International Journal of Agriculture and Biosciences 2026 15(1): 115-124.
https://doi.org/10.47278/journal.ijab/2025.137

RESEARCH ARTICLE
eISSN: 2306-3599; pISSN: 2305-6622

# Fruit Morphology and Clustering Analysis Reveals Diversity among Commercial Melons (*Cucumis melo* L.) in Indonesia

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## ABSTRACT

Melon (*Cucumis melo* L.) is a globally important horticultural crop known for its remarkable morphological and agronomic diversity. However, commercial varieties in Indonesia remain poorly characterized. Here, we evaluated 24 *C. melo* varieties using 14 quantitative and 4 qualitative fruit traits related to size, shape, rind, flesh, seed morphology, and sugar content. Analysis of variance revealed significant differences among varieties (p<0.05) for all traits. Principal component analysis (PC1 = 50.8%, PC2 = 36.7%) and hierarchical clustering identified three major phenotypic groups. Random forest modeling ranked trait importance based on %IncMSE, identifying seed cavity length, seed cavity index, and fruit diameter index as top predictors (importance score >10%). Integration of PCA, heatmap clustering, and variable importance plots confirmed these three traits as robust diagnostic markers. These findings highlight key morphological features for varietal classification and breeding, and provide a phenotypic framework for future genetic studies of melon in Indonesia.

**Keywords:** Phenotyping, Multivariate, Clustering, Classification

**Article History**
Article # 25-318
Received: 02-Jun-25
Revised: 16-Jun-25
Accepted: 14-Jul-25
Online First: 31-Aug-25

## INTRODUCTION

Melon (*Cucumis melo* L.) is an horticultural crop renowned for its remarkable morphological diversity, particularly in traits such as color, shape, taste, size, and texture (Manohar & Murthy 2012; Komala & Kuni 2022). This phenotypic variability reflects both adaptation to diverse agroclimatic conditions and selection for consumer preferences and market value (Park et al., 2018; Walters et al., 2021). In Indonesia, greenhouse-based cultivation has supported the emergence of commercial varieties tailored to local preferences for sweetness, aroma and appearance (Hartono et al., 2022; Kurniasari et al., 2023; Huda & Suwarno 2023; Mahananto et al., 2023). Despite the commercial significance of melon production, detailed phenotypic characterization of locally cultivated varieties remains limited. Assessing fruit morphology is essential for identifying superior traits, improving cultivation, and guiding breeding strategies to enhance yield and quality (Omari et al., 2018; Soltani et al., 2022). Key traits such as fruit shape, size, rind thickness, flesh firmness, and color serve as phenotypic indicators of underlying genetic variability (Farcuh et al., 2020; Ren et al., 2022; Barbosa et al., 2023), influencing not only consumer appeal but also post-harvest handling and storage (Wang et al., 2024).

Morphological characterization helps reveal patterns of variation, cluster-related genotypes and identify commercially valuable traits (Andrade et al., 2019; Pandey et al., 2021). Furthermore, it supports the identification of unique traits that may confer advantages under specific environmental or consumer preference conditions. Such information is indispensable for breeders, producers, and policymakers aiming to strengthen the melon industry through evidence-based strategies. Moreover, studying locally adapted varieties is vital for conserving genetic resources and promoting sustainable melon production in diverse agroecological zones. Nevertheless, comprehensive studies on the morphological diversity of commercial melon varieties in Indonesia are lacking. Addressing this gap is essential for guiding future breeding efforts and conserving valuable phenotypic resources. In this study, we analyzed 24 commercial melon varieties that are widely cultivated and marketed in Indonesia. These varieties were selected based on their market presence and contrasting fruit features

**Cite this Article as:** Herwibawa B, Anwar S, Kusmiyati F, Sas MGA and Saputro TB, 2026. Fruit morphology and clustering analysis reveals diversity among commercial melons (*Cucumis melo* L.) in Indonesia. International Journal of Agriculture and Biosciences 15(1): 115-124. https://doi.org/10.47278/journal.ijab/2025.137

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observed during preliminary surveys. The objective of this study is to assess morphological variation among these varieties using combination of quantitative and qualitative fruit traits, and to identify trait-based groupings that may inform future breeding and selection strategies.

## MATERIALS & METHODS

### Plant Materials

Twenty-four commercial *C. melo* varieties commonly sold in Indonesian markets were evaluated in this study. The varieties included Fujisawa, Royal cantaloupe, Emeralda, Red sweet, Dang sweet, Greeniegal, Golden topaz, Inthanon, Bandungan, Hami sweet, Hamigua, Midori, Sunray, Lavender, Elysia, Golden aroma, Alisha, Sweet net, D165, Aruni, Kirani, Honey dew, Honey globe, and Greeny sweet. Seeds were sourced from local markets in Central Java, Indonesia. Germplasm identification and naming were based on seed packaging and verified through local grower information. Seeds of each variety were sown in pots, and seedlings at the 4–5 leaf stage were transplanted into a greenhouse. The experiment followed a completely randomized design (CRD) with three replicates. Female flowers on the main stem were hand-pollinated at anthesis, and only one fruit per plant was allowed to develop. One fruit per plant was sampled, resulting in three fruits per variety for trait evaluation. Melons were cultivated following standard horticultural practices with modifications based on Hartz et al. (2008) and Wahyudi et al. (2025). Melons were grown in well-drained sandy loam soil with full sunlight, with soil pH adjusted to 6.2–6.8 using compost. A basal application of 10-10-10 fertilizer was incorporated into the growing medium at a rate 5–7g per pot prior to transplanting. An additional side-dressing of 3–5g per pot was applied near the base of the plants at the early vine development stage. Irrigation was applied manually to maintain consistent soil moisture, with approximately 1.5–2.0L of water per pot per day under normal conditions. During the fruit set and ripening stages, the watering volume was increased to 2.5–3.0L per pot per day. Plants were monitored regularly for pest infestation. Common pests include aphids and beetles. Mechanical removal and insecticidal soap were applied as needed. Fruit maturity was assessed through changes in stem attachment and external color.

### Fruit Traits Characterization

Fruits were harvested at their horticultural maturity, determined based on the growth period, peduncle abscission, and characteristic rind color and aroma, as described by Farcuh et al. (2020). For phenotypic diversity analysis, eighteen morphological fruit traits were evaluated across 24 melon varieties. Quantitative traits included fruit weight (FW), fruit length (FL), fruit equatorial diameter (FTD), fruit diameter index (FDI), fruit flesh thickness (FFT), and fruit rind thickness (FRT), seed cavity length (SCL), seed cavity width (SCW), seed cavity index (SCI), seed length (SL), seed width (SW), and seed size ratio (SSR), 1000-seed weight (TSW), and brix (ºbrix). Qualitative traits were visually assessed, including rind color (RC), flesh color (FC), fruit shape (FS; oblate, circular, ovate, elliptic, and elongated), and net type (NT), recorded as either netted or non-netted based on the presence of surface reticulation. Trait characterization was conducted according to the UPOV guidelines for *Cucumis melo* (UPOV Code: CUCUM_MEL), as provided by the International Union for the Protection of New Varieties of Plants (UPOV, 2024).

### Statistical and Clustering Analysis

All statistical analyses were performed in R-4.5.0 for Windows (https://cran.r-project.org/bin/windows/base/) using RStudio 2025.05.0+496 (https://posit.co/download/rstudio-desktop/). A total of 14 quantitative fruit traits were analyzed using one-way analysis of variance (ANOVA) to test for significant differences among varieties, followed by Tukey's Honest Significant Difference (HSD) test for post-hoc comparisons at a significance level of $P<0.05$ using the agricolae package (de Mendiburu, 2023). To investigate phenotypic variation and classify varieties, principal component analysis (PCA) and dendrograms were generated using the factoextra package (Kassambara & Mundt, 2022), with enhanced labeling and color schemes provided by ggrepel (Slowikowski et al., 2024) and randomcoloR (Ammar, 2022). A heatmap and correlation plot were produced using the pheatmap package (Kolde, 2022), and enhanced with RcolorBrewer (Neuwirth, 2025). To identify traits contributing most to varieties' differentiation, variable importance was assessed using the randomForest package (Breiman et al., 2024). Data handling and visualization were supported by functions from dplyr (Wickham et al., 2023), ggplot2 (Wickham et al., 2025a), tidyverse (Wickham, 2023), reshape2 (Wickham, 2022), scales (Wickham et al., 2025b), and patchwork (Pedersen, 2024). While Venn diagram was built using ggVennDiagram (Gao et al., 2021; Gao et al., 2024).

## RESULTS

### Morphological Variation in Fruit Traits

Morphological evaluation of 24 commercial *C. melo* varieties revealed variation across 18 fruit traits, including four qualitative descriptors (Fig. 1, Table 1–3). Fruit weight ranged from 0.84 to 1.91kg. The lowest fruit weight was recorded in Kirani, but it was not significant when compared to Aruni, Honey globe, Bandungan, and Royal cantaloupe. While Red sweet displayed a significantly higher fruit weight than most varieties, except for Emeralda. Red sweet also showed the highest values in fruit equatorial diameter (18.72cm) and fruit flesh thickness (5.78cm), indicating its overall larger fruit size. Fruit length ranged from 13.79 to 20.88cm, with Honey globe having the significantly smallest fruit length. Emeralda exhibited a significantly greater fruit length than the other varieties, although this difference was not significant when compared to Red sweet, Hamigua, Midori, Golden aroma, and Sweet net. Fruit equatorial diameter spanned between 12.91 to 18.72cm. The lowest fruit equatorial diameter was observed in Midori, which was not significantly different from Hami sweet, Kirani, and Honey globe, while the highest was found in Red Sweet, which was significantly different from the other varieties. For

**Table 1:** Variation in fruit morphological traits among 24 *Cucumis melo* varieties

| Varieties | FW (kg) | FL (cm) | FTD (cm) | FDI (cm) | FFT (cm) | FRT (cm) |
|---|---|---|---|---|---|---|
| Fujisawa | 1.60±0.03$^{c}$ | 17.99±0.25$^{fg}$ | 15.82±0.10$^{ef}$ | 1.14±0.01$^{efg}$ | 4.76±0.03$^{ef}$ | 0.13±0.00$^{b}$ |
| Royal cantaloupe | 0.92±0.02$^{jkl}$ | 16.69±0.14$^{hi}$ | 16.71±0.14$^{cd}$ | 1.00±0.02$^{j}$ | 5.33±0.03$^{c}$ | 0.16±0.00$^{a}$ |
| Emeralda | 1.77±0.04$^{ab}$ | 20.58±0.26$^{a}$ | 17.31±0.16$^{bc}$ | 1.19±0.00$^{de}$ | 4.93±0.02$^{d}$ | 0.08±0.00$^{c}$ |
| Red sweet | 1.91±0.05$^{a}$ | 19.88±0.21$^{abcd}$ | 18.72±0.17$^{a}$ | 1.06±0.02$^{ghij}$ | 5.78±0.02$^{a}$ | 0.04±0.00$^{efg}$ |
| Dang sweet | 1.15±0.03$^{fgh}$ | 15.33±0.12$^{j}$ | 15.42±0.10$^{f}$ | 0.99±0.00$^{j}$ | 4.63±0.02$^{gh}$ | 0.08±0.00$^{c}$ |
| Greeniegal | 1.34±0.03$^{de}$ | 17.29±0.21$^{gh}$ | 15.60±0.11$^{ef}$ | 1.11±0.02$^{fghi}$ | 4.80±0.02$^{ef}$ | 0.04±0.00$^{efg}$ |
| Golden topaz | 1.21±0.02$^{def}$ | 16.41±0.19$^{hij}$ | 15.45±0.13$^{f}$ | 1.06±0.02$^{ghij}$ | 4.71±0.02$^{fg}$ | 0.03±0.00$^{gh}$ |
| Inthanon | 1.69±0.04$^{bc}$ | 18.45±0.21$^{ef}$ | 17.62±0.16$^{b}$ | 1.05±0.02$^{ij}$ | 5.68±0.02$^{a}$ | 0.05±0.00$^{efg}$ |
| Bandungan | 0.91±0.02$^{kl}$ | 16.32±0.22$^{hij}$ | 16.26±0.14$^{de}$ | 1.00±0.00$^{j}$ | 4.86±0.02$^{de}$ | 0.05±0.00$^{ef}$ |
| Hami sweet | 1.01±0.02$^{hijk}$ | 18.33±0.25$^{fg}$ | 13.01±0.06$^{j}$ | 1.41±0.01$^{b}$ | 3.34±0.01$^{n}$ | 0.08±0.00$^{c}$ |
| Hamigua | 1.21±0.02$^{def}$ | 20.53±0.22$^{ab}$ | 15.86±0.14$^{ef}$ | 1.29±0.03$^{c}$ | 4.54±0.02$^{h}$ | 0.04±0.00$^{efg}$ |
| Midori | 1.00±0.03$^{ijk}$ | 20.03±0.27$^{abc}$ | 12.91±0.10$^{j}$ | 1.55±0.01$^{a}$ | 3.32±0.02$^{n}$ | 0.04±0.00$^{fgh}$ |
| Sunray | 1.01±0.02$^{hijk}$ | 18.36±0.20$^{efg}$ | 14.15±0.09$^{ghi}$ | 1.30±0.01$^{c}$ | 4.30±0.02$^{i}$ | 0.04±0.00$^{efg}$ |
| Lavender | 1.35±0.03$^{d}$ | 18.26±0.19$^{fg}$ | 14.43±0.14$^{gh}$ | 1.27±0.00$^{cd}$ | 4.26±0.03$^{ij}$ | 0.06±0.00$^{de}$ |
| Elysia | 1.06±0.02$^{ghij}$ | 19.45±0.24$^{bcde}$ | 13.84±0.11$^{hi}$ | 1.40±0.01$^{b}$ | 4.15±0.02$^{jk}$ | 0.07±0.00$^{cd}$ |
| Golden aroma | 1.15±0.03$^{fgh}$ | 20.43±0.17$^{ab}$ | 14.55±0.15$^{g}$ | 1.40±0.00$^{b}$ | 3.78±0.02$^{m}$ | 0.08±0.00$^{c}$ |
| Alisha | 1.11±0.02$^{fghi}$ | 19.08±0.21$^{cdef}$ | 15.84±0.10$^{ef}$ | 1.20±0.01$^{de}$ | 4.78±0.02$^{ef}$ | 0.05±0.00$^{ef}$ |
| Sweet net | 1.25±0.02$^{def}$ | 20.43±0.17$^{ab}$ | 15.69±0.14$^{ef}$ | 1.30±0.02$^{c}$ | 4.80±0.02$^{ef}$ | 0.03±0.00$^{gh}$ |
| D165 | 1.34±0.03$^{d}$ | 15.59±0.15$^{ij}$ | 13.77±0.08$^{hi}$ | 1.13±0.00$^{efgh}$ | 3.98±0.02$^{l}$ | 0.02±0.00$^{h}$ |
| Aruni | 0.90±0.02$^{kl}$ | 16.83±0.25$^{h}$ | 15.78±0.14$^{ef}$ | 1.07±0.02$^{ghij}$ | 4.13±0.02$^{k}$ | 0.02±0.00$^{h}$ |
| Kirani | 0.84±0.02$^{l}$ | 15.69±0.12$^{ij}$ | 13.50±0.11$^{ij}$ | 1.16±0.02$^{ef}$ | 3.91±0.01$^{l}$ | 0.02±0.00$^{h}$ |
| Honey dew | 1.20±0.02$^{efg}$ | 18.80±0.20$^{def}$ | 17.81±0.14$^{b}$ | 1.06±0.00$^{hij}$ | 5.51±0.02$^{b}$ | 0.03±0.00$^{gh}$ |
| Honey globe | 0.85±0.02$^{l}$ | 13.79±0.13$^{k}$ | 12.95±0.12$^{j}$ | 1.06±0.02$^{ghij}$ | 3.93±0.02$^{l}$ | 0.04±0.00$^{efg}$ |
| Greeny sweet | 1.21±0.03$^{def}$ | 19.05±0.20$^{cdef}$ | 17.93±0.16$^{b}$ | 1.06±0.00$^{ghij}$ | 5.35±0.02$^{c}$ | 0.05±0.00$^{ef}$ |

Mean±SE of fruit weight (FW), fruit length (FL), fruit equatorial diameter (FTD), fruit diameter index (FDI), fruit flesh thickness (FFT), and fruit rind thickness (FRT). Distinct superscript letters within each column indicate statistically significant differences among varieties according to Tukey's HSD test (P<0.05).

**Table 2:** Variation in seed-related traits among 24 *Cucumis melo* varieties

| Varieties | SCL (cm) | SCW (cm) | SCI | SL (cm) | SW (cm) | SSR |
|---|---|---|---|---|---|---|
| Fujisawa | 10.57±0.02$^{m}$ | 6.06±0.02$^{h}$ | 1.74±0.00$^{i}$ | 1.11±0.01$^{ij}$ | 0.46±0.01$^{ijk}$ | 2.39±0.02$^{efgh}$ |
| Royal cantaloupe | 9.41±0.02$^{q}$ | 5.81±0.01$^{j}$ | 1.62±0.01$^{j}$ | 1.30±0.01$^{e}$ | 0.59±0.01$^{ab}$ | 2.22±0.01$^{hi}$ |
| Emeralda | 13.39±0.02$^{c}$ | 7.25±0.02$^{b}$ | 1.85±0.00$^{g}$ | 1.37±0.01$^{cd}$ | 0.54±0.01$^{cdef}$ | 2.55±0.06$^{defg}$ |
| Red sweet | 13.01±0.02$^{de}$ | 7.03±0.02$^{d}$ | 1.85±0.00$^{g}$ | 1.25±0.01$^{ef}$ | 0.56±0.01$^{bcd}$ | 2.21±0.06$^{hi}$ |
| Dang sweet | 9.62±0.02$^{p}$ | 5.98±0.02$^{hi}$ | 1.61±0.01$^{j}$ | 1.23±0.02$^{fg}$ | 0.41±0.01$^{lm}$ | 2.98±0.10$^{b}$ |
| Greeniegal | 10.88±0.02$^{l}$ | 5.92±0.01$^{i}$ | 1.84±0.00$^{g}$ | 1.25±0.01$^{ef}$ | 0.52±0.01$^{defg}$ | 2.40±0.06$^{efgh}$ |
| Golden topaz | 10.78±0.02$^{l}$ | 6.00±0.02$^{hi}$ | 1.80±0.00$^{h}$ | 1.31±0.01$^{de}$ | 0.57±0.01$^{abc}$ | 2.28±0.05$^{ghi}$ |
| Inthanon | 11.43±0.02$^{j}$ | 6.17±0.01$^{g}$ | 1.85±0.00$^{g}$ | 1.14±0.01$^{hi}$ | 0.48±0.01$^{ghij}$ | 2.38±0.00$^{efgh}$ |
| Bandungan | 9.64±0.02$^{p}$ | 6.44±0.02$^{f}$ | 1.50±0.00$^{l}$ | 1.26±0.01$^{ef}$ | 0.53±0.01$^{cdef}$ | 2.36±0.02$^{fgh}$ |
| Hami sweet | 11.91±0.02$^{i}$ | 6.19±0.02$^{g}$ | 1.92±0.01$^{e}$ | 1.02±0.01$^{k}$ | 0.46±0.01$^{jkt}$ | 2.23±0.06$^{hi}$ |
| Hamigua | 13.11±0.02$^{d}$ | 6.74±0.02$^{e}$ | 1.95±0.00$^{e}$ | 1.18±0.01$^{gh}$ | 0.47±0.01$^{hij}$ | 2.49±0.06$^{defgh}$ |
| Midori | 14.76±0.03$^{a}$ | 6.17±0.02$^{g}$ | 2.39±0.00$^{a}$ | 1.07±0.01$^{jk}$ | 0.52±0.01$^{defgh}$ | 2.07±0.06$^{i}$ |
| Sunray | 12.04±0.02$^{h}$ | 5.45±0.02$^{l}$ | 2.21±0.01$^{b}$ | 1.40±0.01$^{bc}$ | 0.51±0.01$^{efghi}$ | 2.75±0.01$^{bcd}$ |
| Lavender | 12.42±0.02$^{g}$ | 5.82±0.02$^{j}$ | 2.13±0.00$^{c}$ | 1.26±0.01$^{ef}$ | 0.49±0.01$^{fghij}$ | 2.58±0.04$^{cdef}$ |
| Elysia | 12.99±0.02$^{e}$ | 5.46±0.01$^{l}$ | 2.38±0.00$^{a}$ | 1.07±0.01$^{jk}$ | 0.39±0.01$^{m}$ | 2.72±0.03$^{bcd}$ |
| Golden aroma | 14.01±0.02$^{b}$ | 6.79±0.02$^{e}$ | 2.06±0.00$^{d}$ | 1.12±0.01$^{hij}$ | 0.55±0.01$^{bcde}$ | 2.03±0.05$^{i}$ |
| Alisha | 12.01±0.02$^{hi}$ | 6.17±0.01$^{g}$ | 1.95±0.00$^{e}$ | 1.43±0.01$^{bc}$ | 0.56±0.01$^{bcd}$ | 2.53±0.02$^{defg}$ |
| Sweet net | 12.61±0.02$^{e}$ | 6.05±0.02$^{h}$ | 2.09±0.01$^{d}$ | 1.30±0.01$^{e}$ | 0.46±0.01$^{jkl}$ | 2.85±0.03$^{bc}$ |
| D165 | 10.89±0.02$^{l}$ | 5.78±0.01$^{j}$ | 1.88±0.01$^{f}$ | 1.17±0.01$^{ghi}$ | 0.42±0.01$^{klm}$ | 2.77±0.08$^{bcd}$ |
| Aruni | 9.50±0.02$^{q}$ | 7.48±0.02$^{a}$ | 1.27±0.00$^{m}$ | 1.38±0.01$^{c}$ | 0.54±0.01$^{bcde}$ | 2.54±0.02$^{defg}$ |
| Kirani | 9.77±0.02$^{o}$ | 5.68±0.01$^{k}$ | 1.72±0.01$^{i}$ | 1.45±0.01$^{b}$ | 0.58±0.01$^{abc}$ | 2.50±0.07$^{defgh}$ |
| Honey dew | 10.14±0.02$^{n}$ | 6.79±0.02$^{e}$ | 1.49±0.01$^{l}$ | 1.71±0.01$^{a}$ | 0.48±0.01$^{ghij}$ | 3.58±0.10$^{a}$ |
| Honey globe | 7.82±0.02$^{r}$ | 5.02±0.02$^{m}$ | 1.56±0.00$^{k}$ | 1.16±0.01$^{hi}$ | 0.52±0.01$^{defgh}$ | 2.24±0.01$^{hi}$ |
| Greeny sweet | 11.08±0.02$^{k}$ | 7.15±0.02$^{d}$ | 1.55±0.01$^{k}$ | 1.65±0.01$^{a}$ | 0.62±0.01$^{a}$ | 2.66±0.07$^{cde}$ |

Mean±SE of seed cavity length (SCL), seed cavity width (SCW), seed cavity index (SCI), seed length (SL), seed width (SW), and seed size ratio (SSR). Different superscript letters within each column indicate statistically significant differences among varieties based on Tukey's HSD test (P<0.05).

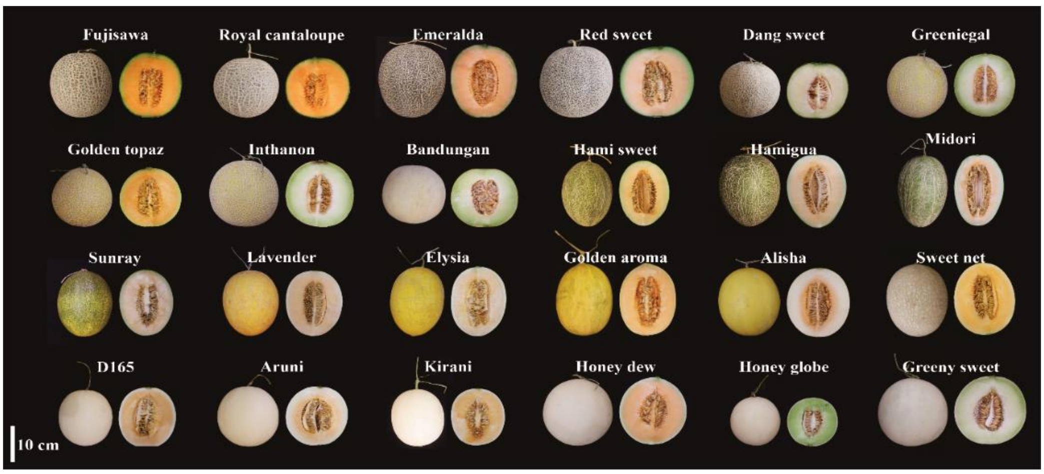


**Fig. 1:** Morphological variation in fruit shape, rind, and flesh color among 24 *Cucumis melo* varieties. Representative cross-sections of mature fruits from each melon variety evaluated in this study, showing the diversity in predominant rind and flesh color, and seed cavity structure. Scale bar, 10cm.

**Table 3:** Variation in seed weight, sweetness and qualitative fruit traits among 24 Cucumis melo varieties

| Varieties | TSW | Brix | RC | FC | FS | NT |
|---|---|---|---|---|---|---|
| Fujisawa | 42.70±0.32$^{a}$ | 16.00±0.58$^{abcd}$ | Light green | Orange | Circular | Netted |
| Royal cantaloupe | 27.17±0.35$^{lm}$ | 12.00±0.58$^{fg}$ | Light green | Orange | Circular | Netted |
| Emeralda | 42.83±0.20$^{a}$ | 17.00±0.58$^{a}$ | Green | Light orange | Circular | Netted |
| Red sweet | 3333±0.23$^{fg}$ | 14.00±0.58$^{bcdef}$ | Deep green | Light orange | Circular | Netted |
| Dang sweet | 29.67±0.26$^{jk}$ | 14.00±0.58$^{bcdef}$ | Light green | White | Circular | Netted |
| Greeniegal | 36.80±0.26$^{c}$ | 13.00±0.58$^{ef}$ | Yellow | Light green | Circular | Netted |
| Golden topaz | 36.30±0.17$^{cd}$ | 16.67±0.33$^{ab}$ | Yellow | Orange | Circular | Netted |
| Inthanon | 27.27±0.26$^{lm}$ | 14.67±0.33$^{abcdef}$ | Yellow | Light green | Circular | Netted |
| Bandungan | 26.97±0.24$^{m}$ | 10.00±0.58$^{g}$ | Yellow | Light green | Circular | Netted |
| Hami sweet | 34.23±0.26$^{ef}$ | 15.00±0.58$^{abcde}$ | Green | Orange | Ovate | Netted |
| Hamigua | 40.83±0.26$^{b}$ | 13.67±0.33$^{cdef}$ | Green | Light orange | Ovate | Netted |
| Midori | 36.77±0.26$^{c}$ | 16.00±0.58$^{abcd}$ | Green | Light orange | Ovate | Netted |
| Sunray | 33.53±0.29$^{efg}$ | 14.00±0.58$^{bcdef}$ | Green | Light orange | Elliptic | Non-netted |
| Lavender | 27.93±0.26$^{lm}$ | 15.00±0.58$^{abcde}$ | Yellow | Light orange | Elliptic | Netted |
| Elysia | 32.57±0.26$^{gh}$ | 13.33±0.33$^{def}$ | Yellow | Light orange | Elliptic | Netted |
| Golden aroma | 34.07±0.32$^{ef}$ | 14.00±0.58$^{bcdef}$ | Yellow | Orange | Elliptic | Non-netted |
| Alisha | 31.70±0.29$^{hi}$ | 12.00±0.58$^{fg}$ | Yellow | White | Elliptic | Non-netted |
| Sweet net | 25.37±0.26$^{n}$ | 15.00±0.58$^{abcde}$ | White | Orange | Elliptic | Netted |
| D165 | 30.87±0.26$^{ij}$ | 16.33±0.33$^{abc}$ | White | Light orange | Circular | Non-netted |
| Aruni | 28.53±0.23$^{kl}$ | 14.67±0.33$^{abcdef}$ | White | Light orange | Circular | Non-netted |
| Kirani | 34.90±0.26$^{de}$ | 16.00±0.58$^{abcd}$ | White | Light orange | Circular | Non-netted |
| Honey dew | 32.93±0.23$^{fgh}$ | 14.33±0.33$^{abcdef}$ | White | Light orange | Circular | Non-netted |
| Honey globe | 22.13±0.20$^{o}$ | 15.00±0.58$^{abcde}$ | White | Green | Circular | Non-netted |
| Greeny sweet | 26.73±0.26$^{mn}$ | 12.00±0.58$^{fg}$ | White | White | Circular | Non-netted |

Mean±SE of thousand seed weight (TSW, g) and total soluble solids (Brix, °Brix). Qualitative traits include rind color (RC), flesh color (FC), fruit shape (FS), and netting type (NT). Different superscript letters within TSW and Brix columns indicate statistically significant differences among varieties based on Tukey's HSD test ($P<0.05$).

the fruit diameter index, values ranged from 0.99 to 1.55cm. The lowest fruit diameter index, with no significant differences among them, was observed in Royal cantaloupe, Red sweet, Dang sweet, Golden topaz, Inthanon, Bandungan, Aruni, Honey dew, Honey globe, and Greeny sweet. Midori had the highest fruit diameter index, which differed significantly from other varieties, indicating a more elongated fruit shape. Fruit flesh thickness varied from 3.32 to 5.78cm. Midori had the thinnest flesh, which was not significantly different from Hami Sweet. Red Sweet exhibited the thickest flesh, although it was statistically similar to Inthanon. Fruit rind thickness also showed wide variation, ranging from 0.02 to 0.16cm. Significantly thinner rinds were observed in Kirani, Aruni, Honey dew, D165, Sweet net, and Midori. In contrast, Royal cantaloupe had the thickest rind, which differed significantly from all other evaluated varieties.

Seed cavity length ranged from 7.82 to 14.76cm, with Honey globe exhibiting the shortest cavity and Midori the longest. These two varieties differed significantly from the others. Seed cavity width varied between 5.02 and 7.48cm, where Honey globe recorded the lowest and Aruni the highest value, both significantly different compared to other varieties. Seed cavity index, defined as the ratio of seed cavity length to seed cavity width, ranged from 1.27 to 2.39. Aruni had the lowest seed cavity index, while the highest value was observed in Midori, which did not differ significantly from Elysia. In terms of seed dimensions, seed length ranged from 1.02 to 1.71cm. The shortest seeds were found in Hami sweet, which did not significantly differ from Midori and Elysia. The longest seeds were found in Honey dew, which was statistically similar to Greeny Sweet. Seed width also showed marked variation, ranging from 0.39 to 0.62cm. The narrowest seeds were recorded in Elysia, which did not significantly differ from Dang sweet and D165, while the widest seeds were found in Greeny sweet, with no significant differences compared to Kirani, Golden topaz, and Royal cantaloupe. The seed size ratio, calculated as the ratio of seed length to seed width, ranged from 2.03 to 3.58. The lowest seed size ratio was observed in Golden aroma, indicating relatively rounder seeds, while the highest seed size ratio was recorded in Honey dew, reflecting a more elongated seed shape.

The thousand-seed weight ranged from 22.13 g to 42.83 g. The lowest value was recorded in Honey globe, which was significantly different from the others, while the highest value was observed in Emeralda, not significantly different from Fujisawa. Brix values, representing total soluble solids and thus an indicator of sweetness, ranged from 10.00° to 17.00° Brix. The lowest values were found in Bandungan, which did not differ significantly from Royal cantaloupe, Alisha, and Greeny sweet. The highest Brix was observed in Emeralda, with no significant differences compared to Golden topaz, D165, Fujisawa, Hami sweet, Sweet net, Midori, Honey globe, Lavender, Inthanon, Aruni, Kirani, and Honey dew. Qualitative fruit traits also showed clear variation across the studied varieties. Rind color ranged across deep green, green, light green, yellow, and white, with yellow being the most frequently observed. Flesh color included green, light green, white, light orange, and orange, with light orange dominating across the varieties. Fruit shape was classified as circular, elliptic, or ovate, with circular being the most common form. Netting type was categorized as either netted or non-netted, and most varieties exhibited a netted rind. These findings highlight the considerable morphological and quality-related diversity present among the evaluated melon varieties, which can be exploited in future breeding programs.

**Multivariate Analysis of Fruit Traits**

Phenotypic diversity among melon varieties was assessed using principal component analysis (PCA) of quantitative fruit traits. The first two principal components (PC1 and PC2) explained 31.1 and 23.5% of the total variance, respectively (Fig. 2A). Variables with positive loadings on both PC1 and PC2 (quadrant I) included fruit

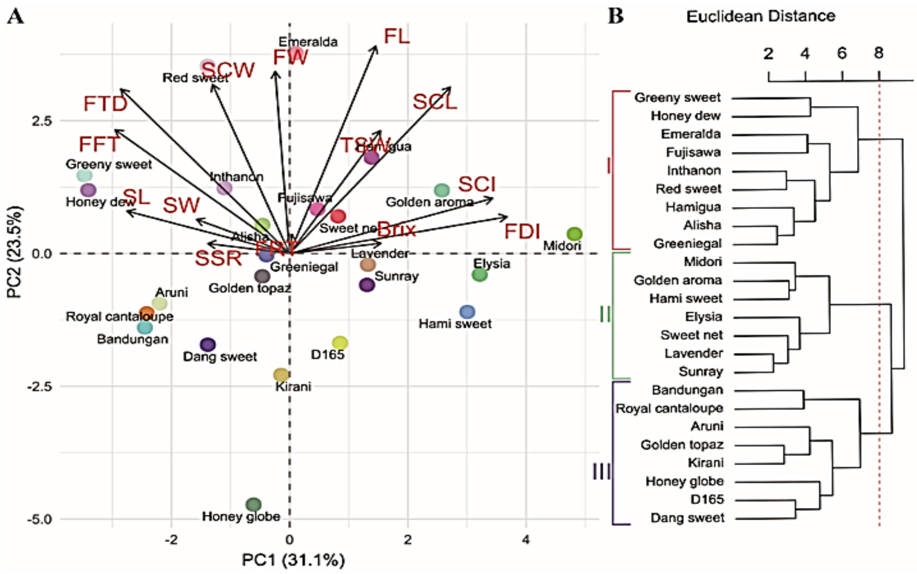


**Fig. 2:** Multivariate analysis of 24 *Cucumis melo* varieties based on 14 quantitative fruit traits. (A) Principal component analysis (PCA) showing the distribution of melon varieties. (B) Hierarchical cluster analysis (HCA) using Euclidean distance. Quantitative traits include fruit weight (FW,kg), fruit length (FL), fruit equatorial diameter (FTD), fruit diameter index (FDI), fruit flesh thickness (FFT), fruit rind thickness (FRT), seed cavity length (SCL), seed cavity width (SCW), seed cavity index (SCI), seed length (SL), seed width (SW), seed size ratio (SSR), thousand seed weight (TSW,g) and total soluble solids (Brix, °Brix)—all length units in cm.

diameter index, fruit length, fruit rind thickness, seed cavity index, seed cavity length, thousand seed weight, and Brix. In quadrant II, variables such as fruit weight, fruit equatorial diameter, fruit flesh thickness, seed cavity width, seed length, seed width, and seed size ratio showed negative PC1 but positive PC2 loadings. Based on the PCA clustering, Midori, Sweet net, Golden aroma, Fujisawa, Hamigua, and Emeralda were positioned in quadrant I. These varieties appear to combine large fruit size and high sugar content, traits desirable for fresh consumption. Red sweet, Inthanon, Greeny sweet, Honey dew, and Alisha clustered in quadrant II, where emphasis is placed on fruit weight and flesh thickness with medium seed size, potentially catering to other consumer demands. Greeniegal spanned quadrants II and III, indicating intermediate trait combinations. Golden topaz, Aruni, Royal cantaloupe, Bandungan, Dang sweet, Kirani, and Honey globe were grouped in quadrant III, suggesting smaller fruit sizes and lower seed indices. Finally, Elysia, Lavender, Sunray, Hami sweet, and D165 were located in quadrant IV, representing a unique combination of traits, such as reduced flesh thickness or overall fruit weight, which distinguishes them as specialized or premium types.

A hierarchical cluster analysis (HCA) based on Euclidean distance was performed (Fig. 2B). At a dissimilarity threshold of 8, the varieties were separated into three major clusters. The first cluster grouped Greeny sweet, Honey dew, Emeralda, Fujisawa, Inthanon, Red sweet, Hamigua, Alisha, and Greeniegal. These varieties largely correspond to the PCA quadrant I, which combines large fruit size and high sugar content. The second cluster included Midori, Golden aroma, Hami sweet, Elysia, Sweet net, Lavender, and Sunray. This cluster shows a partial overlap with PCA quadrant I (large fruit, high sugar) and quadrant IV (specialized or premium types), reflecting mixed trait combinations. Meanwhile, the third cluster consisted of Bandungan, Royal cantaloupe, Aruni, Golden topaz, Kirani, Honey globe, D165, and Dang sweet. This group aligns well with PCA quadrant III, characterized by smaller fruit sizes and lower seed indices. From these analyses, the key traits differentiating the evaluated melon varieties were large fruit size and high sugar content on one side, and smaller fruit size with lower seed indices on the other.

To investigate how these quantitative traits relate to each other, we generated a Pearson correlation matrix visualized as a clustered heatmap (Fig. 3A). Fruit weight showed strong positive correlations with fruit rind thickness, seed cavity width, fruit flesh thickness, fruit equatorial diameter, seed cavity index, Brix, seed cavity length, fruit length, and thousand seed weight. Similarly, Brix was positively associated with fruit weight, seed cavity index, fruit diameter index, seed cavity length, and thousand seed weight. Fruit diameter index correlated positively with seed cavity index, Brix, seed cavity length, fruit length, and thousand seed weight. Hierarchical clustering of the correlation matrix resolved two major trait groups. The first included thousand seed weight, fruit length, seed cavity length, Brix, fruit diameter index, and seed cavity index, traits linked to fruit size and sweetness. The second encompassed seed length, seed size ratio, fruit equatorial diameter, fruit flesh thickness, fruit weight, seed cavity width, fruit rind thickness, and seed width, primarily reflecting seed morphology and structural characteristics.

We additionally generated a hierarchical clustering heatmap (Fig. 3B). Cluster I, consisting of Alisha, Greeniegal, Hamigua, Red sweet, Inthanon, Fujisawa, Emeralda, Honey dew, and Greeny sweet, displayed no clear separation of high or low trait values, reflecting a heterogeneous mix of circular (black class), ovate (yellow class), and elliptic (green class) fruit forms, but tended to show higher fruit weight compared to Cluster II and III. Cluster II, which grouped Sunray, Lavender, Sweet net, Elysia, Hami sweet, Golden aroma, and Midori, predominantly comprised elliptic-shaped fruits with two ovate exceptions, and showed consistently high values for fruit length, seed cavity index, fruit diameter index, seed cavity index, and thousand seed weight. In contrast, Cluster III, including Dang sweet, D165, Honey dew, Kirani, Golden topaz, Aruni, Royal cantaloupe, and Bandungan, was clearly defined by circular fruit shapes and exhibited low values across these same parameters. Notably, Brix levels remained consistently high across nearly all clusters, underscoring the broad selection for sweetness across diverse melon types.

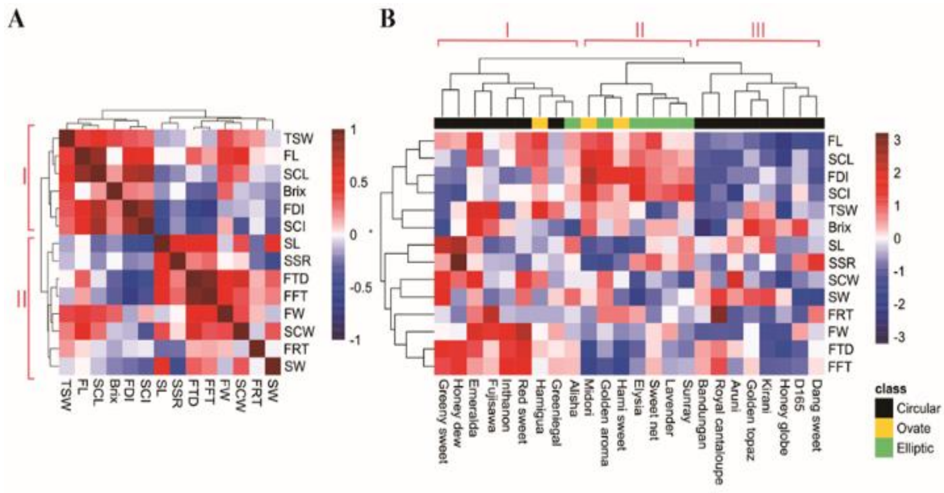


**Fig. 3:** Clustering analysis of 14 quantitative traits of melons. (A) Correlation plot. (B) Heatmap plot. A higher score (red) indicates a stronger positive. In the heatmap, values represent normalized trait measurements. Quantitative traits include fruit weight (FW,kg), fruit length (FL), fruit equatorial diameter (FTD), fruit diameter index (FDI), fruit flesh thickness (FFT), fruit rind thickness (FRT), seed cavity length (SCL), seed cavity width (SCW), seed cavity index (SCI), seed length (SL), seed width (SW), seed size ratio (SSR), thousand seed weight (TSW, g) and total soluble solids (Brix, °Brix). All length units in cm.

**Defining Diagnostic Morphological Characters**

A multi-analytical framework combining machine learning, multivariate statistics, and hierarchical clustering identified key diagnostic traits shaping phenotypic variation among commercial melon varieties in Indonesia. We used variable importance plots (VIP, %IncMSE), principal component analysis (PCA) biplots, normalized heatmaps with hierarchical clustering, and Venn diagrams to identify the top seven quantitative traits among the 14 measured (Fig. 4). The random forest VIP highlighted seed cavity length, seed cavity index, fruit flesh thickness, fruit equatorial diameter, fruit diameter index, seed length, and seed cavity width as key predictors distinguishing melon varieties (Fig. 4A). The PCA biplot showed these traits driving variation along PC1 (50.8%) and PC2 (36.7%), with fruit diameter index, seed cavity length, seed cavity index, and fruit length grouped in quadrant IV, while seed cavity width, fruit equatorial diameter, and fruit flesh thickness clustered in quadrant III (Fig. 4B). The heatmap with hierarchical clustering revealed clear grouping patterns between traits and varieties, separating Cluster I which showed consistently lower trait values, from Cluster 2 (Fig. 4C). Integration of VIP, PCA, and heatmap results using a Venn diagram identified three overlapping diagnostic traits, fruit diameter index, seed cavity index, and seed cavity length (Fig. 4D), which emerged as key markers distinguishing these varieties. The convergence of results across methods highlights key diagnostic traits with potential utility for varietal identification and breeding in Indonesian melons.

## DISCUSSION

Our study offers a comprehensive characterization of 24 commercial *Cucumis melo* varieties commonly cultivated in Indonesia. This research helps address a significant gap in both regional and global efforts to assess melon variability. Yildiz et al. (2014) reported wide variation in fruit weight, length, and soluble solids content among Turkish melon landraces, with clustering primarily influenced by fruit shape and seed cavity dimensions, patterns that align closely with the trait groupings observed in our PCA and HCA analyses. Similarly, Flores-León et al. (2022) identified seed cavity dimensions as a major trait distinguishing Spanish melon accessions, which mirrors the differences we observed, such as the elongated seed cavity in Midori and the compact cavity in Honey Globe. In line with this, Abraham-Juárez et al. (2018) showed that in Mexican melons, a large mesocarp (flesh thickness) typically correlates with a smaller seed cavity, and vice versa, an inverse relationship also evident in our study. Duong et al. (2021), working with Vietnamese melon groups, emphasized fruit shape index (fruit length to diameter ratio) and overall size as critical traits for classification.

These trends are also reflected in our dataset, particularly among varieties such as Royal Cantaloupe, Red Sweet, Dang Sweet, Golden Topaz, Inthanon, Bandungan, Aruni, Honey Dew, Honey Globe, and Greeny Sweet, all of which exhibited a low fruit diameter index. In contrast, Midori showed the highest fruit diameter index, highlighting its distinctly elongated shape and distinguishing it from the other varieties. Together, these studies emphasize that the morphological diversity observed in Indonesia's commercial melons is not isolated but reflects broader global trends. Our findings suggest that the domestic market has been significantly shaped by international germplasm exchange.

By integrating detailed fruit morphology, external and internal traits, this work reveals a rich spectrum of diversity, reflecting both the broad genetic variation within this species and targeted selection for agronomic and market-preferred traits. Consistent with previous observations in melon germplasm, significant variability was found across key quantitative attributes, such as fruit weight, length, equatorial diameter, and flesh thickness, alongside qualitative descriptors (Kustanto, 2023). Notably, Red sweet and Emeralda exhibited superior size-related traits, with Red Sweet showing the greatest flesh thickness, an attribute valued by consumers and associated with enhanced marketability (Xu et al., 2015). Differences in fruit shape, as captured by the fruit diameter index, clearly discriminated elongated types like Midori from spherical varieties such as Royal cantaloupe, Red sweet, Golden topaz, Bandungan, Aruni, Honey dew, Honey globe, and Greeny sweet. This shape-based classification is known to Influence both processing

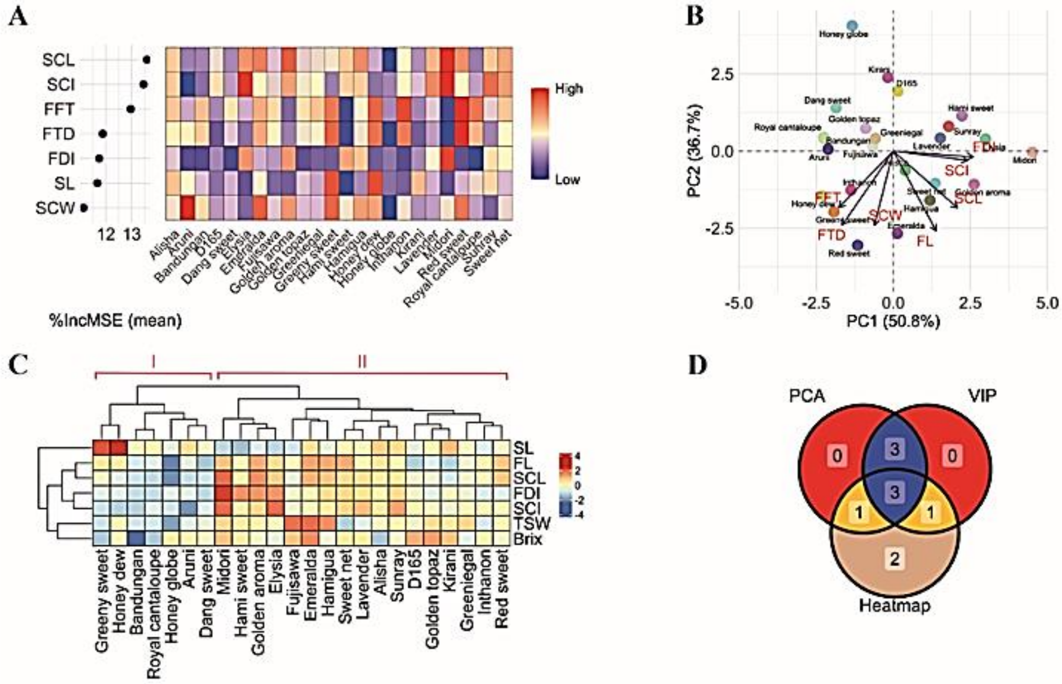


**Fig. 4:** Important morphological characters defining 24 melon varieties. (A) Variable importance plot (VIP) showing the relative contribution of each trait to clustering, with higher values indicating greater importance. (B) PCA biplot illustrating the direction and strength of each trait's contribution to principal components. (C) Heatmap with hierarchical clustering showing normalized character weights across varieties, with color intensity reflecting relative values. (D) Venn diagram identifying the seven key traits overlapping across VIP, PCA, and heatmap analyses. Quantitative traits include fruit weight (FW,kg), fruit length (FL,cm), fruit equatorial diameter (FTD,cm), fruit diameter index (FDI,cm), fruit flesh thickness (FFT,cm), fruit rind thickness (FRT,cm), seed cavity length (SCL,cm), seed cavity width (SCW,cm), seed cavity index (SCI), seed length (SL,cm), seed width (SW,cm), seed size ratio (SSR), thousand seed weight (TSW, g), and total soluble solids (Brix, °Brix).

compatibility and consumer appeal (Liu et al., 2024). Moreover, variation in rind thickness may have implications for transport resilience and shelf-life (Fernández-Muñoz et al., 2022). Internal fruit morphology added another layer of phenotypic complexity. Traits like seed cavity length, width, and index are particularly important as they influence edible portion and are tied to consumer acceptance (Grumet et al., 2023). Midori and Aruni, for example, represented contrasting morphotypes with elongated and compact cavities, respectively, features that reflect distinct horticultural classifications and usage preferences. Seed-related traits, including seed length, width, and size ratio, also varied considerably; Honey dew produced elongated seeds, while Golden aroma had more rounded ones. These differences are agronomically meaningful since seed morphology can affect germination, seedling vigor, and local adaptation (Ginwal et al., 2005; Zhang et al., 2021). Although the genetic control of these traits remains underexplored, the phenotypic data presented here provide a basis for future genetic dissection and marker-assisted selection.

Complementary traits such as thousand seed weight and Brix value further highlight the functional diversity within this germplasm. Thousand seed weight may correlate with seedling vigor (Zhang et al., 2017), while Brix levels are indicative of fruit sweetness (Wen et al., 2023; Ercan et al., 2024). Qualitative descriptors, including rind and flesh color, surface netting, and overall fruit shape, revealed a general preference for yellow-rind and light orange-flesh phenotypes, aligning with global market trends and consumer expectations (Shahwar et al., 2023). Multivariate statistical approaches provided further resolution into the complex phenotypic architecture (Zafar et al., 2022; Zafar et al., 2023; Zafar et al., 2024). Principal component analysis (PCA) and hierarchical cluster analysis (HCA) effectively distinguished varietal groups based on suites of traits related to fruit size, sugar content, and seed morphology (Fig. 2), traits that are central to both market classification and breeding decisions. For instance, Midori, Emeralda, and Sweet net clustered in PCA quadrant I, characterized by large fruit size, elongated shape, and high Brix. In contrast, Royal cantaloupe, Honey globe, and Bandungan are grouped separately, defined by smaller fruit dimensions and lower seed indices (Fig. 2A). The hierarchical clustering analysis (HCA) further refined varietal differentiation by separating the evaluated accessions into three main clusters (Fig. 2B). Cluster I largely overlapped with PCA quadrant I, representing large-fruited, high sugar types. Cluster II partially overlaps with PCA quadrants I and IV, which correspond to specialized market types. Meanwhile, Cluster III aligned with PCA quadrant III, characterized by smaller fruit size and lower seed indices. These contrasting profiles underscore the importance of large fruit size and high sugar content as key drivers of market differentiation. On the other hand, smaller-fruited varieties with lower seed index may cater to special preferences. Trait correlation analysis revealed strong positive associations between fruit weight and rind thickness, flesh thickness, seed cavity dimensions, and Brix (Fig. 3A), reaffirming the integrated nature of fruit development and quality traits (Chikh-Rouhou et al., 2024).

The fruit diameter index emerged as a central integrative metric, bridging external morphology with internal quality parameters and correlating positively with cavity size, sugar content, and seed weight (Miccolis & Saltveit 1991). Hierarchical clustering heatmap refined varietal differentiation by integrating morphometric traits (Fig. 3B). Cluster II, primarily composed of elliptic-fruited varieties, exhibited high values for fruit length, seed cavity dimensions, and Brix. Meanwhile, Cluster III, composed mainly of circular-fruited varieties, displayed generally lower trait values but retained high Brix levels. Notably, when clustering was based solely on morphological characteristics, the grouping patterns differed, reflecting the influence of shape-related traits on varietal differentiation. Our integrative analytical framework, which combined supervised (random forest) and unsupervised (PCA, clustering) methods, identified a core set of diagnostic morphological traits critical for varietal differentiation. Among the 14 quantitative traits analyzed, seed cavity length, seed cavity index, and fruit diameter index consistently emerged as the most informative and discriminative features across all statistical platforms. These traits were ranked highly by Random Forest variable importance scores, contributed strongly to the first two principal components in PCA, and served as major axes of differentiation in hierarchical clustering. The seed cavity index and length, by contrast, are tied to internal fruit architecture, directly affecting nutritional composition and edible yield (Romo-Tovar, 2024). This ratio-based trait offers greater comparability across fruits of varying sizes, making it a robust metric for characterizing internal fruit architecture. Compared to traits like Brix, which can fluctuate due to environmental or harvest conditions (Ercan et al., 2024), seed cavity index is a structural trait with greater phenotypic stability, and therefore more reliable for consistent varietal classification. Furthermore, the seed cavity is closely tied to edible portion yield, a key determinant of consumer preference and post-harvest market value. Fruit diameter index, associated with fruit elongation, plays a pivotal role in market segmentation and consumer acceptance, particularly in distinguishing based on six botanical groups, including Flexuosus, Conomon, Cantalupensis, Inodorus, Chito, Dudaim, and Momordica (Luan et al., 2008; Omari et al., 2018). These traits represent not only reliable identifiers of varietal identity but also valuable targets for selection due to their influence on agronomic performance and post-harvest characteristics. Moving forward, integrating these findings with molecular tools such as SNP-based genome-wide association studies (GWAS) or QTL mapping will provide deeper insight into the genetic architecture of these traits and accelerate the development of elite cultivars tailored to local environments and consumer preferences.

### Conclusion

Our integrative analysis of 24 commercial *Cucumis melo* varieties in Indonesia reveals that a small set of morphological traits, notably seed cavity length, seed cavity index, and fruit diameter index, underpin most of the observed phenotypic variation. These traits not only distinguish varietal groups but also link directly to agronomic performance and market value. Together, our findings provide a phenotypic framework for accelerating melon breeding and lay the groundwork for future molecular dissection of key horticultural traits.

## DECLARATIONS

**Funding:** This study was funded by the Faculty of Animal and Agricultural Sciences, Universitas Diponegoro (Grant No. 21/UN7.F5/PP/I/2025).

**Acknowledgement:** The authors gratefully acknowledge the Laboratory of Plant Physiology and Breeding for providing the research facilities. Special thanks are extended to the technical support team of the Molecular Crop Research Unit, whose assistance in preparation, maintenance, and data collection was essential to the success of this study.

**Conflict of Interest:** The authors declare no conflict of interest.

**Data Availability:** All the data is available in the article.

**Ethics Statement:** This study did not involve human participants or animals. All experimental procedures complied with institutional, national, and international guidelines for research on cultivated plants. The plant materials used in this research were commercially available melon (*Cucumis melo* L.) varieties, and their use complied with relevant institutional and national regulations.

**Author's Contribution:** BHE, SAN, and FKS were involved in the conceptualization, methodology, project administration, and funding acquisition for the study. BHE and MGA were responsible for the investigation, including sample collection, phenotypic measurements, statistical analysis, data curation, and visualization. SAN and FKS provided resources and supervision. The original draft of the manuscript was written by BHE, with review and editing contributions from TBS. All authors read and approved the final manuscript.

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