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Reducing damage to mangosteen (*Garcinia mangostana* L.) during distribution and storage through corrugated paperboard packaging design

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Abstract

Damage to mangosteen primarily results from compressive forces during distribution and uneven temperature distribution. Therefore, an optimized packaging design that mitigates these factors is essential. This study aimed to (1) determine the most suitable packaging dimensions for the distribution of climacteric fruits, such as mangosteen, and (2) evaluate ventilation (dimensions and types) and types of flutes that can minimise damage due to shocks during transportation and temperature fluctuations during storage. This study was conducted in two stages. Stage I involved designing and determining the packaging dimensions using a 5 kg full-flap BC flute packaging. Stage II focused on determining the ventilation dimensions, types of ventilation, and flute types. The designed packaging was tested under different transportation conditions, including rough asphalt, intercity, and urban roads. The Stage II research employed a completely randomized factorial design with three treatment factors: (I) Ventilation type (round and oval); (II) Flute type (single and double); and (III) Ventilation dimension (1.2%, 2.4%, and 3.6% of the total packaging area). All treatments were conducted in duplicate. Data were analyzed with ANOVA, followed by DMRT. The results showed that the optimal packaging was a 27.5 cm × 22.5 cm × 22.5 cm full-flap packaging, achieving a packaging density of 58.20%. Additionally, the interaction among ventilation type, flute type, and ventilation dimensions significantly affected fruit quality after transportation and storage. The best packaging configuration for preserving mangosteen quality was a 27.5 cm × 22.5 cm × 22.5 cm full-flap packaging with oval ventilation (3.6%) and a double flute type.

Key words: mechanical damage*, mangosteen*, distribution, packaging design, corrugated paperboard.

Introduction

Fresh horticultural products are highly susceptible to mechanical damage, which can subsequently trigger physiological deterioration due to pressure or impact during distribution (Al-Dairi *et al.*, 2022; Pathare and Al-Dairi, 2022). Mechanical injuries are primarily caused by factors such as transportation vibrations or accidental drops during handling (Boaca *et al.*, 2021, 2024; Pathare and Al-Dairi, 2022). Previous studies have demonstrated that vibrations significantly affect the quality of fruits and vegetables during transportation, as observed in broccoli, bananas, tomatoes, and mushrooms (Rozana *et al.*, 2021; Sairi *et al.*, 2023; Pathare and Al-Dairi, 2022; Walkowiak-Tomczak *et al.*, 2021). In addition to vibration and pressure, the accumulation of uneven temperatures within the packaging also contributes to fruit deterioration (Iñiguez-Moreno *et al.*, 2020; Walkowiak-Tomczak *et al.*, 2021). Therefore, the implementation of appropriate packaging is crucial in minimizing mechanical damage that can lead to physiological deterioration in fresh fruit (Iñiguez-Moreno *et al.*, 2020).

One of the horticultural products highly susceptible to quality deterioration due to excessive pressure and temperature fluctuations is climacteric fruit. Several studies have demonstrated that the quality decline in climacteric fruits with short shelf lives is primarily attributed to high storage temperatures. For instance, bananas have a shelf life of only five days (Quitos *et al.*, 2024), and mangoes less than a week (Kiran *et al.*, 2023). Meanwhile, tomatoes stored in cold storage at 4 °C has a shelf life of up to 25 days (Al-Dairi *et al.*, 2022). Among various climacteric fruits, mangosteen exhibits an exceptionally high respiration rate and one of the shortest shelf lives, making it highly perishable.

To mitigate fruit damage caused by uneven temperature accumulation, proper ventilation in the packaging is essential (Iñiguez-Moreno *et al.*, 2020). Reducing physical and mechanical damage during distribution can be achieved through well-designed packaging that considers factors such as packaging type, dimensions, and capacity, all of which should align with the specific characteristics of the fruit being packaged (Rozana *et al.*, 2021). However, even the most carefully designed packaging may not perform optimally if efforts to minimize damage during refrigerated storage are not also implemented. The incorporation of ventilation in packaging inevitably influences its maximum compressive strength, thereby affecting its ability to withstand stacking loads in cold storage. Consequently, further research is needed on various flute types used in packaging materials, as each flute exhibits different load-bearing capacities.

Corrugated cardboard packaging is a widely used material that helps mitigate mechanical pressure and vibration-induced damage during product transportation (Li *et al.*, 2023; Pathare *et al.*, 2021). This packaging material effectively reduces product dumping during transit (Al-Dairi *et al.*, 2022; Boaca *et al.*, 2024;

Li *et al.*, 2023; Ran and Liu, 2019; Tao *et al.*, 2021). In addition to the packaging material type, ventilation properties, such as size and type, play a crucial role in maintaining fruit quality during transportation and storage (Li *et al.*, 2023; Pathare *et al.*, 2012; Pathare and Al-Dairi, 2022). The accumulation of high temperatures caused by inadequate air circulation during storage accelerates metabolic processes, leading to a decline in the quality of fresh fruits and vegetables (Al-Dairi *et al.*, 2022; Boaca *et al.*, 2024; Fauziana *et al.*, 2023; Walkowiak-Tomczak *et al.*, 2021). Integrating ventilation into corrugated cardboard packaging is an effective strategy to enhance temperature regulation, ensuring more efficient and uniform cooling (Al-Dairi *et al.*, 2022; Boaca *et al.*, 2024; Fauziana *et al.*, 2023). The homogeneity of the cooling process is significantly influenced by the structural and design characteristics of the packaging system, particularly the type of flute used (Li *et al.*, 2023). Based on the aforementioned explanation, this study aims to determine the most suitable packaging dimensions for the distribution of climacteric fruits such as mangosteen and to evaluate ventilation (dimensions and types) and types of flutes that can minimize damage due to shocks during transportation and temperature fluctuations during storage

Materials and methods

Material: BC Flute-type corrugated cardboard with a grammage of 125/150/125, net foam, and mangosteen fruit with a ripeness index of 2 and quality grade 1, with diameters ranging from 6.0 cm to 6.5 cm (Indonesian National Standard, 1992). The equipment utilized included a digital scale (Adventurer™ Pro Av 8101, Ohaus, New York, USA), a refractometer (Atago P-1, °Brix: 0–32%, Japan), a texture analyzer (T.A. XT Plus, England), an Instron universal testing machine, a Cosmotector Quantek Instruments Model 902 D Dual Trak, a pH meter, as well as trucks for transporting the packaged products and cold storage facilities.

Phase I (Designing Packaging Dimensions): Phase I focused on designing and determining the optimal packaging dimensions to provide maximum protection for the product during distribution. This phase began with the characterization of grade I mangosteen fruit, including major diameter, minor diameter, fruit stalk height, compressive strength, and bioyield point. The packaging design calculations utilized the Face-Centered Cubic (FCC) fruit arrangement equation, as proposed by Rozana *et al.* (2021), as illustrated in Fig. 1. The calculation of the number of fruits (N) in a package is determined based on the packaging capacity, adhering to the following equation:

N = number of fruits in 1 kg (fruits/kg) x packaging capacity (kg) (1)

$$\text{Non-ymmetrical row pattern (N)}= \frac{K_A K_B K_C}{\text{Weight of sample}} \quad (2)$$

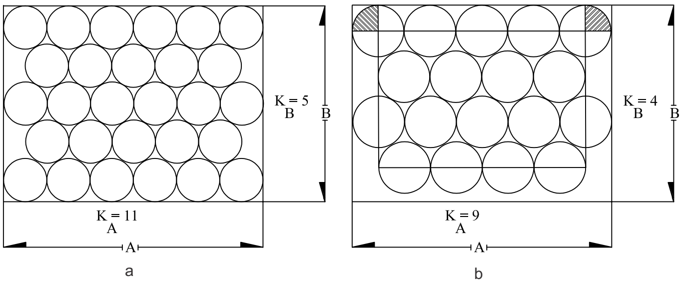

Fig. 1 (a) Symmetrical row pattern (b) Non- symmetrical row pattern (Peleg 1985)

$$\text{Symmetrical row pattern (N)}= \frac{K_A K_B K_C+1}{\text{Weight of sample}} \quad (3)$$

Based on the number of fruits obtained from Equation 1, the number of fruits that fit along the length (K_A), width (K_B), and height (K_C) directions within the packaging can be calculated using one of the following equations.

The next stage involved determining the packaging dimensions, where a represents the minor diameter of the fruit and b denotes the major diameter of the mangosteen fruit,

$$\text{Packaging width dimension FCC (B)} = (1.41\ KB + 0.59)\ b \quad (4)$$

$$\text{Packaging height dimension FCC (C)} = (1.41\ KC + 0.59)\ b \quad (5)$$

The selected packaging dimensions were determined based on the product with the highest density level. In Phase I, the design and determination of packaging dimensions were conducted using a packaging capacity of 5 kg with a full-flap BC flute packaging type, featuring a grammage of 125/150/125. Based on the calculation results, the packaging dimensions with the highest density value were selected.

Phase II (Determination of Ventilation Dimensions and Types): The study focused on determining the appropriate ventilation type, ventilation dimensions, and flute types to minimize fruit damage during transportation and storage. The packaging used in this phase was developed based on the findings from Phase I. Packaging performance was assessed by arranging the fruit inside and subjecting it to transportation across various road conditions, including poor asphalt roads, out-of-town roads, and inner-city roads, covering a total distance of 172 km. Upon arrival at the destination, the packaged fruit was stored in cold storage for two days. Subsequently, the fruit from each treatment combination was removed from the packaging for quality assessment. This evaluation aimed to determine the effects of ventilation characteristics (dimensions and types) and flute types on air distribution within the packaging, as well as the packaging's effectiveness in mitigating damage caused by shocks during transportation and storage.

Phase II research employed a completely randomized factorial design with three treatment factors. The first factor was the type of ventilation (V), the second factor was the type of flute used (F), and the third factor was the ventilation dimension (D). Factor I consisted of two levels: round-type ventilation (V_c) and oval-type ventilation (V_o). The second factor consisted of two flute types: single flute (F_1) and double flute (F_2). The third factor consisted of three levels, namely 1.2% (D_1), 2.4% (D_2), and 3.6% (D_3) of the total packaging area.

Statistical analysis: In this study, each treatment was repeated twice, the combined data from these repetitions were then subjected to statistical analysis using Analysis of Variance (ANOVA). If the ANOVA results indicated a significant effect of the treatment on the observed parameters, a post-hoc analysis was conducted using Duncan's Multiple Range Test (DMRT). This test was applied to determine which specific treatments differed significantly from the others, thereby allowing for a more detailed and accurate interpretation of the experimental results

Observed variables: The variables examined in this study included the distribution of air temperature within the packaging during storage and the quality of mangosteen fruit following transportation and storage. Quality parameters assessed comprised the percentage of physical damage, weight loss, and respiration rate. All quality variables, except for physical damage, were measured and observed daily until the fruit was deemed unfit for consumption.

Results and discussion

Physical characteristics of mangosteen fruit: The physical characteristics of mangosteen fruit serve as the foundation for designing appropriate packaging for its distribution. These characteristics are presented in Table 1**.**

Table 1. Results of measurements of the physical properties of mangosteen fruit

Measurement variables	average value	Standard Deviation
Fruit weight (g)	119.72	5 .80
Major diameter (cm)	6.38	1.30
Minor diameter (cm)	6.16	1.22
Stem height (cm)	2.52	0.45
Fruit height (cm)	5.83	1.70

The low standard deviation in the measurement results of various mangosteen fruit characteristics indicates minimal variation in the physical properties of the fruit used, particularly in terms of fruit diameter, stalk height, and fruit height. The FCC-pattern fruit arrangement with net foam is designed to maintain a consistent number of fruits within a given packaging capacity. Based on Table 1, it can be estimated that a 5 kg package accommodates approximately 40 mangosteens, with an average total weight of 5 ± 0.1 kg per package.

The compressive strength of mangosteen fruit reflects its ability to withstand maximum vertical loads within the packaging before sustaining physical damage. Damage resulting from loads exceeding the fruit's compressive strength is characterized by cracked skin and/or a concave deformation of the fruit surface (dents). The mechanical properties of mangosteen fruit were evaluated based on its compressive strength, which determines its ability to withstand maximum loads along the Y-axis without sustaining physical damage, such as cracked skin or concave deformations (dents). The measurement results indicate that mangosteen fruit exhibits a maximum texture hardness of 6.53 N. This suggests that the fruit can maintain its structural integrity under a maximum pressure of 6.53 N; however, forces exceeding this threshold are likely to cause deformation and tissue damage. Previous research has demonstrated that climacteric fruits exhibit varying texture values. For instance, avocado fruit has a firmness value of 10.5 N (Mishra *et al.*, 2021). Furthermore, given that the average weight of a mangosteen fruit is 120 g and its maximum load-bearing capacity is 6.53 N, the maximum number of fruits that can be stacked vertically is 42.

Designed packaging: Key variables in packaging design include the suitability of packaging dimensions to the intended capacity and the packaging density. A higher packaging density is preferable, as it indicates greater efficiency in space utilization. Increased density minimizes gaps within the packaging, thereby reducing friction between fruits. Mechanical damage, such as bruising, abrasion, and softening, often results from the random movement of fresh produce during transportation (Fernando *et al.*, 2020; Li and Thomas, 2014). Based on the dimensions of the designed packaging, the density of the FCC-pattern arrangement using net foam reached 58.20%. The use of the FCC pattern for arranging mangosteen fruit in corrugated cardboard packaging produces a fruit density of 65% with a damage level of only 2.46%. In comparison, random arrangement in the same packaging dimensions produces a maximum fruit density of only 34%, with fruit damage reaching 15.61% (Rozana *et al.*, 2021). Based on the calculation results, the combination of packaging dimensions length, width, and height yielded a density range of 51.55% to 58.20%. This density value represents the ratio between the packaging volume and the total fruit volume within the packaging. Among the 10 dimension combinations presented in Table 2, the selected packaging dimensions were 25.5 × 20.5 × 20.5 cm. Considering the thickness of the corrugated cardboard and the net foam used to protect the fruit, the final net packaging dimensions were adjusted to 27.5 × 22.5 × 22.5 cm. The detailed design specifications for the corrugated cardboard packaging with the FCC-pattern fruit arrangement are presented in Table 2.

Table 2. Details of result design packaging

Variables	FCC Net Foam Pattern
Amount Fruit in One packaging	5 kg
Amount of Fruit in packaging (fruit)	40
L long (fruit)	5
W width (fruit)	4
H height (fruit)	4
Dimensions packaging	
L length (cm)	27.5
W width (cm)	22.5
H height (cm)	22.5
Density packaging (%)	58.20

Determination of dimensions and type of ventilation: Based on the research results and calculations carried out, the number of ventilation holes for each unit was obtained, as shown in Table 3 below. The ventilation position for each treatment was placed on each side of the packaging's side surface, as shown in Fig. 2.

Table 3. Dimensions and number of ventilation results from calculations

Treatments	Packaging surface area (cm^3)	Area per vent (cm)	Number of Ventilation (pieces)
V c.F1.D1 (Round, Single, 1.2%)	13068	7.06	6
V c.F1.D2 (Round, Single, 2.4%)	13068	7.06	12
Vc. F1. D3 (Round, Single, 3.6%)	13068	7.06	18
Vc .F2. D1 (Round, Double, 1.2%)	13068	7.06	6
Vc. F2. D2 (Round, Double, 2.4%)	13068	7.06	12
Vc. F2. D3 (Round, Double, 3.6%)	13068	7.06	18
Vo. F1. D1 (Oval, Single, 1.2%)	13068	21.19	2
Vo. F1. D2 (Oval, Single, 2.4%)	13068	21.19	4
Vo. F1. D3 (Oval, Single, 3.6%)	13068	21.19	6
Vo. F2. D1 (Oval, Double, 1.2%)	13068	21.19	2
Vo. F2. D2 (Oval, Double, 2.4%)	13068	21.19	4
Vo. F2. D3 (Oval, Double, 3.6%)	13068	21.19	6

Temperature distribution in packaging: The results indicate that packaging with oval-shaped ventilation, covering 3.6% of the total surface area, achieved the most rapid temperature reduction, aligning closely with the ambient temperature of the refrigerator used. This trend was observed across both flute types, namely single flute and double flute. A faster temperature adjustment within the packaging reduces the risk of product damage due to exposure to elevated temperatures. Pathare *et al.* (2012) reported that the total area, size, and positioning

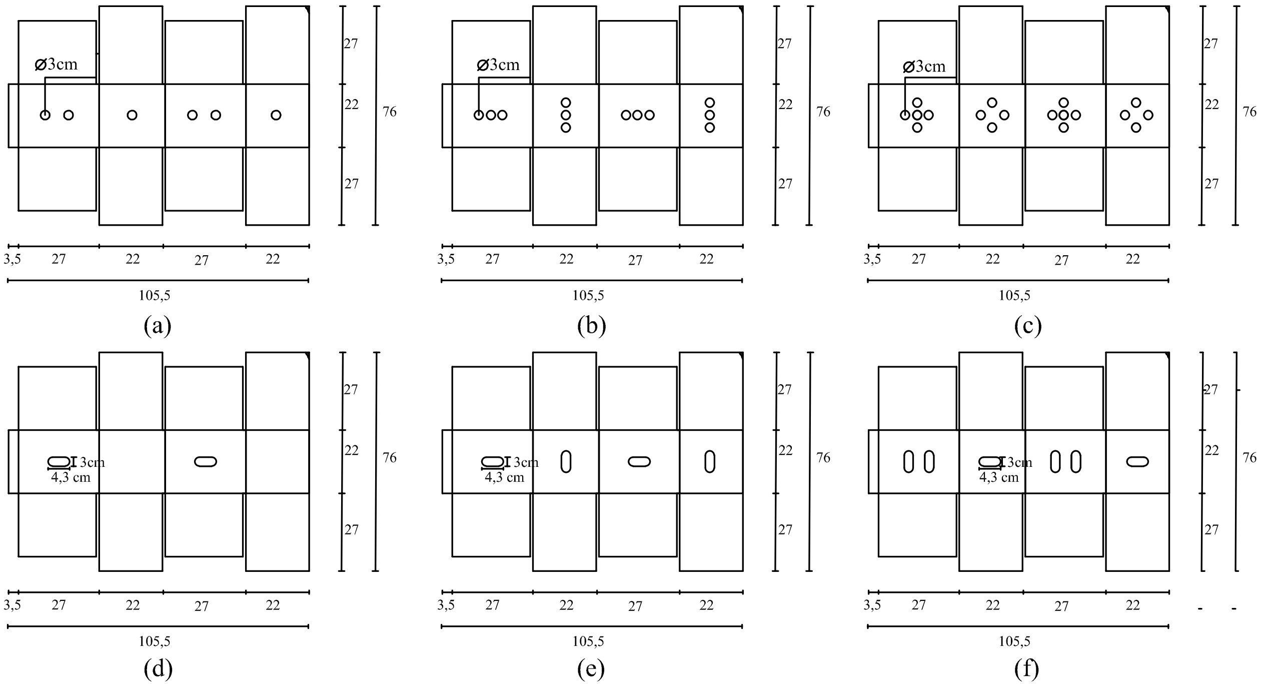

Fig. 2. Packaging ventilation (a) round type 1.2%; (b) round type 2.4%; (c) round type 3.6%; (d) oval type 1.2%; (e) oval type 2.4% and (f) oval type 3.6%

of ventilation significantly influence pressure drop, air distribution uniformity, and cooling efficiency within the packaging. Additionally, Pathare *et al.* (2018) stated that packaging with standard ventilation of 3.1% in a corrugated cardboard packaging for citrus fruits had a higher compression strength value than using supervenes with larger dimensions. The use of ventilation with a small percentage would not affect the resistance of the packaging structure but would limit airflow so that the air temperature in the packaging becomes inhomogeneous. The cooling function can be improved by using ventilation on the side of the packaging (Pham *et al.*, 2021) . The results of the data analysis indicated that the interaction between each treatment had a significant effect on the average temperature distribution across different layers within the packaging. As illustrated in Fig. 3, packaging with a single-flute structure tends to exhibit the highest temperature across all observed layers.

Physical damage to fruit after transportation and storage: The damage observed in this study primarily involved the indentation of the fruit skin into the flesh (denting) and discoloration of the skin surface caused by impact and pressure during transportation. Based on the data obtained, the highest damage rate (6%) was recorded in mangosteen fruit packaged using single-flute packaging with round-type ventilation (Table 4). This finding indicates that single-flute packaging has the lowest capacity to absorb vibrations during transportation. Consequently, when shocks and vibrations occur, the packaging fails to effectively dissipate the impact, resulting in skin indentation and deformation of the fruit. The structural strength of corrugated cardboard is significantly influenced by both the flute type and the number of flutes used (Al-Dairi *et al.*, 2022; Li *et al.*, 2023).

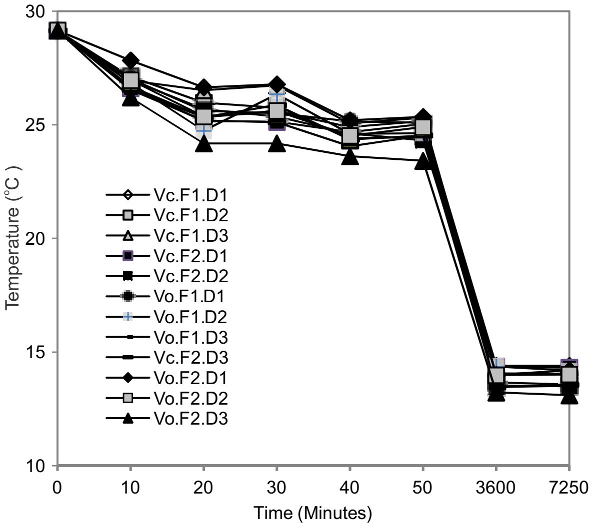

Fig. 3. Temperature variations inside packaging under different treatments

A different outcome was observed in mangosteen fruit packaged using double-flute packaging with oval ventilation across all ventilation dimensions. No instances of fruit damage, such as sunken skin, loose cephala, or broken fruit stalks, were detected. This can be attributed to the improved ability of double-flute packaging to absorb vibrations and shocks during transportation compared to single-flute packaging. This finding aligns with the study conducted by Boaca *et al.* (2024), which reported higher physical damage rates in fruit packaged using ventilated single-flute packaging. Furthermore, research by Boaca *et al.* (2021) indicated that the use of double-flute (double-wall) corrugated cardboard packaging in China accounts for 70% of the market compared to single-flute packaging, primarily due to its impact on the shelf life of packaged products.

In this study, the double flute was the BC-type flute, while the single flute was the B-type flute. The BC flute is commonly used as a packaging material due to its enhanced ability to withstand pressure, making it more effective in protecting the packaged product during transportation and storage. Boaca *et al.* (2021) stated that the space between the liner paper and the flute serves as an insulator, offering protection against fluctuating atmospheric conditions during handling and storage.

Weight loss: Mangosteen is an agricultural commodity sold by weight; therefore, weight loss after transportation and

Table 4. Percentage of physical damage after transportation and during storage

Treatment	Physical damage (%)
V c.F1.D1 (Round, Single, 1.2%)	6.0
V c.F1.D2 (Round, Single, 2.4%)	5.0
Vc. F1. D3 (Round, Single, 3.6%)	5.0
Vc .F2. D1 (Round, Double, 1.2%)	2.5
Vc. F2. D2 (Round, Double, 2.4%)	2.5
Vc. F2. D3 (Round, Double, 3.6%)	3.0
Vo. F1. D1 (Oval, Single, 1.2%)	0.0
Vo. F1. D2 (Oval, Single, 2.4%)	2.5
Vo. F1. D3 (Oval, Single, 3.6%)	2.5
Vo. F2. D1 (Oval, Double, 1.2%)	0.0
Vo. F2. D2 (Oval, Double, 2.4%)	0.0
Vo. F2. D3 (Oval, Double, 3.6%)	0.0

storage is a critical concern for both producers and consumers (Fauziana *et al.*, 2023). Weight loss in fruits such as mangosteen can indicate product deterioration, the greater the extent of damage sustained by the fruit, the higher the weight loss percentage observed (Pathare and Al-Dairi 2022).

The results of the variance analysis indicated that the interaction between ventilation type, ventilation dimension, and flute type significantly affected the average percentage of fruit weight loss after transportation and storage. The data revealed that the lowest percentage of weight loss, 0.10%, was observed in mangosteen fruit packed using corrugated cardboard packaging with oval-shaped ventilation, a double flute structure, and ventilation dimensions accounting for 3.6% of the total packaging surface area $V_o.F_2.D_3$. Furthermore, this treatment did not exhibit a statistically significant difference from the $V_o.F_2.D_2$ treatment, in which mangosteen fruit was packed using similar packaging but with ventilation dimensions of 2.4%.

The minimal weight loss observed in these two treatments was likely due to reduced physical damage to the fruit compared to other treatments. This can be attributed to the superior ability of double-flute packaging to withstand compressive forces when stacked and to provide greater shock absorption compared to single-flute packaging. Additionally, using oval-shaped ventilation with a higher percentage of total packaging surface area facilitated more rapid temperature equilibration between the packaging and the cooling environment. Elevated temperatures activate enzymatic processes involved in the Krebs cycle, leading to glucose breakdown and the subsequent production of water, CO_2, and energy. Physiologically, higher temperatures accelerate enzyme activity, increasing CO_2 formation and thereby enhancing metabolic processes, which ultimately affects the quality of climacteric fruits (Wang and Ajji, 2022). Consequently, immediate post-harvest cooling is an essential strategy to minimize weight loss (Iñiguez-Moreno *et al.*, 2020; Le *et al.*, 2021). Moreover, Pathare and Al-Dairi (2022) reported that weight loss in fresh fruit increases when stored at higher temperatures. This phenomenon is primarily driven by respiration rates, which result in carbon loss during the ripening process, often exacerbated by temperature fluctuations (Weber *et al.*, 2020). Conversely, the highest weight loss percentage was observed in mangosteen fruit packaged with 2.4% single-flute round-type ventilation ($Vc.F_1.D2$), reaching 0.17%. This is attributed to the inability of single-flute packaging to effectively absorb pressure and shocks, unlike double-flute packaging, leading to increased fruit damage and, consequently, higher weight loss. Treatments that induce excessive shaking stimulate more significant water loss from the fruit through respiration and transpiration processes, directly contributing to weight reduction (Al-Dairi *et al.*, 022). This finding is supported by data indicating greater physical damage in fruits packaged using single-flute round-ventilated packaging across all ventilation dimensions (Boaca *et al.*, 2024). Furthermore, Boaca *et al.* (2021) reported that in China, the use of double-flute (double-wall) corrugated cardboard packaging accounts for 70% of total packaging, highlighting its superior role in extending the shelf life of packaged products compared to single-flute alternatives.

Respiration Rate: The respiration rate serves as a key indicator of the storage capacity of fruit after harvest. The results of the variance analysis indicate that the interaction between ventilation type, ventilation dimension, and flute type significantly influences the rate of CO_2 production in mangosteen fruit after transportation and during storage. Similar to the weight loss parameter, the lowest respiration rate of CO_2 production was observed in mangosteen fruit packaged with oval-shaped ventilation measuring 3.6% of the total surface area, combined with double-flute corrugated cardboard ($V_o.F_2.D_3$). This treatment yielded an average CO_2 production rate of 4.18 mL/kg per hour. The lower CO_2 production in this treatment can be attributed to the ability of cold storage temperatures to reduce heat accumulation and suppress fruit respiration activity during storage. The use of 3.6% oval-shaped ventilation in the $V_o.F_2.D_3$ treatment facilitated more efficient cold air distribution within the packaging, thereby enhancing cooling effectiveness compared to other treatments. Previous studies have shown that ventilation patterns resembling rectangular shapes better maintain the compressive strength of corrugated packaging while ensuring adequate air circulation (Boaca *et al.*, 2021; Jasmani *et al.*, 2021).

Respiration rates in fruit increase under elevated temperatures, accelerating ripening processes (Wang and Ajji, 2022). Maintaining low temperatures throughout the cold chain is crucial for preserving the quality of fresh produce during storage (Pham *et al.*, 2021). Higher temperatures provide greater kinetic energy to molecular systems, fulfilling Arrhenius' law, which results in increased molecular collisions and heightened enzymatic activity associated with respiration (Ho *et al.*, 2020). High temperatures stimulate enzymatic processes involved in the Krebs cycle, leading to the breakdown of glucose with oxygen to produce water, CO_2, and energy. Consequently, higher temperatures accelerate

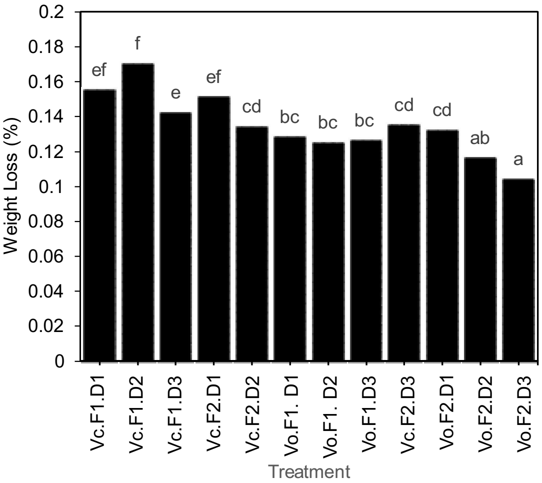

Fig. 4. The average weight loss of mangosteen fruit after transportation

enzymatic activity, increasing CO_2 production (Walkowiak-Tomczak *et al.*, 2021).

$V_o.F_2.D_3$ treatment exhibited the lowest CO_2 production rate. This reduced respiration rate is attributed to the protective function of double-flute corrugated cardboard, which effectively absorbs mechanical shocks and impacts during transportation (Fig. 5). One of the primary causes of increased respiration in fruit is mechanical bruising, which exacerbates physiological damage (Al-Dairi *et al.*, 2022; Pathare and Al-Dairi, 2022).

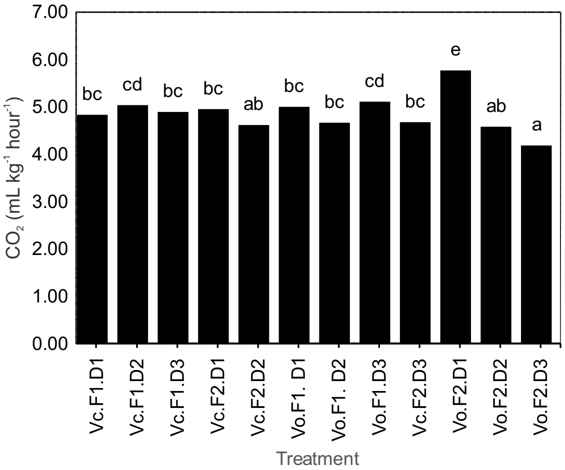

Fig. 5. Average CO_2 production of mangosteen fruit during storage

The study findings indicate that the optimal packaging design for mangosteen fruit, with a capacity of 5 kg, features a face-centered cubic (FCC) fruit arrangement within packaging dimensions of 27.5 cm × 22.5 cm × 22.5 cm with a density of 58.20%. The interaction between ventilation type, flute type, and ventilation dimensions significantly affects the quality of mangosteen fruit after transportation and storage. The most effective packaging design was a full-flap type box with oval ventilation (3.6%) and a double-flute structure, which provided superior protection against mechanical damage and facilitated the fastest temperature adjustment in cold storage.

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