

Pomelo Varietal Evaluation Trial

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1. Introduction

Citrus fruits are one of the most important fruit crops, with a global production of over 120 million tons per year (FAO, 2016). In Asia and some parts of Africa and Australia, a citrus variety commonly known as “pomelo” (also spelled as “pummelo”) or “shaddock” is a popular fruit widely grown and consumed fresh or processed into juice (Sirisomboon et al., 2024). Due to hybridization with other citrus species, there have been numerous pomelo cultivars being cultivated in many countries. In Southeast Asia and other parts of the world, pomelo has been growing in popularity and is now one of the five most widely cultivated and consumed citrus fruits, along with orange, mandarin, lemon, and grapefruit (Puglisi et al., 2017). Genetic studies have revealed extensive diversity among pomelo germplasms, with distinct subgroups identified based on geographical origin and genetic structure. For example, pomelo accessions from Thailand, Vietnam, and different regions of China display unique genetic features, while Indian collections show wide variation in both morphological and chemical fruit characteristics (Wang, 2019; Nguyen and Tran, 2021; Singh, 2020). This diversity is not only important for conservation but also provides opportunities for breeding programs aimed at improving specific traits (Zhou, 2018).

Among the most desirable traits in pomelo cultivation are large fruit weight, high juice content, and elevated total soluble solids (TSS), which contribute to better yield, consumer appeal, and fruit quality. Certain clones and regional varieties have been identified with superior fruit size (exceeding 2 kg), higher juice percentage, and TSS values above 10.5°Brix, making them particularly attractive for both fresh consumption and processing (Chen, 2017; Li and Zhao, 2020). These traits are highly sought after by growers and breeders, as they directly impact marketability and profitability (Kumar, 2019).

In Bhutan, the citrus market is currently dominated by mandarin oranges, which are a major export crop and have contributed significantly to the national economy (Dorji et al, 2016). However, this saturation presents an opportunity to diversify Bhutan’s citrus industry by introducing alternative citrus crops; pomelo, as reported by SciOpen (2023), has been gaining popularity in other Asian markets.

Despite the potential, there is a notable lack of scientific studies and varietal evaluation trials on pomelo in Bhutan. This gap accentuates the need for research to identify suitable pomelo varieties that can thrive in local agro-climatic conditions and meet market requirements. To address this, the present study conducts a varietal evaluation trial of three pomelo varieties;

Bangpeiyu, R3P4, and R4P5; focusing on key agronomic and fruit quality traits. The objective is to assess and compare their performance, with the aim of identifying superior genotypes that could support the diversification and sustainable development of Bhutan's citrus sector.

2. Materials and Methods

2.1. Experimental site

The Varietal evaluation trial was conducted at Agriculture Research and Development Centre (ARDC), Bajo.

2.2. Data collection

Data collection was conducted at the maturity stage of the pomelos, during the harvest seasons of 2024 and 2025. For each variety, ten randomly selected, healthy-looking fruits were harvested from three randomly chosen trees (n=30).

2.2.1. Morphological and Physicochemical Parameters.

- I. Fruit Weight and Seed weight were measured using a digital weighing scale
- II. Fruit Length, Peel Thickness and Fruit Diameter were measured using digital callipers at the maximum dimensions.
- III. Juice Content was extracted manually, and the volume was measured using a 100 ml graduated cylinder with 1 ml precision.
- IV. TSS was determined using a digital refractometer (0-53% Brix) at room temperature. A drop of juice was placed on the prism, and the reading was taken. It was calibrated before the data was collected.
- V. Citric acid content was determined by titration with 0.1 N NaOH using phenolphthalein as an indicator.
- VI. Seed content was determined by manually extracting and counting all seeds from each fruit.
- VII. Peel Weight Ratio and Pulp Weight Ratio were calculated by dividing the respective weights by the fruit weight, after converting all weights to grams.

2.3. Methodology

2.3.1. PCA (Principal Component Analysis)

Principal Component Analysis (PCA) was conducted using the *prcomp()* function in R statistical software (version [4.4.3]). Prior to PCA, the data for the Fruit Weight, Fruit Length, Fruit Diameter, Peel Thickness, Pulp Weight, Seed Content, Seed Weight, TSS, Juice Content and Citric Acid Content was scaled (centered and divided by the standard deviation) using the

scale() function to ensure that variables with larger scales did not disproportionately influence the results. This standardization effectively transformed the data to have a mean of zero and a standard deviation of one for each variable, allowing the analysis to be based on correlations rather than covariances.

The principal components (PCs) are linear combinations of the original variables. Mathematically, each principal component PC_i can be expressed as:

$$PC_i = a_{i1}X_1 + a_{i2}X_2 + \cdots + a_{ip}X_p$$

where:

PC_i is the score of the i -th principal component for a given sample.

X_j represents the value of the j -th original variable (after scaling).

a_{ij} is the loading of the j -th original variable on the i -th principal component. These loadings are the elements of the eigenvectors of the correlation matrix of the scaled data.

prcomp() uses Singular Value Decomposition (SVD) of the scaled data (equivalent to correlation matrix eigendecomposition) to yield these loadings and principal component scores. Variance explained by each PC was derived from eigenvalues.

The first two principal components (PC1 and PC2), capturing the largest portion of total variance, were chosen for detailed interpretation and visualization in a biplot to reveal major patterns and relationships among pomelo varieties and variables. The biplot displays sample scores and variable loadings simultaneously.

2.3.2. Quality Index

A Quality Index (QI) was developed to provide an overall ranking of pomelo varieties based on a superiority scale of several desirable traits: Juice Content, TSS, TSS/Acid Ratio, low Peel Weight Ratio, low Seed Content, low Seed Weight, and high Pulp Weight Ratio. For each trait, varieties were ranked from 1 (most desirable) to 3 (least desirable) based on their mean values. These ranks were weighted as follows: Rank 1 = 3, Rank 2 = 2, and Rank 3 = 1. The QI for each variety was calculated as the sum of the weighted ranks across all seven traits:

$$QI = \sum_{i=1}^7 (w_{rank_i} \times r_i)$$

where r_i is the rank of the variety for the i -th trait, and w_{ranki} is the corresponding weight. Higher QI scores indicate a higher overall quality based on the defined desirable characteristics and weighting. The varieties were subsequently ranked based on their total QI scores.

2.3.3. Mass Modeling

To investigate the relationship between fruit dimensions and fruit weight for each pomelo variety, several regression models; linear, quadratic, S-curve, and power functions, were fitted to the collected data using the statistical software R (version 4.4.3).

For each variety, separate models were evaluated to predict fruit weight based on fruit length and fruit diameter. The coefficient of determination (R-squared) was used to assess the goodness of fit for each model, with higher values indicating a better predictive capability. Linear models were fitted using the *lm()* function, while non-linear models were implemented using non-linear least squares (*nls()*). The model exhibiting the highest R-squared value was identified as the most suitable for describing the dimensional influence on weight for each specific variety and predictor.

3. Results

3.1. Descriptive Statistics for Pomelo Varieties

Table 1 presents the mean values and standard deviations for the morphological and physicochemical parameters measured for each pomelo variety. Analysis of variance (ANOVA) was used to determine if there were significant differences in these parameters among the different varieties.

The analysis revealed significant inter-varietal variation in several key pomelo fruit characteristics. Specifically, fruit weight ($p = 0.0003$), pulp weight ($p = 0.0003$), seed weight ($p = 0.004$), citric acid content ($p = 0.03$), and juice content ($p = 0.0001$) exhibited statistically significant differences among the Banpeiyu, R3P4, and R4P5 varieties, as determined by ANOVA. Banpeiyu fruits were characterized by a higher mean fruit weight (0.74 kg), pulp weight (0.49 kg), seed weight (20.93 g), citric acid concentration (1.75%), and juice volume (99.84 ml) relative to the other varieties. R3P4 displayed the lowest mean values for these parameters (0.42 kg fruit weight, 0.22 kg pulp weight, 4.92 g seed weight, 1.23% citric acid, and 26.49 ml juice content). In contrast, fruit length ($p = 0.55$), fruit diameter ($p = 0.47$), peel thickness ($p = 0.33$), peel weight ($p = 0.11$), pulp length ($p = 0.55$), seed content ($p = 0.78$), and total soluble solids (TSS) ($p = 0.59$) did not show statistically significant differences among the varieties. Notably, R3P4 exhibited elevated standard deviations for fruit length (30.64 cm) and diameter (31.35 cm), indicating greater intra-varietal variability for these morphological traits.

Post-hoc analysis using Tukey's HSD revealed significant differences among the pomelo varieties for several fruit quality parameters. Fruit weight varied significantly, with Banpeiyu exhibiting the highest mean fruit weight (0.74 kg), followed by R4P5 (0.67 kg), and R3P4 having the lowest (0.42 kg). A similar trend was observed for pulp weight, where Banpeiyu (0.49 kg) > R4P5 (0.41 kg) > R3P4 (0.22 kg). Seed weight also differed significantly, with Banpeiyu (20.93 g) > R4P5 (12.31 g) > R3P4 (4.92 g). For citric acid content, Banpeiyu (1.75%) had the highest concentration, significantly greater than R3P4 (1.23%), while R4P5 (1.48%) was intermediate and not significantly different from Banpeiyu. Finally, juice content showed significant differences, with Banpeiyu (99.84 ml) > R4P5 (80.07 ml) > R3P4 (26.49 ml).

Table 1. Mean and standard deviation of pomelo characteristics, with ANOVA p-values and Tukey's HSD results ($p < 0.05$).

Parameter	Variety	Mean	SD	p-value
Fruit Weight (KG)	Banpeiyu	0.74 ^a	0.18	0.0003
	R3P4	0.42 ^b	0.09	
	R4P5	0.67 ^c	0.19	
Fruit Length (CM)	Banpeiyu	12.08	0.76	0.55
	R3P4	12.58	30.64	
	R4P5	12.19	0.88	
Fruit Diameter (CM)	Banpeiyu	12.22	1.35	0.47
	R3P4	13.33	31.35	
	R4P5	11.15	1.14	
Peel Thickness (mm)	Banpeiyu	1.35	0.50	0.33
	R3P4	1.62	0.41	
	R4P5	1.83	1.96	
Peel Weight (KG)	Banpeiyu	0.21	0.05	0.11
	R3P4	0.20	0.05	
	R4P5	0.25	0.05	
Pulp Length (cm)	Banpeiyu	11.05	22.86	0.55
	R3P4	8.14	15.74	
	R4P5	8.12	1.06	
Pulp Weight (KG)	Banpeiyu	0.49 ^a	0.19	0.0003
	R3P4	0.22 ^b	0.06	
	R4P5	0.41 ^c	0.16	
Seed Content (No)	Banpeiyu	85.14	30.35	0.78
	R3P4	73.43	34.64	
	R4P5	43.06	52.65	
Seed Weight (g)	Banpeiyu	20.93 ^a	12.74	0.004
	R3P4	4.92 ^b	4.99	
	R4P5	12.31 ^c	14.32	
TSS (%)	Banpeiyu	11.39	1.80	0.59
	R3P4	11.92	1.87	
	R4P5	10.85	2.28	
Citric Acid (%)	Banpeiyu	1.75 ^a	0.64	0.03
	R3P4	1.23 ^{ab}	0.47	
	R4P5	1.48 ^b	0.24	
Juice Content (ml)	Banpeiyu	99.84 ^a	69.46	0.0001
	R3P4	26.49 ^b	14.60	
	R4P5	80.07 ^c	32.02	

3.2. Mass Modeling

Fruit length and diameter were used to determine which better predicts fruit weight.

3.2.1. Fruit Length as a Predictor of Fruit Weight

The ability of fruit length to predict fruit weight varied considerably among the pomelo varieties (Table 2). Overall, fruit length demonstrated a poor capacity to predict fruit weight, with all models exhibiting low explanatory power ($R^2 < 0.01$). However, for Variety R4P5, the quadratic model showed a substantially stronger relationship ($R^2 = 0.9$), indicating that fruit weight can be reasonably well predicted by a quadratic function of fruit length in this variety. The linear model also showed some predictive ability ($R^2 = 0.44$) for R4P5. In contrast, fruit length was a weak predictor for R3P4 and Banpeiyu, with R^2 values consistently below 0.22 across all models.

Table 2. R^2 Values for Fruit Weight Prediction Models Using Fruit Length

Variety	Linear	Quadratic	S-curve	Power
Overall	0.01	0.01	0.00	0.01
R4P5	0.44	0.90	0.58	0.52
R3P4	0.02	0.16	0.04	0.07
Banpeiyu	0.20	0.21	0.13	0.17

3.2.2. Fruit Diameter as a Predictor of Fruit Weight

Fruit diameter proved to be a more effective predictor of fruit weight in certain varieties (Table 3). Overall, diameter was a poor predictor of fruit weight ($R^2 < 0.01$). Diameter was a strong predictor of fruit weight in R4P5, with the quadratic model again showing the highest explanatory power ($R^2 = 0.94$). Linear, S-curve, and Power models also performed well ($R^2 > 0.91$) for R4P5. Banpeiyu also showed a strong relationship between fruit diameter and fruit weight, with R^2 values around 0.80-0.90 for all models. Subsequently, fruit diameter was a poor predictor of fruit weight for R3P4, with R^2 values below 0.17 across all models.

Table 3. R-squared Values for Fruit Weight Prediction Models Using Fruit Diameter

Variety	Linear	Quadratic	S-curve	Power
Overall	0.01	0.01	0.00	0.02
R4P5	0.92	0.94	0.92	0.93
R3P4	0.03	0.16	0.04	0.07
Banpeiyu	0.89	0.90	0.80	0.88

3.3. Fruit Characteristics and their relationships/Correlation

Correlations between fruit dimensions (length and diameter) and internal characteristics (pulp weight, juice content) showed distinct patterns (Table 4). R3P4 displayed strong positive correlations, indicating that larger fruit dimensions are associated with larger internal dimensions in this variety. The correlation between pulp length and fruit length was -0.29 for Banpeiyu, 1 for R3P4, and 0.63 for R4P5. The correlation between pulp length and fruit diameter was >0 for Banpeiyu, 1 for R3P4, and 0.80 for R4P5. In contrast, Banpeiyu showed weak or even negative correlations, suggesting a less direct relationship between external and internal size.

Juice content varied significantly, with Banpeiyu exhibiting the highest mean juice content (138 ml) and R3P4 the lowest (29.6 ml). R4P5 had an intermediate mean juice content of 86.3 ml. Juice content was positively correlated with pulp and fruit weight across all varieties, implying that heavier fruits tend to contain more juice. The correlation between juice content and pulp weight was 0.70 for Banpeiyu, 0.43 for R3P4, and 0.66 for R4P5. The correlation between juice content and fruit weight was 0.60 for Banpeiyu, 0.37 for R3P4, and 0.65 for R4P5 (Table 5)

Total Soluble Solids (TSS) ranged from 10.85% to 11.92% across the varieties (Table 6). R3P4 had the highest average TSS (12.1%), followed by Banpeiyu (11.6%), and R4P5 had the lowest (11.1%). Mean citric acid content also varied, with Banpeiyu having the highest content (1.94%) and R3P4 the lowest (1.32%). The ratio of TSS to citric acid was highest in R3P4 (11.2), indicating a relatively less acidic taste profile compared to Banpeiyu (8.56) and R4P5 (7.50).

Seed characteristics also differed among varieties (Table 7). Banpeiyu had the highest mean seed number (91.3) and seed weight (26.4 g), while R4P5 had the lowest mean seed number (43.06), and R3P4 had the lowest mean seed weight (6.9 g). The ratio of seed weight to pulp weight varied, with Banpeiyu having the highest ratio (0.04) and R3P4 the lowest (0.03).

Table 4. Correlation between fruit dimension and Internal Characteristics

Variety	Pulp Length~Fruit Length	Pulp length~Fruit Diameter	Pulp weight~Fruit Length	Pulp weight ~Fruit Diameter
Banpeiyu	-0.29	0.00	0.28	0.92
R3P4	1.00	1.00	-0.29	-0.29
R4P5	0.63	0.81	0.56	0.88

Table 5. Juice Content Summary and Correlation

Variety	Mean Juice content (ml)	SD Juice Content	Juice~Pulp weight correlation	Juice~Fruit weight correlation
Banpeiyu	138.00	73.20	0.70	0.60
R3P4	29.60	15.40	0.43	0.37
R4P5	86.30	33.80	0.66	0.65

Table 6. TSS, Citric Acid and TSS/Citric Acid Ratio

Variety	Mean TSS (%)	SD TSS	Mean Citric Acid (%)	SD Citric Acid	TSS/ACID Ratio	SD TSS/Acid Ratio
Banpeiyu	11.60	1.90	1.94	0.67	8.56	9.25
R3P4	12.10	1.97	1.32	0.50	11.20	6.98
R4P5	11.10	2.40	1.50	0.26	7.50	1.49

Table 7. Seed Characteristics

Variety	Mean Seed Number	SD Seed Number	Mean Seed Weight (g)	SD Seed Weight	Seed/Pulp Ratio	SD Seed/Pulp Ratio
Banpeiyu	91.30	32.00	26.40	13.40	0.05	0.01
R3P4	81.40	36.50	6.90	5.26	0.03	0.02
R4P5	78.60	55.50	20.90	15.10	0.04	0.03

3.4. Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was performed to figure out the relationships among the measured fruit characteristics and to identify the main sources of variation between the pomelo varieties.

The eigenvalues and the percentage of variance explained by each principal component are presented in Table 8. The first two principal components (PC1 and PC2) accounted for 65.10% of the total variance. Specifically, PC1 had an eigenvalue of 4.28 and explained 42.84% of the variance, while PC2 had an eigenvalue of 2.23 and it explained 22.27% of the variance. Subsequent principal components individually explained a much smaller proportion of the total variance (Table 8), with no single component explaining more than 15%.

The scree plot (Figure 1) visually supports the focus on the first two components, showing a steep decline in explained variance up to PC2, followed by a gradual decrease for the remaining components. The loadings of the variables on PC1 and PC2 reveal the primary drivers of variation.

PC1 was strongly negatively loaded with fruit weight (-0.45), pulp weight (-0.47), seed weight (-0.46), and juice content (-0.40), indicating that varieties with higher values for these characteristics tend to have lower scores on PC1. PC2 was strongly negatively loaded with fruit length (-0.58) and fruit diameter (-0.58), suggesting that varieties with larger fruit dimensions tend to have lower scores on PC2. The loadings for all ten principal components are attached in Annexure II.

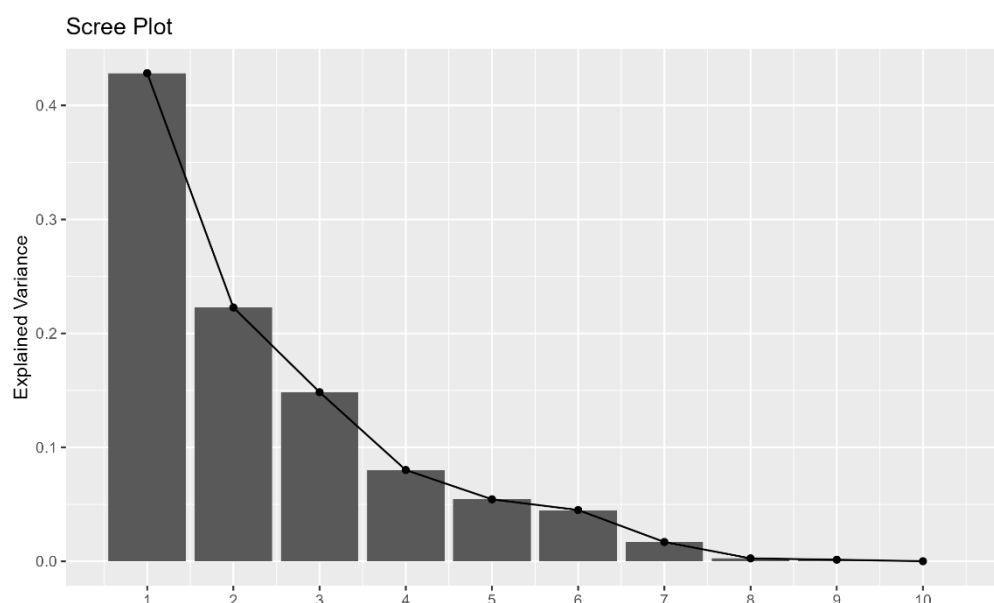


Figure 1. Scree Plot

Table 8. Eigenvalues and Explained Variance of Principal Components

Principal Component	Eigenvalue	Variance Explained (%)	Cumulative Variance Explained (%)
PC1	4.28	42.84	42.84
PC2	2.23	22.27	65.11
PC3	1.48	14.84	79.95
PC4	0.8	8.01	87.96
PC5	0.54	5.44	93.4
PC6	0.45	4.5	97.9
PC7	0.17	1.7	99.6
PC8	0.03	0.26	99.86
PC9	0.01	0.14	100
PC10	0	0.01	100.01

3.5. Quality Index

A quality index was calculated for each pomelo variety by summing the ranks of seven key parameters; juice content, TSS, TSS/acid ratio, peel/weight ratio, seed content, seed weight, and pulp/weight ratio.

The calculated quality index for each variety is presented in Table 9. Banpeiyu exhibited the highest quality index (15), followed by R3P4 (14), and R4P5 (13). Banpeiyu consistently ranked highly in juice content, TSS, TSS/acid ratio, peel weight ratio, and pulp weight ratio. R3P4 demonstrated the highest rank in TSS and TSS/acid ratio but ranked lower in juice content and pulp weight ratio. R4P5 achieved the top rank in seed content and seed weight but had lower ranks in juice content and TSS/acid ratio.

Table 9. Quality Index for each variety

Variety	Juice Content	TSS	TSS/Acid Ratio	Peel/Weight Ratio	Seed Content	Seed Weight	Pulp/Weight Ratio	Quality Index
Banpeiyu	1	2	2	1	3	3	1	15
R3P4	3	1	1	3	2	1	3	14
R4P5	2	3	3	2	1	2	2	13

4. Discussion

4.1. Varietal Differences in Fruit Sizes and Composition.

The analysis of variance revealed significant differences in several key fruit quality parameters among the pomelo varieties; Banpeiyu, R3P4, and R4P5. In commercial agriculture, fruit weight is a primary factor influencing yield and market value. Larger fruits often translate to greater economic returns for growers with larger fruit size results in higher prices at farm gate (Reginato et al., 2007). The greater pulp weight in Banpeiyu also suggests a higher proportion of edible fruit, which is a key desirable trait for both fresh consumption and processing in Juice Industry. A lower peel weight ratio, as observed in Banpeiyu, also implies a higher proportion of edible fruit.

R3P4, with its smaller fruit and pulp weight, might be less desirable for direct fresh market sales where larger fruit sizes are often favored. However, smaller fruit size could be advantageous in specific situations as they have niche market for their smaller size. There is strong evidence that niche markets can provide valuable opportunities for small or uniquely sized fruits, which may not be as desirable in mainstream fresh markets. Smaller size fruits are popular in direct-to-consumer channels like farmers markets, roadside stands, and community-supported agriculture, where freshness, local origin, and unique varieties are highly valued, with consumers seeking out these products specifically at local markets (Callies, 2020). Smaller fruit size can also be beneficial for certain food processing techniques, as size reduction increases operational efficiency, decreases energy consumption, and can improve product quality. In food processing, smaller fruits or fruit pieces allow for more uniform mixing, faster processing times, and can enhance the consistency and texture of the final product (Prater, 2024).

Juice content is a critical factor determining the quality and consumer acceptability of pomelos, as it directly influences taste, texture, and overall sensory experience (Sirisomboon & Lapcharoensuk, 2012; Sahrawat & Chaturvedi, 2023). Banpeiyu's significantly higher juice volume suggests a superior eating experience in terms of juiciness, which aligns with findings by Sahrawat & Chaturvedi (2023) that sensory attributes such as juiciness and flavor are key drivers of consumer preference and marketability for fruit juices. High juice content is also desirable for juice processing, where greater extraction efficiency is economically advantageous, as it allows for higher yields and better utilization of raw materials in commercial juice production (Gupta et al., 2020).

The balance between TSS (Total Soluble Solids) and citric acid content is a key determinant of fruit taste, as the TSS/acid ratio directly influences the perceived sweetness and acidity of citrus fruits. A higher TSS/acid ratio generally results in a sweeter taste profile, while a lower ratio emphasizes acidity. While Banpeiyu had the highest citric acid content, R3P4's high TSS/acid ratio suggests a potentially sweeter taste profile. Consumer preferences for sweetness versus acidity can vary, making both high and low TSS/acid profiles desirable depending on the target market(Ikegaya et al., 2019).

Consumer sensory evaluations of pomelo products prioritize usability and flavor(Hung et al., 2023), these traits directly are compromised by high seed content in fresh fruit. R3P4's lower seed weight addresses this concern.

4.2.Mass Modeling Analysis

Mass Modeling, as reported by Kong et al. (2020) and Khairunniza-Bejo et al. (2014), established relationships between fruit dimensions (length and diameter, in the case of this study) and fruit weight, which can contribute to varietal characterization by revealing how size and weight interact as key morphological traits.

This model enables non-destructive weight estimation, critical for yield prediction, harvest management, and postharvest sorting while minimizing physical damage to fruit. For R4P5, a quadratic model demonstrated a strong relationship between fruit length and weight ($R^2 = 0.90$), suggesting weight increases non-linearly with length, likely due to disproportionate girth expansion during elongation, a pattern observed by Kong et al., (2020) in Thai pomelos. Similarly, fruit diameter was a robust predictor for R4P5 ($R^2 = 0.94$ across models) and Banpeiyu ($R^2 = 0.80\text{--}0.90$), aligning with findings conducted by Khairunniza-Bejo et al., (2014) in Malaysian pomelos where width-based quadratic models achieved high accuracy. By identifying which dimensions best predict weight, the model pinpoints key traits for varietal identification and selection, improving production efficiency through non-destructive methods.

In contrast, R3P4 demonstrated no clear relationship between fruit dimensions and weight, indicating that factors such as variable shape, pulp density, or rind thickness may predominantly influence its mass. This finding is consistent with the study conducted by Ortiz et al. (2011), which reported a similar phenomenon in irregularly shaped citrus varieties. This varietal-specificity emphasises the need to evaluate each cultivar independently, as universal models may not apply. The models provide practical tools for growers to estimate yields,

monitor growth, and optimize sorting, enhancing crop management and marketability (Magwaza & Opara, 2015).

The strong relationship observed in R4P5 and Banpeiyu suggests that non-destructive estimation of fruit weight might be possible for these varieties using fruit diameter (and to some extent, fruit length for R4P5). This could be valuable for sorting fruits into size grades, predicting yield in the orchard without harvesting, or monitoring fruit growth over time.

The specific equations for each model are provided in Annexure I.

4.3.Fruit Characteristics and Their Relationships/Correlation.

Analysis of fruit characteristics across the studied varieties revealed distinct patterns in how external fruit dimensions relate to internal quality attributes. In R3P4, strong positive correlations were observed between fruit dimensions (length and diameter) and internal characteristics such as pulp weight and juice content. This indicates that, for R3P4, larger fruits tend to have proportionally greater internal mass and juice yield, a pattern consistent with findings in other fruit crops where size metrics are closely linked to internal composition (Drvodelić et al., 2018). In this variety, breeders could prioritize selecting for larger diameter fruits to efficiently increase pulp yield in subsequent generations. Conversely, Banpeiyu exhibited weak or even negative correlations between external and internal characteristics, suggesting that in this variety, larger fruit size does not necessarily predict higher pulp weight or juice content. Such variability in correlation strength has also been documented in other fruit trees, notably in a research conducted by Holland et al.,(2011), where some varieties show strong associations between fruit size and internal yield, while others do not.

Juice content displayed significant variation among the varieties, with Banpeiyu achieving the highest mean juice content (138 ml), while R3P4 had the lowest (29.6 ml). Across all varieties, juice content was positively correlated with both pulp and fruit weight, supporting the general observation that heavier fruits tend to yield more juice (Drvodelić et al., 2018). Total Soluble Solids (TSS), an indicator of sweetness, ranged from 10.85% to 11.92%, with R3P4 recording the highest average TSS (12.1%), followed by Banpeiyu (11.6%), and R4P5 the lowest (11.1%). These differences in TSS are important for flavor profiling and consumer preference (Holland et al., 2011). The box plot illustrating Total Soluble Solids (TSS) levels across the studied varieties (Figure 3) provides a visual comparison of sweetness indicators. R3P4 exhibits the highest median TSS, supporting the finding that this variety tends to be the sweetest.

Mean citric acid content also varied, with Banpeiyu showing the highest (1.94%) and R3P4 the lowest (1.32%). (Figure 2)

The ratio of TSS to citric acid; a key determinant of perceived taste, was highest in R3P4 (11.2), suggesting a sweeter and less acidic flavor profile compared to Banpeiyu (8.56) and R4P5 (7.50). The scatter plot illustrating the relationship between TSS and citric acid content (Figure 4) further clarifies the distinct flavor profiles of the pomelo varieties. Banpeiyu fruits are predominantly clustered in the upper-mid region, indicating a generally high citric acid content coupled with moderate to high TSS levels. This visual representation supports the calculated lower TSS/acid ratio for Banpeiyu, suggesting a tangier taste. In contrast, R3P4 fruits are primarily located towards the right side of the plot, showing a trend towards higher TSS levels and a wider range of citric acid content, including some fruits with notably low acidity. This aligns with the calculated higher TSS/acid ratio for R3P4, indicating a sweeter and less acidic profile on average. R4P5 fruits are distributed across a broader range of both TSS and citric acid content, occupying a middle ground between Banpeiyu and R3P4 in terms of flavor components

The seed weight to pulp weight ratio, as shown in figure 5, is an important indicator of how fruit varieties allocate resources between edible pulp and seeds. Banpeiyu's higher ratio means a larger portion of the fruit is seeds, which is generally less desirable to consumers due to reduced edible content and can negatively affect marketability (Bhagyalekshmi et al., 2020; Thakur et al., 2008). In contrast, R3P4's lower ratio reflects greater pulp allocation, resulting in higher edible yield which is a trait favored in fruits like mango and aonla for both fresh consumption and processing (Bhagyalekshmi et al., 2020; Chittiraichelvan & Shanmugavelu, 1988). R4P5 shows an intermediate ratio, balancing seed and pulp development. Additionally, Banpeiyu's wider variability in seed-to-pulp ratio, evident from the interquartile ranges and whiskers in Figure 5, suggests inconsistency in seediness, which may impact consumer satisfaction and processing uniformity (Silva et al., 2019). Overall, varieties with higher pulp and lower seed content are preferred for breeding, consumption, and industrial use, supporting the implications of this study (Bhagyalekshmi et al., 2020; Thakur et al., 2008; Chittiraichelvan & Shanmugavelu, 1988; Silva et al., 2019). Varieties like R3P4, where larger fruit size reliably indicates greater internal yield, can be prioritized to maximize productivity and consumer

satisfaction (Drvodelić et al., 2018). In contrast, varieties with weak correlations, such as Banpeiyu, may require more detailed internal assessments to accurately select superior fruits.

These results highlight significant differences among pomelo varieties, and further lets us know the complex relationships between external morphology and internal fruit quality, highlighting the need for variety-specific management and breeding strategies. The relatively small sample size (n=30) might have contributed to generalising of the findings. Further research with larger sample sizes will be conducted hence forth.

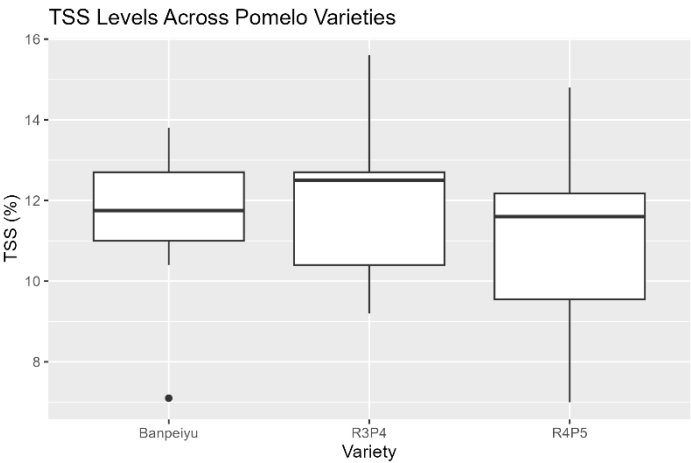


Figure 3 TSS Level Across Pomelo Varieties

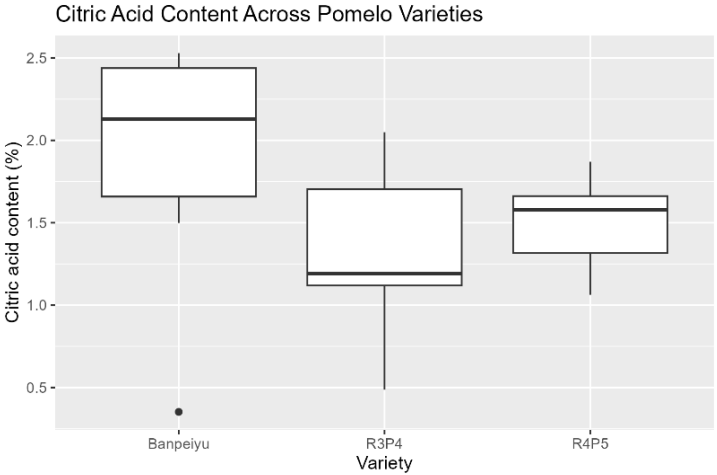


Figure 2 Citric Acid Content Across Pomelo Varieties

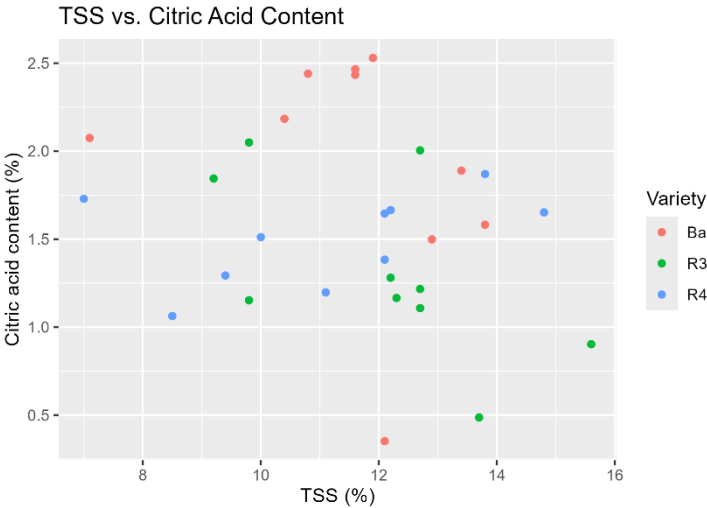


Figure 5 TSS Vs. Citric Acid Content

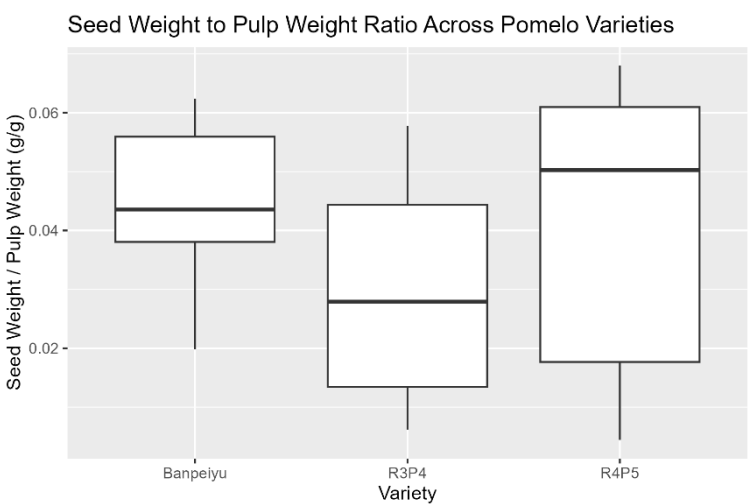


Figure 4 Seed Weight to Pulp Weight Ratio

4.4. Principal Component Analysis (PCA)

The PCA results, visually represented by the biplot (Figure 6), revealed that the primary variation among pomelo varieties is captured by two main components: PC1, representing size and mass attributes (strongly negatively loaded with pulp weight, seed weight, and fruit weight), and PC2, representing a combination of fruit shape and sweetness (strongly negatively loaded with fruit length, diameter, and TSS). The biplot illustrates this, with vectors for mass-related traits pointing left (negative PC1) and vectors for size/sweetness traits pointing down (negative PC2). Varieties like Banpeiyu (pink points) cluster on the left, indicating larger, heavier fruits, while R3P4 (green points) tends towards the right (smaller, lighter fruits) and R4P5 (blue points) is intermediate.

First Principal Component (PC1) tells us that fruits with larger size and greater mass tend to have lower PC1 scores, reflecting a gradient from smaller, lighter fruits to larger, heavier ones with more pulp and seeds. The moderate negative loadings for juice content and seed number further support this interpretation. But fruit length and diameter show weak positive loadings on PC1, suggesting that external dimensions are somewhat unrelated from overall mass and internal content in this component. This pattern aligns with previous studies in citrus and other fruit crops, where size and mass traits often cluster together and serve as key indicators of fruit yield and quality (Singh et al., 2015; Holland et al., 2011).

The second principal component (PC2), in this particular study; represented a combination of fruit shape and sweetness characteristics. The strong negative loadings of fruit length, diameter, and total soluble solids (TSS) suggest that fruits scoring lower on PC2 tend to be larger in dimension and sweeter, while smaller, less sweet fruits score higher. The moderate negative loading of seed number and positive loading of seed weight and citric acid content indicate a complex relationship between seed traits and acidity, which may influence flavor perception. The minimal loadings of pulp weight, fruit weight, and juice content on PC2 imply that these traits are largely independent of the shape-sweetness axis. These findings are consistent with literature demonstrating that fruit shape and sweetness often vary independently from size and mass, reflecting different genetic and physiological controls (Mukul et al., 2022; Holland et al., 2011).

This differentiation (PC1 and PC2) is useful for breeding and selection programs, as it suggests that improving fruit size and yield may require different strategies than enhancing

sweetness and shape attributes. Moreover, understanding these trait groupings can help optimize fruit quality for different market preferences, balancing size, sweetness, and seed characteristics to meet consumer demands (Mukul et al., 2022; Singh et al., 2015).

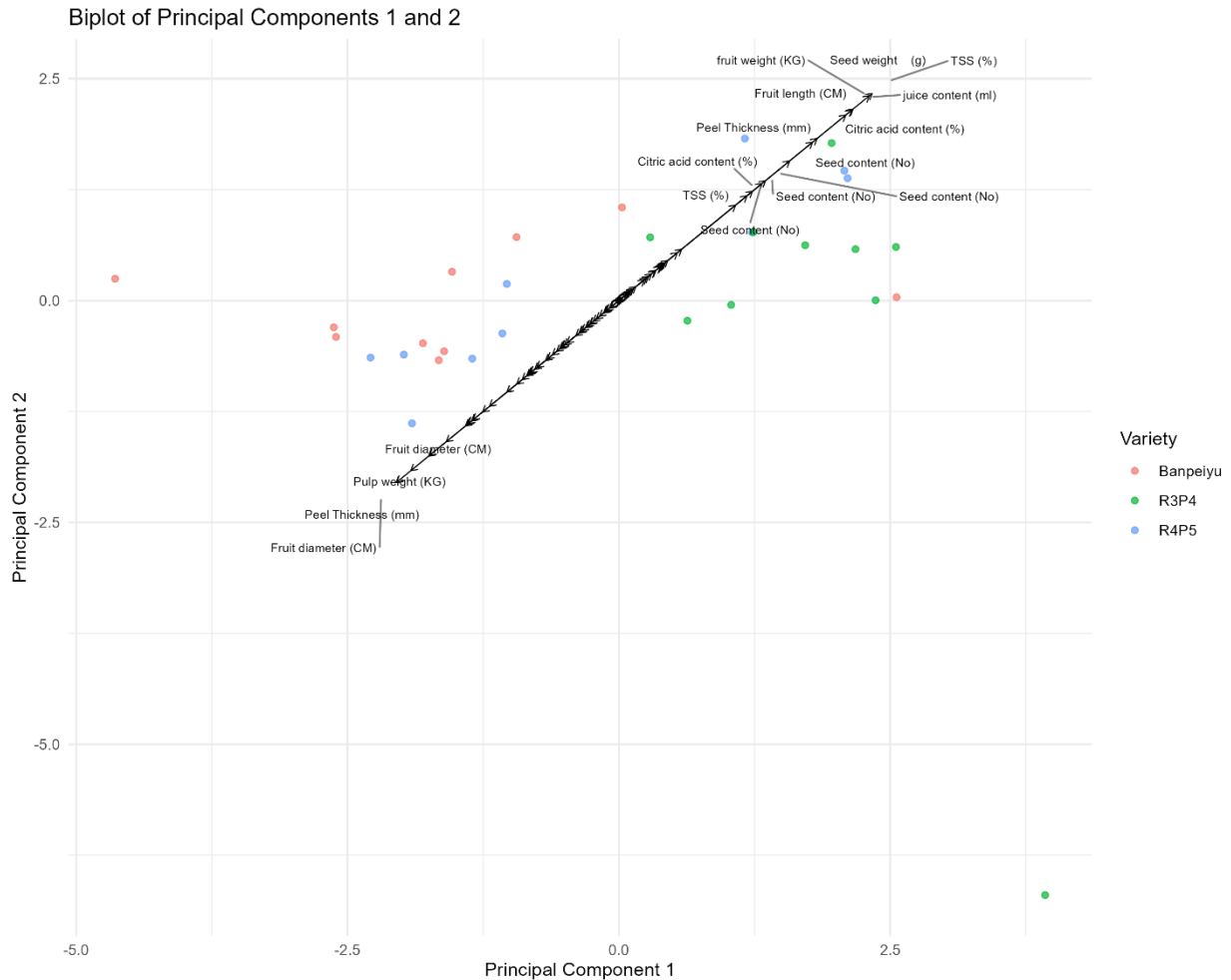


Figure 6 PCA Biplot

4.5. Complimentary Insights from Correlation and PCA analysis

The correlation analysis and Principal Component Analysis (PCA) offer complementary perspectives on the complex relationships among pomelo fruit traits, providing a more nuanced understanding than either method alone. While the correlation analysis tells the specific variety-dependent connection between pairs of traits, PCA offers a broader, multivariate overview of the major axes of variation across all varieties. For instance, the correlation analysis reveals the strong positive relationship between fruit diameter and pulp weight in R3P4, suggesting that larger R3P4 fruits consistently yield more pulp. This is consistent with the general trend extracted by PCA, where fruit weight and pulp weight load strongly on PC1,

indicating that these traits are major contributors to overall fruit size and yield variation across all varieties.

4.6. Quality Index

The quality index, calculated by summing the ranks of seven key parameters, provides a comprehensive and practical tool for grading pomelo varieties based on overall fruit quality (Sun et al., 2020). This integrative approach combines critical traits such as juice content, peel/weight ratio, pulp/weight ratio, total soluble solids (TSS), and TSS/acid ratio, which are widely recognized as important determinants of consumer preference and market value (Salihah et al., 2015; ScienceDirect, 2024). In this study, Banpeiyu achieved the highest quality index (15), reflecting a balanced profile with superior juice yield, higher edible pulp proportion, and favorable sweetness and flavor balance. These traits align with consumer demands for palatable and efficient fruit (Gao et al., 2024; Salihah et al., 2015).

R3P4, with a slightly lower quality index (14), performed better in sweetness and flavor attributes, ranking highest in TSS and TSS/acid ratio, which are critical for taste grading (Sun et al., 2020). However, its lower juice content and pulp/weight ratio suggest a trade-off between flavor intensity and edible yield, an important consideration in grading systems that balance sensory and production traits (Gao et al., 2024).

R4P5, with the lowest quality index (13), showed higher seed content and seed weight, which are describes as undesirable traits by SciDirect, (2024) that negatively influence grading due to reduced consumer appeal and lower juice content and sweetness, further lowering its overall grade

Using a quality index for grading allows breeders, growers, and marketers to objectively classify pomelo varieties by integrating multiple quality dimensions into a single score, facilitating selection of superior cultivars and meeting market standards (Gao et al., 2024; Sun et al., 2020). This method is increasingly adopted in citrus breeding programs and quality control protocols to enhance fruit quality and consumer satisfaction (Salihah et al., 2015).

5. Conclusion

The varietal evaluation trial successfully showed us the distinct fruit quality attributes among the three pomelo varieties, providing valuable insights into their potential for commercial application and consumer preference. The results show that each variety presents unique strengths, which align with the trade-offs commonly observed in fruit breeding.

Banpeiyu demonstrated superiority with its larger fruit and pulp weights, higher juice content, and a favorable quality index, positioning it as a strong contender for both fresh consumption and juice processing markets. However, its higher seed count and lower sweetness limit its appeal in certain consumer segments, such as those seeking convenience (preferring fruits with fewer seeds) and those who prioritize sweetness, such as consumers in fresh fruit markets or juice products that emphasize a sweeter flavor profile.

R3P4, on the other hand, while smaller in fruit size, exhibited a higher TSS/acid ratio, suggesting a sweeter taste profile that appeals to specific consumer preferences. Its lower seed weight and higher pulp yield further enhance its desirability for both direct consumption and processing efficiency.

R4P5 exhibited a notable correlation between fruit dimensions and weight, which makes it suitable for non-destructive yield estimation and efficient sorting practices. However, its lower juice content and higher seed content contributed to a reduced overall quality index compared to the other varieties. These traits position R4P5 more for mechanized processing and grading rather than premium fresh market sales.

The findings emphasize the importance of aligning varietal selection with market demands and breeding objectives. While larger fruit sizes, such as those in Banpeiyu, tend to attract higher prices in mainstream markets, the niche appeal of sweeter, smaller fruits like R3P4 should not be overlooked. The use of Principal Component Analysis, the Quality Index, and correlation analysis proved to be effective tools in evaluating the pomelo varieties.

For further validation, future studies should incorporate a larger sample size and extend the trial across multiple growing seasons to further strengthen the current findings of this paper.

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Annexture I

Equations For Each Model

1. Predicting fruit weight from length

R4P5:

1. Linear

$$\text{Weight} = \frac{\text{Length} - 100368.4}{3.138531 \times 10^{-8}}$$

2. Quadratic

$$\text{Weight} = \frac{-4.463108 \times 10^{-7} \pm \sqrt{(4.463108 \times 10^{-7})^2 - 4(-3.143622 \times 10^{-19})(\text{Length} + 25204.17)}}{2(-3.143622 \times 10^{-19})}$$

3. S-curve

$$\text{Weight} = \frac{1}{\frac{143729.2 - \text{Length}}{1.374216 \times 10^{16}}}$$

4. Power

$$\text{Weight} = \left(\frac{\text{Length}}{6.753051} \right)^{\frac{1}{0.1820843}}$$

R3P4

1. Linear

$$\text{Weight} = \frac{\text{Length} + 23724.05}{5.232009 \times 10^{-7}}$$

2. Quadratic

$$\text{Weight} = \frac{-1.636092 \times 10^{-5} \pm \sqrt{(1.636092 \times 10^{-5})^2 - 4(-1.869197 \times 10^{-17})(\text{Length} + 3218320)}}{2(-1.869197 \times 10^{-17})}$$

3. S-curve

$$\text{Weight} = \frac{1}{\frac{476744.5 - \text{Length}}{1.127067 \times 10^{17}}}$$

4. Power

$$\text{Weight} = \left(\frac{\text{Length}}{-10.95992} \right)^{\frac{1}{0.8482855}}$$

Banpeiyu

1. Linear

$$\text{Weight} = \frac{\text{Length} - \mathbf{106803.3}}{\mathbf{1.851905} \times 10^{-8}}$$

2. Quadratic

$$\text{Weight} = \frac{\mathbf{1.480486} \times 10^{-8} \pm \sqrt{(\mathbf{1.480486} \times 10^{-8})^2 - 4(\mathbf{2.245062} \times 10^{-20})(\text{Length} - \mathbf{118407.6})}}{\mathbf{4.490124} \times 10^{-20}}$$

3. S-curve

$$\text{Weight} = \frac{1}{\frac{\mathbf{130517.3} - \text{Length}}{\mathbf{6.813047} \times 10^{15}}}$$

4. Power

$$\text{Weight} = \left(\frac{\text{Length}}{\mathbf{8.900196}} \right)^{\frac{1}{\mathbf{0.1024865}}}$$

2. Predicting Fruit Weight from Diameter

R4P5

1. Linear

$$\text{Weight} = \frac{\text{Diameter} - \mathbf{72266.82}}{\mathbf{5.870209} \times 10^{-8}}$$

2. Quadratic

$$\text{Weight} = \frac{-\mathbf{1.65943} \times 10^{-7} \pm \sqrt{(\mathbf{1.65943} \times 10^{-7})^2 - 4(-\mathbf{8.124949} \times 10^{-20})(\text{Diameter} - \mathbf{39811.56})}}{2(-\mathbf{8.124949} \times 10^{-20})}$$

3. S-curve

$$\text{Weight} = \frac{1}{\frac{\mathbf{148134.2} - \text{Diameter}}{\mathbf{2.236238} \times 10^{16}}}$$

4. Power

$$\text{Weight} = \left(\frac{\text{Diameter}}{\mathbf{2.388873}} \right)^{\frac{1}{\mathbf{0.3394356}}}$$

R3P4

1. Linear

$$\text{Weight} = \frac{\text{Diameter} + \mathbf{23012.86}}{\mathbf{5.417838} \times 10^{-7}}$$

2. Quadratic

$$\text{Weight} = \frac{-\mathbf{1.688296} \times 10^{-5} \pm \sqrt{(\mathbf{1.688296} \times 10^{-5})^2 - 4(-\mathbf{1.928616} \times 10^{-17})(\text{Diameter} + \mathbf{3319161})}}{2(-\mathbf{1.928616} \times 10^{-17})}$$

3. S-curve

$$\text{Weight} = \frac{1}{\frac{\mathbf{495063.8} - \text{Diameter}}{\mathbf{1.166413} \times 10^{17}}}$$

4. Power

$$\text{Weight} = \left(\frac{\text{Diameter}}{-\mathbf{11.3657}} \right)^{\frac{1}{\mathbf{0.8656189}}}$$

Banpeiyu

1. Linear

$$\text{Weight} = \frac{\text{Diameter} - \mathbf{69302.81}}{\mathbf{7.004589} \times 10^{-8}}$$

2. Quadratic

$$\text{Weight} = \frac{-\mathbf{3.987148} \times 10^{-8} \pm \sqrt{(\mathbf{3.987148} \times 10^{-8})^2 - 4(\mathbf{2.032877} \times 10^{-20})(\text{Diameter} - \mathbf{79810.39})}}{2(\mathbf{2.032877} \times 10^{-20})}$$

3. S-curve

$$\text{Weight} = \frac{1}{\frac{\mathbf{164893.2} - \text{Diameter}}{\mathbf{2.998949} \times 10^{16}}}$$

4. Power

$$\text{Weight} = \left(\frac{\text{Diameter}}{\mathbf{0.7679684}} \right)^{\frac{1}{\mathbf{0.400457}}}$$

Annexture II

Loadings For Each Principal Components

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
fruit weight	-0.4524394	-0.167479	0.034187	0.0523532	-0.1782749	-0.2039907	-0.2582903	-0.2834209	0.7193799	-0.1593642
Fruit length	0.1505212	-0.5810443	-0.2786825	-0.119472	-0.1912106	0.0914709	0.0288036	0.0082753	0.1278634	0.6968629
Fruit diameter	0.1435782	-0.5845342	-0.277404	-0.1220268	-0.1821416	0.1112241	0.0375035	-0.0006278	-0.1756601	-0.6841432
Peel Thickness	-0.0091639	-0.0424824	0.6089865	-0.6825071	-0.3437342	-0.0693293	0.1796861	0.0785223	-0.0042513	0.000291
Pulp weight	-0.4658649	-0.0878053	-0.0292854	-0.0593909	-0.0976103	-0.2192608	-0.2516282	-0.4711486	-0.6388798	0.1407376
Seed content	-0.2714463	-0.2252964	0.4104306	0.4504847	-0.0473164	0.5246601	0.4401173	-0.1746492	-0.0442577	0.0223
Seed weight	-0.4620525	-0.1132992	0.0452174	0.0853218	-0.0900267	0.1316522	-0.3438383	0.7779678	-0.1220715	0.0234331
TSS	0.0434576	-0.4482157	0.3585247	-0.0383152	0.7696821	-0.251653	-0.1024816	0.030806	0.0037018	0.0011142
juice content	-0.3970927	-0.0021049	-0.3135884	-0.0787635	0.1141615	-0.4181338	0.7158463	0.1931318	0.0125983	-0.0028783
Citric acid content	-0.2969282	0.136553	-0.2740742	-0.5299659	0.393717	0.5949811	-0.0240759	-0.132181	0.1003446	-0.0083835

ANNEXTURE III

PICTURES SHOWING POMELO VARIETIES AND DATA COLLECTION PROCESS

