form $\sqrt{(x + c)}$, where c is a constant, was applied to ensure the data met ANOVA assumptions. Statistical significance was considered at $p \leq 0.05$. Principal Component Analysis (PCA) was performed using GRAPES software (https://www.kaugrapes.com) to identify patterns of variation and trait contributions among guava genotypes across different developmental stages (Fig . 2).

Results and Discussion

The results are presented genotype-wise for various fruit traits at different developmental stages (Table 1-11). Different guava genotypes showed variable developmental patterns with respect to five developmental stages. Significant differences were observed among genotypes and across developmental stages for all five fruit parameters: fruit weight, fruit length, fruit width, core diameter and pulp thickness. The maximum values for all traits were observed at PM (Table 1-11). All traits showed progressive increase from 35 DAF to PM. The progressive increase in fruit weight, size and pulp-related parameters across genotypes aligns with previously reported developmental trends in guava (14, 15). One previous study

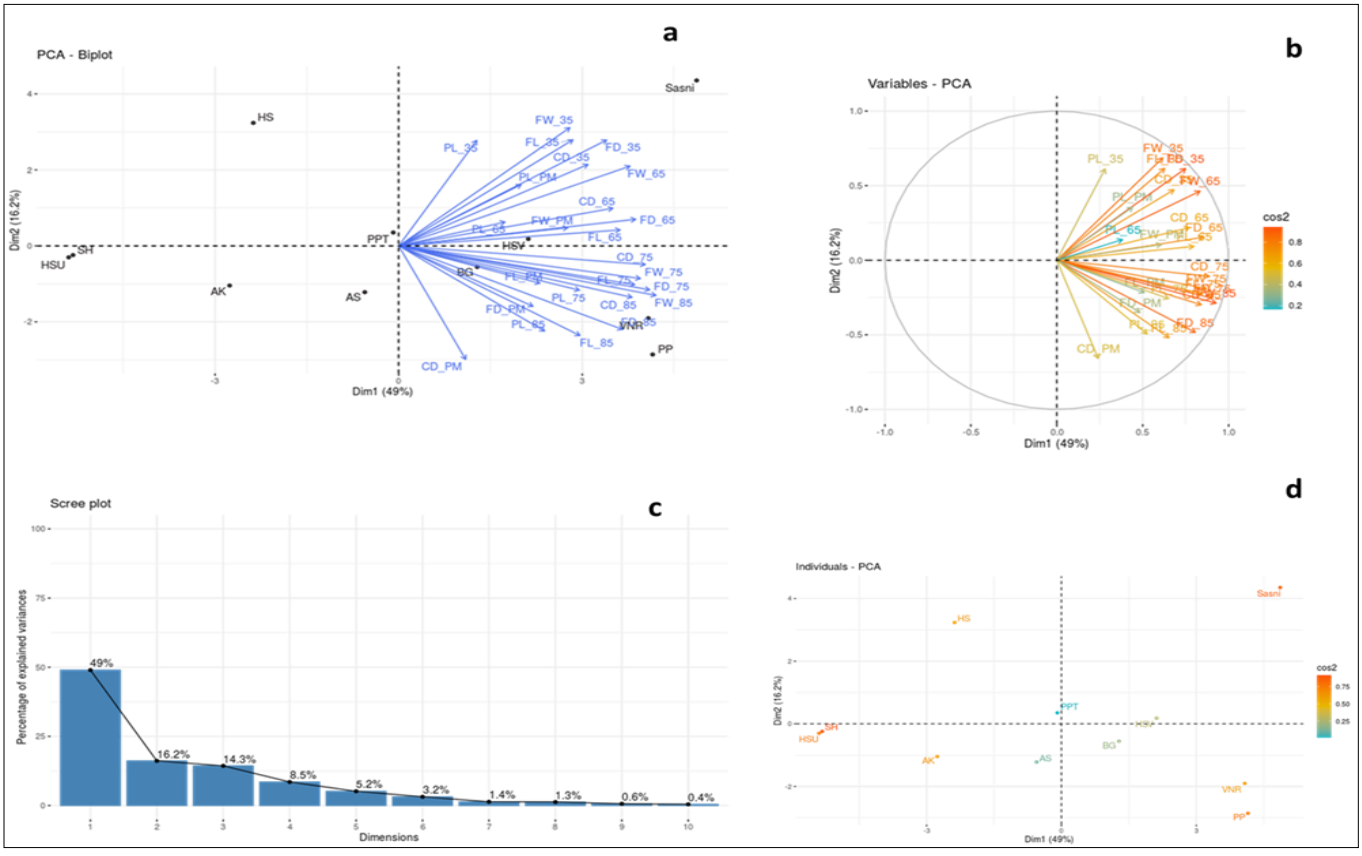

Fig. 2. Principal component analysis (PCA) of guava genotypes based on fruit traits across developmental stages, depicting **a.** PCA biplot, **b.** Loading plot, **c.** Scree plot, **d.** Individual PCA.

Table 1. Fruit parameters of Arka Kiran at different stages of development

Stage	Fruit weight (g)	Fruit length (mm)	Fruit width (mm)	Seed core diameter (mm)	Pulp thickness (mm)
35 DAF	1.67^{e} (1.47)	14.52^{d} (3.87)	14.38^{d} (3.86)	10.02^{e} (3.24)	2.18^{d} (1.64)
65 DAF	10.00^{d} (3.22)	28.33^{c} (5.36)	26.98^{c} (5.23)	17.92^{d} (4.28)	4.53^{c} (2.23)
75 DAF	28.50^{c} (5.38)	37.76^{b} (6.18)	36.63^{b} (6.09)	24.13^{c} (4.96)	6.25^{bc} (2.60)
85 DAF	58.00^{b} (7.65)	48.47^{a} (7.00)	47.14^{a} (6.90)	30.09^{b} (5.53)	8.52^{ab} (3.00)
PM	83.33^{a} (9.15)	52.72^{a} (7.29)	54.66^{a} (7.43)	36.35^{a} (6.07)	9.16^{a} (3.11)
SE m±	(0.142)	(0.148)	(0.137)	(0.108)	(0.099)
LSD (P ≤ 0.05)	(0.446)	(0.466)	(0.433)	(0.343)	(0.314)
C.V.	(4.564)	(4.311)	(4.033)	(3.911)	(6.855)
Range	1.67 - 83.33	14.52 - 52.72	14.38 - 54.66	10.02 - 36.35	2.18 - 9.16

*****The values in parentheses indicate transformed value. Means followed by different letters are significantly different. **DAF** - Days after flowering, **PM** - Physiological maturity, **SE m±** - Standard error of mean, **LSD** (P ≤ 0.05) - Least significant difference at 5 % probability level, **CV** - Coefficient of variation.

Table 2. Fruit parameters of Allahabad Safeda at different stages of development

Stage	Fruit weight (g)	Fruit length (mm)	Fruit width (mm)	Seed core diameter (mm)	Pulp thickness (mm)
35 DAF	3.00^{d} (1.82)	15.50^{e} (3.97)	16.97^{e} (4.17)	9.44^{d} (3.13)	3.73^{c} (2.05)
65 DAF	9.50^{d} (3.14	24.63^{d} (5.01)	26.30^{d} (5.17)	18.85^{c} (4.39)	3.76^{c} (2.06)
75 DAF	29.33^{c} (5.46	36.53^{c} (6.08)	37.54^{c} (6.17)	28.31^{b} (5.37)	4.62^{c} (2.26)
85 DAF	76.00^{b} (8.74	50.38^{b} (7.13)	51.07^{b} (7.18)	36.32^{ab} (6.07)	7.38^{b} (2.80)
PM	224.83^{a} (14.98	68.49^{a} (8.30)	78.08^{a} (8.86)	44.66^{a} (6.72)	16.71^{a} (4.14)
SEm±	(0.375)	(0.184)	(0.142)	(0.154)	(0.093)
LSD (P ≤ 0.05)	(1.183)	(0.580)	(0.450)	(0.487)	(0.294)
C.V.	(9.527)	(5.225)	(3.921)	(5.213)	(6.073)
Range	3.00 - 224.83	15.50 - 68.49	16.97 - 78.08	9.44 - 44.66	3.73 - 16.71

*****The values in parentheses indicate transformed value. Means followed by different letters are significantly different. **DAF** - Days after flowering, **PM** - Physiological maturity, **SE m±** - Standard error of mean, **LSD** (P ≤ 0.05) - Least significant difference at 5 % probability level, **CV** - Coefficient of variation.

Table 3. Fruit parameters of Black Guava at different stages of development

Stage	Fruit weight (g)	Fruit length (mm)	Fruit width (mm)	Seed core diameter (mm)	Pulp thickness (mm)
35 DAF	6.50^{d} (2.62)	24.27^{e} (4.97)	22.73^{d} (4.81)	18.45^{c} (4.34)	2.14^{c} (1.62)
65 DAF	17.42^{cd} (4.21)	31.27^{d} (5.63)	30.86^{cd} (5.60)	23.52^{bc} (4.90)	3.67^{c} (2.04)
75 DAF	34.58^{bc} (5.91)	39.03^{c} (6.29)	38.97^{c} (6.28)	27.77^{b} (5.309)	5.60^{bc} (2.43)
85 DAF	67.67^{b} (8.24)	55.57^{b} (7.49)	51.75^{b} (7.23)	33.66^{b} (5.83)	9.05^{ab} (3.08)
PM	172.17^{a} (13.06)	66.55^{a} (8.19)	72.91^{a} (8.56)	50.00^{a} (7.10)	11.46^{a} (3.45)
SEm±	(0.529)	(0.135)	(0.178)	(0.206)	(0.186)
LSD (P ≤ 0.05)	(1.670)	(0.427)	(0.562)	(0.652)	(0.587)
C.V.	(13.481)	(3.604)	(4.758)	(6.520)	(12.791)
Range	6.50 - 172.17	24.27 - 66.55	22.73 - 72.91	18.45 - 50.00	2.14 - 11.46

*****The values in parentheses indicate transformed value. Means followed by different letters are significantly different. **DAF** - Days after flowering, **PM** - Physiological maturity, **SE m±** - Standard error of mean, **LSD** (P ≤ 0.05) - Least significant difference at 5 % probability level, **CV** - Coefficient of variation.

Table 4. Fruit parameters of Hisar Safeda at different stages of development

Stage	Fruit weight (g)	Fruit length (mm)	Fruit width (mm)	Seed core diameter (mm)	Pulp thickness (mm)
35 DAF	5.50^{d} (2.44)	21.78^{d} (4.72)	21.53^{d} (4.69)	15.10^{c} (3.95)	4.52^{b} (2.18)
65 DAF	16.00^{c} (4.06)	29.62^{c} (5.49)	30.26^{c} (5.54)	20.62^{b} (4.59)	6.49^{ab} (2.60)
75 DAF	19.75^{c} (4.50)	29.91^{c} (5.51)	32.33^{c} (5.73)	21.72^{b} (4.71)	6.64^{ab} (2.67)
85 DAF	35.33^{b} (5.98)	37.53^{b} (6.16)	40.47^{b} (6.40)	26.87^{a} (5.23)	8.76^{ab} (3.02)
PM	60.67^{a} (7.81)	47.99^{a} (6.96)	50.82^{a} (7.16)	29.03^{a} (5.43)	14.08^{a} (3.77)
SEm±	(0.166)	(0.121)	(0.122)	(0.079)	(0.321)
LSD (P ≤ 0.05)	(0.524)	(0.384)	(0.387)	(0.250)	(1.013)
C.V.	(5.809)	(3.663)	(3.606)	(2.867)	(19.563)
Range	5.50 - 60.67	21.78 - 47.99	21.53 - 50.82	15.10 - 29.03	4.52 - 14.08

*****The values in parentheses indicate transformed value. Means followed by different letters are significantly different. **DAF** - Days after flowering, **PM** - Physiological maturity, **SE m±** - Standard error of mean, **LSD** (P ≤ 0.05) - Least significant difference at 5 % probability level, **CV** - Coefficient of variation.

Table 5. Fruit parameters of Hisar Surkha at different stages of development

Stage	Fruit weight (g)	Fruit length (mm)	Fruit width (mm)	Seed core diameter (mm)	Pulp thickness (mm)
35 DAF	1.83^{d} (1.53)	19.20^{d} (4.44)	13.58^{e} (3.75)	10.20^{d} (3.27)	1.69^{c} (1.48)
65 DAF	5.83^{cd} (2.50)	28.76^{c} (5.41)	18.31^{d} (4.34)	13.42^{c} (3.73)	2.44^{c} (1.71)
75 DAF	11.83^{c} (3.49)	30.81^{c} (5.595)	24.34^{c} (4.98)	18.59^{b} (4.37)	2.88^{c} (1.84)
85 DAF	30.67^{b} (5.58)	51.17^{b} (7.19)	33.12^{b} (5.80)	20.58^{b} (4.59)	6.27^{b} (2.60)
PM	126.67^{a} (11.27)	65.09^{a} (8.09)	63.01^{a} (7.97)	41.24^{a} (6.46)	10.88^{a} (3.37)
SEm±	(0.217)	(0.122)	(0.087)	(0.075)	(0.082)
LSD (P ≤ 0.05)	(0.685)	(0.384)	(0.275)	(0.235)	(0.260)
C.V.	(7.733)	(3.439)	(2.822)	(2.883)	(6.505)
Range	1.83 - 126.67	19.20 - 65.09	13.58 - 63.01	10.20 - 41.24	1.69 - 10.88

*****The values in parentheses indicate transformed value. Means followed by different letters are significantly different. **DAF** - Days after flowering, **PM** - Physiological maturity, **SE m±** - Standard error of mean, **LSD** (P ≤ 0.05) - Least significant difference at 5 % probability level, **CV** - Coefficient of variation.

Table 6. Fruit parameters of Hisar Surkha variant at different stages of development

Stage	Fruit weight (g)	Fruit length (mm)	Fruit width (mm)	Seed core diameter (mm)	Pulp thickness (mm)
35 DAF	6.00^{b} (2.53)	20.01^{c} (4.52)	22.06^{c} (4.74)	12.10^{c} (3.55)	4.98^{b} (2.33)
65 DAF	22.17^{b} (4.74)	31.87^{b} (5.69)	34.20^{b} (5.88)	22.95^{b} (4.84)	5.63^{b} (2.47)
75 DAF	65.50^{a} (8.09)	48.64^{a} (7.00)	50.54^{a} (7.14)	30.37^{a} (5.55)	9.61^{a} (3.18)
85 DAF	80.00^{a} (8.95)	50.46^{a} (7.13)	54.04^{a} (7.38)	31.32^{a} (5.64)	11.13^{a} (3.41)
PM	104.90^{a} (10.19)	53.99^{a} (7.38)	58.81^{a} (7.70)	36.56^{a} (6.08)	11.84^{a} (3.51)
SEm±	(0.515)	(0.187)	(0.155)	(0.115)	(0.111)
LSD (P ≤ 0.05)	(1.623)	(0.590)	(0.488)	(0.363)	(0.349)
C.V.	(12.928)	(5.113)	(4.088)	(3.890)	(6.455)
Range	6.00 - 104.90	20.01 - 53.99	22.06 - 58.81	12.10 - 36.56	4.98 - 11.84

*****The values in parentheses indicate transformed value. Means followed by different letters are significantly different. **DAF** - Days after flowering, **PM** - Physiological maturity, **SE m±** - Standard error of mean, **LSD** (P ≤ 0.05) - Least significant difference at 5 % probability level, **CV** - Coefficient of variation.

Table 7. Fruit parameters of Punjab Pink at different stages of development

Stage	Fruit weight (g)	Fruit length (mm)	Fruit width (mm)	Seed core diameter (mm)	Pulp thickness (mm)
35 DAF	5.33^{b} (2.41)	21.57^{b} (4.70)	20.58^{b} (4.60)	17.10^{b} (4.19)	1.74^{b} (1.48)
65 DAF	16.50^{b} (4.11)	32.68^{b} (5.76)	30.02^{b} (5.52)	23.16^{b} (4.86)	3.43^{b} (1.98)
75 DAF	88.17^{a} (9.29)	58.34^{a} (7.64)	51.70^{a} (7.22)	35.64^{a} (5.99)	8.03^{a} (2.92)
85 DAF	108.17^{a} (10.42)	65.60^{a} (8.12)	62.32^{a} (7.91)	40.90^{a} (6.43)	10.71^{a} (3.33)
PM	122.14^{a} (11.07)	70.10^{a} (8.39)	65.91^{a} (8.14)	43.60^{a} (6.64)	11.15^{a} (3.40)
SEm±	(0.504)	(0.278)	(0.221)	(0.203)	(0.184)
LSD (P ≤ 0.05)	(1.589)	(0.877)	(0.697)	(0.639)	(0.579)
C.V.	(11.710)	(6.969)	(5.743)	(6.247)	(12.151)
Range	5.33 - 122.14	21.57 - 70.10	20.58 - 65.91	17.10 - 43.60	1.74 - 11.15

*****The values in parentheses indicate transformed value. Means followed by different letters are significantly different. **DAF** - Days after flowering, **PM** - Physiological maturity, **SE m±** - Standard error of mean, **LSD** (*P≤0.05*) - Least significant difference at 5 % probability level, **CV** - Coefficient of variation.

Table 8. Fruit parameters of Pant Prabhat at different stages of development

Stage	Fruit weight (g)	Fruit length (mm)	Fruit width (mm)	Seed core diameter (mm)	Pulp thickness (mm)
35 DAF	4.67^{e} (2.23)	18.88^{d} (4.40)	20.39^{c} (4.55)	16.02^{c} (4.048)	2.19^{c} (1.63)
65 DAF	15.67^{d} (3.99)	27.77^{c} (5.31)	30.92^{b} (5.60)	26.30^{b} (5.18)	2.31^{c} (1.66)
75 DAF	40.00^{c} (6.35)	38.13^{b} (6.21)	37.13^{b} (6.13)	28.34^{ab} (5.37)	4.40^{bc} (2.21)
85 DAF	75.50^{b} (8.71)	47.24^{a} (6.91)	53.87^{a} (7.370)	33.76^{ab} (5.83)	8.03^{b} (2.89)
PM	113.00^{a} (10.63)	52.86^{a} (7.30)	63.18^{a} (7.98)	37.80^{a} (6.19)	14.71^{a} (3.90)
SEm±	(0.366)	(0.100)	(0.184)	(0.213)	(0.187)
LSD (P ≤ 0.05)	(1.154)	(0.317)	(0.580)	(0.673)	(0.590)
C.V.	(9.944)	(2.890)	(5.034)	(6.954)	(13.214)
Range	4.67 - 113.00	18.88 - 52.86	20.39 - 63.18	16.02 - 37.80	2.19 - 14.71

*****The values in parentheses indicate transformed value. Means followed by different letters are significantly different. **DAF** - Days after flowering, **PM** - Physiological maturity, **SE m±** - Standard error of mean, **LSD** (*P≤0.05*) - Least significant difference at 5 % probability level, **CV** - Coefficient of variation.

Table 9. Fruit parameters of Shweta at different stages of development

Stage	Fruit weight (g)	Fruit length (mm)	Fruit width (mm)	Seed core diameter (mm)	Pulp thickness (mm)
35 DAF	1.67^{e} (1.46)	13.17^{e} (3.69)	13.92^{e} (3.80)	9.25^{d} (3.12)	2.34^{d} (0.91)
65 DAF	7.00^{d} (2.72)	20.60^{d} (4.59)	22.79^{d} (4.82)	15.85^{c} (4.04)	3.47^{c} (1.09)
75 DAF	23.92^{c} (4.94)	28.82^{c} (5.41)	29.37^{c} (5.46)	21.86^{bc} (4.73)	3.75^{b} (1.15)
85 DAF	39.00^{b} (6.27)	36.09^{b} (6.04)	37.75^{b} (6.18)	25.97^{b} (5.13)	5.89^{ab} (1.19)
PM	88.74^{a} (9.43)	55.75^{a} (7.50)	61.37^{a} (7.99)	41.59^{a} (6.48)	10.89^{a} (1.23)
SEm±	(0.242)	(0.129)	(0.121)	(0.170)	(0.137)
LSD (P ≤ 0.05)	(0.765)	(0.408)	(0.382)	(0.538)	(0.431)
C.V.	(8.467)	(4.120)	(3.724)	(6.290)	(10.224)
Range	1.67 - 88.74	13.17 - 55.75	13.92 - 61.37	9.25 - 41.59	2.34 - 10.89

*****The values in parentheses indicate transformed value. Means followed by different letters are significantly different. **DAF** - Days after flowering, **PM** - Physiological maturity, **SE m±** - Standard error of mean, **LSD** (*P≤0.05*) - Least significant difference at 5 % probability level, **CV** - Coefficient of variation.

Table 10. Fruit parameters of VNR Bihi at different stages of development

Stage	Fruit weight (g)	Fruit length (mm)	Fruit width (mm)	Seed core diameter (mm)	Pulp thickness (mm)
35 DAF	4.83^{d} (2.14)	18.82^{d} (4.34)	18.55^{d} (4.31)	12.86^{d} (3.60)	2.85^{c} (1.82)
65 DAF	28.00^{cd} (5.30)	37.51^{c} (6.16)	36.85^{c} (6.11)	20.79^{cd} (4.61)	8.03^{b} (2.92)
75 DAF	56.50^{bc} (7.54)	42.15^{bc} (6.53)	50.01^{bc} (7.10)	27.23^{bc} (5.25)	11.39^{ab} (3.42)
85 DAF	113.60^{b} (10.65)	53.62^{ab} (7.36)	60.95^{ab} (7.83)	35.81^{ab} (6.02)	12.57^{ab} (3.61)
PM	229.83^{a} (15.07)	65.53^{a} (8.12)	77.55^{a} (8.82)	46.66^{a} (6.86)	15.45^{a} (3.98)
SE m ±	(0.731)	(0.248)	(0.300)	(0.280)	(0.188)
LSD (P ≤ 0.05)	(2.302)	(0.782)	(0.946)	(0.883)	(0.592)
C.V.	(15.550)	(6.614)	(7.611)	(9.215)	(10.326)
Range	4.83 - 229.83	18.82 - 65.53	18.55 - 77.55	12.86 - 46.66	2.85 - 15.45

*****The values in parentheses indicate transformed value. Means followed by different letters are significantly different. **DAF** - Days after flowering, **PM** - Physiological maturity, **SE m±** - Standard error of mean, **LSD** (P ≤ 0.05) - Least significant difference at 5 % probability level, **CV** - Coefficient of variation.

Table 11. Fruit parameters of Sasni at different stages of development

Stage	Fruit weight (g)	Fruit length (mm)	Fruit width (mm)	Seed core diameter (mm)	Pulp thickness (mm)
35 DAF	23.67^{d} (4.83)	32.85^{c} (5.72)	30.66^{c} (5.53)	22.14^{b} (4.70)	4.26^{b} (2.06)
65 DAF	39.16^{cd} (6.16)	35.19^{c} (5.92)	33.69^{c} (5.80)	24.39^{b} 4.93)	4.65^{b} (2.13)
75 DAF	62.16^{bc} (7.82)	47.58^{b} (6.89)	43.23^{b} (6.57)	32.70^{a} (5.71)	5.27^{b} (2.29)
85 DAF	93.83^{b} (9.65)	50.77^{b} (7.12)	45.87^{b} (6.77)	34.82^{a} (5.89)	5.53^{b} (2.34)
PM	276.41^{a} (16.60)	71.59^{a} (8.46)	68.92^{a} (8.30)	37.01^{a} (6.08)	15.96^{a} (3.99)
SEm±	(0.611)	(0.152)	(0.109)	(0.111)	(0.118)
LSD (*P≤0.05*)	(6.234)	(1.513)	(1.084)	(1.104)	(1.173)
C.V.	(11.742)	(3.854)	(2.860)	(3.509)	(7.956)
Range	23.67 - 276.41	32.85 - 71.59	30.66 - 68.92	22.14 - 37.01	4.26 - 15.96

*****The values in parentheses indicate transformed value. Means followed by different letters are significantly different. **DAF** - Days after flowering, **PM** - Physiological maturity, **SE m±** - Standard error of mean, **LSD** (P ≤ 0.05) - Least significant difference at 5 % probability level, **CV** - Coefficient of variation.

observed that fruit weight and size followed a general pattern of steady increase until maturity, across seeded and seedless guava cultivars, with the most rapid growth occurring between 45 to 90 days after fruit set (16). One previous study reported significant length and diameter increases between 2-12 weeks, peaking by week 14 (approximately 98 days after anthesis), marking physiological maturity in the case of guava (17). The change in fruit weight and pulp thickness between 85 DAF and PM was sharp (Fig. 3), indicating the period is crucial for cultural management purposes i.e. irrigation etc. This noticeable change in fruit weight and pulp thickness may be due to the cell expansion and metabolite accumulation in the cells of fruit pericarp during third phase of fruit development. Selecting distinct developmental stages during fruit growth can play a crucial role in designing effective transcriptomic studies for future research. Research indicates that sampling at biologically meaningful stages, such as during cell division, expansion, or the onset of ripening, enables the detection of key gene expression changes associated with traits like fruit size, weight, pulp development, sugar accumulation and antioxidant activity in mango, peach, cucumber, olive and sweet orange (18-22). In this context, stage-based knowledge can be used for selecting / refining appropriate stages for molecular studies like transcriptome analysis and such integration of phenotypic and molecular studies may help identify candidate genes regulating important physico-biochemical traits in the case of fruit crops.

Based on fruit weight, all the 11 guava genotypes can be divided into three broad categories like low fruit weight (< 100 g), moderate fruit weight (100-200 g) and heavy fruit (> 200 g) weight genotypes based on their values at maturity. AK, HS and SH happened to be in the low fruit weight category, whereas Sasni, VNR and AS fall into the heavy fruit weight category. The remaining 5 genotypes were found to be moderate fruit weight genotypes. The genotypes AK, PPT and SH (Table 1, 8 and 9) had significant differences in fruit weight at all five stages of fruit development. In genotypes HSV and PP (Table 6-7), fruit weight showed no significant variation in later stages of fruit development (75 DAF, 85 DAF and PM values were at par with each other). These observations were in line with a gradual and significant increase in fruit weight from 30 days after anthesis (DAA) to harvest maturity (23). They also highlighted that the rate of increase was more pronounced 60 to 90 days after flowering, coinciding with cell expansion and sugar accumulation. Based on seed core diameter at maturity, the 11 guava genotypes showed wide variation in their final seed core diameter (Table 1-11). Genotypes AK, AS, SH and VNR (Tables 1, 2, 9 and 10) exhibited significant differences in seed core

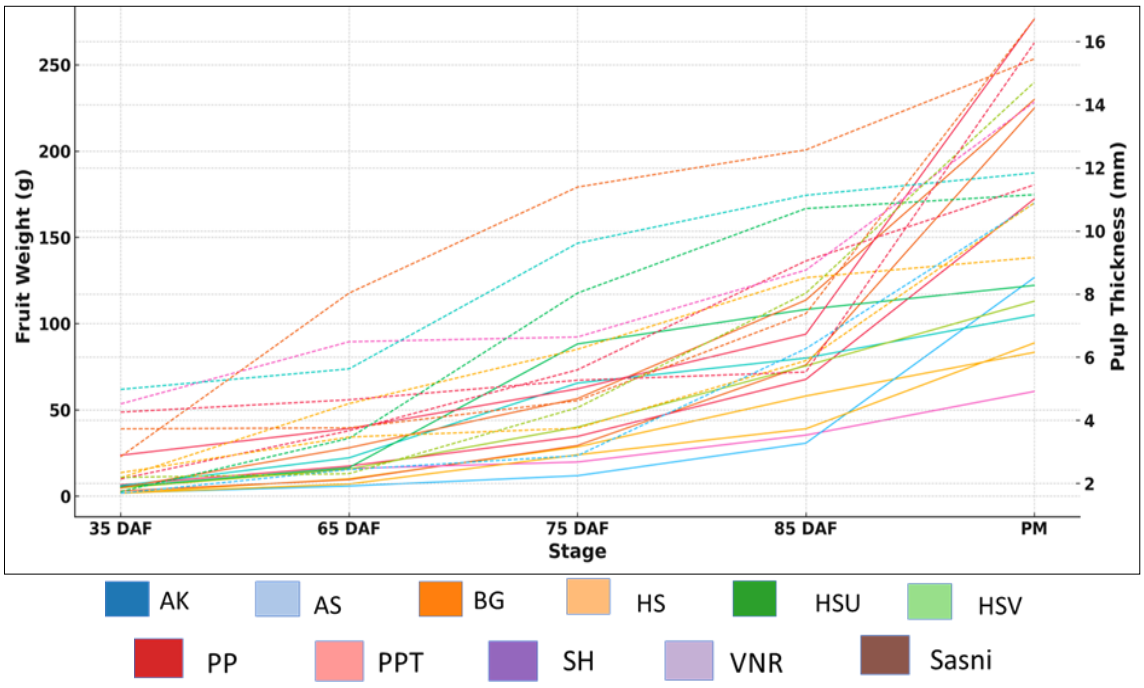

Fig. 3. Comparative incremental pattern of fruit weight and pulp thickness at 35 DAF, 65 DAF, 75 DAF, 85 DAF, and PM among 11 guava genotypes

diameter at all five developmental stages, indicating continuous expansion of the seed cavity throughout fruit growth. In contrast, genotypes including HSV, PP and Sasni (Table 6, 7 and 11), the significant variation in seed core diameter values occurs during the initial development period with values differing non significantly during later stages (75 DAF, 85 DAF and PM). Guava genotypes PP and HSV showed the same developmental pattern for fruit weight, pulp thickness and seed core diameter during all stages under study.

The PCA analysis is presented in Fig. 2a-d. The PCA biplot represents the variation among 11 guava genotypes based on five fruit parameters, i.e. fruit weight (FW), fruit length (FL), fruit diameter (FD), core diameter (CD) and pulp thickness (PT), measured across five developmental stages (Fig. 2a). The first three principal components (PCs) together explain 79.46 % of the total variation, as shown in the Scree plot (Fig. 2c). PC1 (48.97 %) is mainly driven by fruit weight, fruit diameter and core diameter, especially at later stages (75 DAF, 85 DAF and PM). These traits had the longest vectors, indicating a strong contribution to genotype separation along this axis. PC2 (16.15 %) is influenced by pulp thickness and core diameter at early to intermediate stages, reflecting variation in tissue development during mid-fruit growth, whereas PC3 (14.34 %) is associated with additional variability in fruit length and pulp thickness, particularly at the maturity stage. Genotypes like Sasni, VNR Bihi and Punjab Pink cluster in the direction of strong positive contributors like FW_PM, FD_PM and CD_PM, suggesting high values in fruit size and weight traits at maturity. In contrast, genotypes like Arka Kiran, Hisar Surkha and Shweta appear on the opposite side, indicating comparatively lower values for those traits. The plot effectively highlights which parameters at specific stages contribute most to genetic variation, supporting targeted selection of superior genotypes. In another study, across 28 guava genotypes, PCA and k-means clustering were applied to 16 quantitative traits, explaining 93.3 % of the total variation across six principal components. The first PC (50.6 %) captured traits such as fruit weight, length, width, pulp weight and shape-related characteristics. These analyses effectively grouped genotypes with high fruit weight and size, such as Allahabad Safeda, Sasni and VNR, into distinct clusters (24). Similarly, research highlights the PCA on cluster and berry-related traits on muscadine grapes, where PC1 (40.5 %) and PC2 (20.9 %) explained ~61.4 % of variance. Highly correlated traits such as berry weight, cluster size and seed number enabled differentiation of cultivars, mirroring our findings where fruit size, weight and core diameter cluster strongly in PC1 (25).

Conclusion

The present study provides a detailed understanding of physical trait dynamics across guava genotypes and developmental stages. Future research could integrate biochemical and molecular markers to link phenotypic growth patterns with underlying genetic regulation. Expanding the study across multiple seasons or agro-climatic zones would help validate trait stability and genotype performance. High-performing genotypes like Sasni and VNR Bihi may be advanced for breeding programs focused on fruit size and pulp content. The multi-trait selection indices developed from PCA and correlation outcomes can aid in the early selection of superior genotypes. Ultimately, laying the foundation for cultivar improvement targeting both table and processing markets.

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Authors' contributions

SJ carried out the investigation and prepared the draft manuscript. MT designed the methodology, supervised the work, validated the results and contributed to the review and editing. AN, RB, MS and

NDG contributed to conceptualisation and methodology. PM, PS, CA and LL assisted in the investigation. AKG and CK contributed to methodology development. EV analysed the data. AMS contributed to manuscript editing, result interpretation and presentation. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

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

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