Effects of Phosphorus Fertilization on Physico-mechanical Properties of Citron Watermelon Rind and Biochemical Properties of Fruit Pulp

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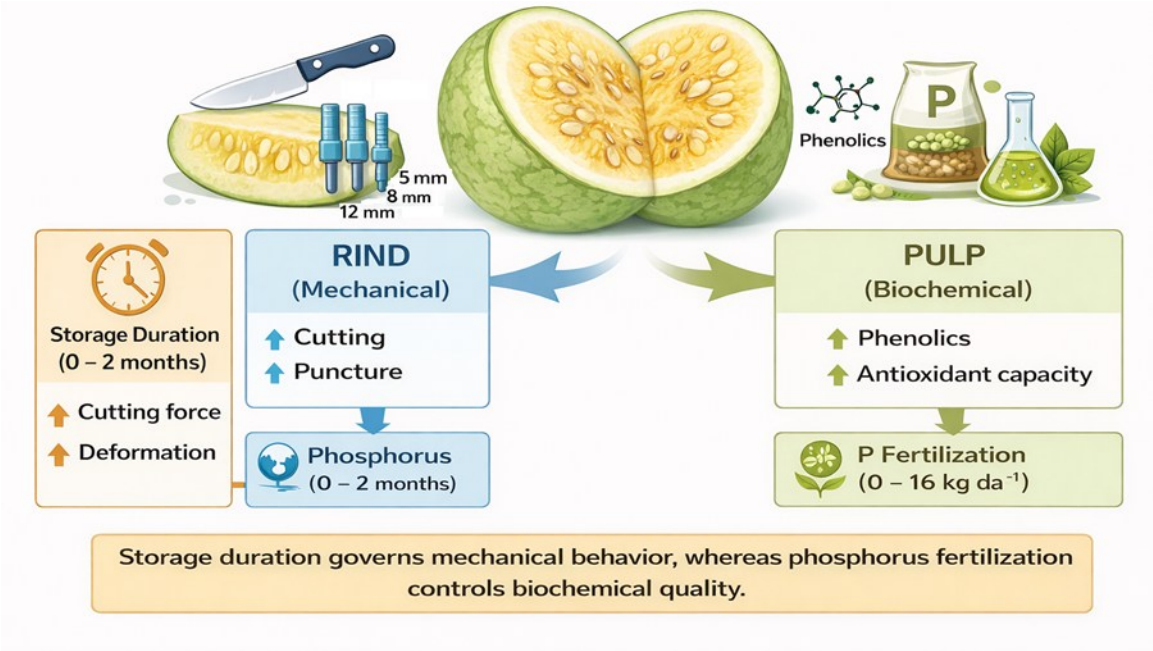
GRAPHICAL ABSTRACT



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The combined effects of phosphorus fertilization (applied as triple superphosphate, TSP; $Ca(H_2PO_4)_2 \cdot H_2O$, 43 to 44% P_2O_5) and storage duration were studied relative to the physico-mechanical and biochemical properties of citron watermelon (*Citrullus lanatus* var. citroides). Five phosphorus application rates and three storage durations under ambient conditions were evaluated. Storage duration significantly impacted both quality and mechanical traits. Moisture content decreased progressively during storage, accompanied by increases in rind lightness (L^*), yellowness (b^*), and chroma (C^*). After two months of storage, cutting force and deformation increased significantly, reflecting storage-induced modifications in tissue structure and viscoelastic behavior. Prolonged storage was also associated with a general decline in antioxidant-related biochemical parameters, suggesting degradation of bioactive compounds over time. Phosphorus fertilization did not significantly affect ($P > 0.05$) fruit weight, dimensional characteristics, color attributes, puncture resistance, or cutting-related mechanical parameters. In contrast, increasing phosphorus doses significantly enhanced total phenolic and flavonoid contents, total antioxidant activity, and chlorophyll contents, indicating the effect of phosphorus on secondary metabolism and antioxidant capacity. Overall, storage duration was the dominant factor influencing the structural and mechanical behavior of citron watermelon rind, whereas phosphorus fertilization primarily governed biochemical composition and antioxidant potential.

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Keywords: Citron watermelon; Rind biomass; Phosphorus fertilization; Storage duration; Mechanical properties; Phenolic compounds; Antioxidant capacity

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INTRODUCTION

The watermelon (*Citrullus lanatus* (Thunb.) Matsum. and Nakai) is a widely cultivated horticultural crop that is valued for its high water content and nutritional quality. However, the citron watermelon (*C. lanatus var. citroides*) differs markedly from the dessert type (*C. lanatus var*. *lanatus*) in that it has a firm rind, low-sugar flesh, and an exceptional storage capacity. This underutilized variety is traditionally used to make preserves and pickles, and it is also used as animal feed and as a potential raw material for biofuel production (Dumitru and Tutunea 2017; Ngwepe *et al*. 2019).

The citron watermelon has a long history of domestication. Archaeological findings suggest that it was cultivated over 4,000 years ago in Northeastern Africa. Previous studies

have provided an overview of the domestication process, emphasizing its early use in this region (Dane and Liu 2007). This species has substantial genetic diversity, making it a valuable resource for broadening the genetic base of cultivated watermelon and improving its tolerance to environmental stresses (Levi *et al*. 2002). Recent studies have demonstrated that *Citrullus lanatus var*. *citroides* is an effective rootstock due to its tolerance to drought, salinity, and temperature extremes. Such tolerance enhances the vigor and stability of grafted plants under adverse conditions (Suárez-Hernández *et al*. 2022; Coşkun *et al*. 2025). In addition to its tolerance of abiotic stresses, this taxon shows resistance to important biotic stresses, such as root-knot nematodes (*Meloidogyne* spp.), which are a major constraint in commercial watermelon production (Thies and Levi 2007).

Seed physiology contributes to the resilience of citron watermelon; seeds exhibit high germination capacity across a wide range of environmental conditions (Ramirez *et al*. 2014). Additionally, the seeds' high linoleic acid content and bioactive compounds make them suitable for use in edible oils, biodiesel, and functional foods, while vine fibers have shown potential as reinforcing materials for bio-composites (Dumitru and Tutunea 2017; Khan *et al*. 2022; Olubi *et al*. 2024).

Beyond its conventional uses, the rind of citron watermelon represents an underutilized agricultural byproduct with potential for utilization as a lignocellulosic bioresource. Plant peel tissues are characterized by an organized cell wall structure comprising pectin, cellulose, hemicellulose, and lignin, which together form a compact matrix influencing mass transfer and material disintegration during preprocessing (Mushtaq *et al*. 2014). In engineering-oriented studies, lignocellulosic matrices have been shown to govern mechanical resistance and processing behavior, emphasizing the need for mechanical characterization prior to material utilization (Ravichandran *et al*. 2025). Consequently, determining the physico-mechanical response of citron watermelon rind is essential for applications involving cutting, separation, and size reduction as preliminary steps in biomass valorization. Within this context, it is essential to understand the physical and mechanical properties of watermelons in order to design efficient harvesting, handling, storage, and processing systems (Yılmaz and Gökduman 2020; Jahun and Babajide 2024). Engineering parameters such as fruit dimensions, rind hardness, puncture and cutting forces, and rolling behavior directly affect harvesting efficiency, transport stability, and the retention of postharvest quality (Wang *et al*. 2024). Previous studies have shown that rind thickness and penetration resistance significantly impact the peeling performance and mechanical handling requirements of watermelons, underscoring the necessity of thorough mechanical characterization (Bande *et al*. 2012). Although the mechanical properties of dessert watermelon and other cucurbit species have been studied extensively, research focusing specifically on citron watermelon remains limited.

The processing behavior of many agricultural materials is largely influenced by moisture-dependent physical and mechanical properties. Studies on egusi melon and related cucurbits have shown that changes in moisture content substantially influence deformation behavior, frictional properties, density, and structural integrity. These parameters directly affect the design of equipment for cutting, peeling, conveying, and storage (Obi and Offorha 2015; Asoiro *et al*. 2018). Similar findings in other horticultural products show that mechanical responses, such as firmness, fracture behavior, and energy absorption, are closely linked to tissue moisture content and structural composition (Yılmaz and Gökduman 2014). Agronomic practices, including grafting and harvest timing, have also been shown to alter the composition and quality attributes of watermelon, demonstrating the close link between production conditions and postharvest behavior

(Tokgöz *et al*. 2015). Despite these insights, the combined effects of phosphorus fertilization and storage duration on the mechanical properties of citron watermelons have not yet been examined systematically. To date, no study has systematically quantified the interaction between phosphorus fertilization and storage-induced mechanical changes in citron watermelon. This lack of research limits the fruit's integration into postharvest engineering and processing applications.

Citron watermelon, although traditionally of limited use for direct human consumption, has attracted increasing attention in recent years due to its high biomass yield and rich biochemical composition, which make it suitable for alternative utilization pathways (Mandizvo *et al*. 2021). The flesh and rind of this species contain considerable amounts of bioactive compounds, including phenolic compounds, flavonoids, natural antioxidants, and structural carbohydrates, and their high fiber and moisture contents indicate a strong potential for use as roughage or feed additives in ruminant nutrition (Benmeziane and Derradji 2023). Antioxidant and phenolic compounds reported in members of the Cucurbitaceae family are known to contribute to functional effects in animal feeding, such as the mitigation of oxidative stress, improvement of digestive health, and enhancement of immune responses (Salehi *et al*. 2021). In particular, the utilization of citron watermelon rind, which is generated as an agricultural by-product during production and processing, represents an important opportunity for sustainable biomass management while simultaneously reducing feed costs in animal production systems (Ngwepe *et al*. 2019). In this context, the characterization of the biochemical properties of citron watermelon is of significant scientific importance for understanding its potential use as a functional feed ingredient in animal nutrition (Benmeziane and Derradji 2023).

Phosphorus is a key macronutrient involved in plant energy metabolism, root development, and fruit quality. Its effects on traits such as fruit size, weight, sugar content, and firmness have been demonstrated in several cucurbit and fruit species (Thies and Levi 2007; Ngwepe *et al*. 2019). However, no comprehensive studies have examined how phosphorus fertilization interacts with postharvest storage to affect the structural and mechanical properties of citron watermelon, such as puncture resistance, cutting force, and rolling behavior. Understanding these interactions is essential to optimizing postharvest systems, designing mechanical processing, and engineering applications for this underutilized crop.

Phosphorus is a key macronutrient that plays a vital role in cellular energy transfer and photosynthetic metabolism. It influences carbon assimilation and related metabolic processes by being involved in ATP synthesis and phosphorylation reactions (Malhotra *et al.* 2018; He *et al.* 2022). In cucurbit crops, phosphorus nutrition has been reported to affect the quality of fruits and the accumulation of antioxidant-related compounds, including phenolic compounds and pigments (Martuscelli *et al.* 2016). However, evidence of phosphorus's direct influence on rind physico-mechanical behavior remains limited. Thus, it is hypothesized that phosphorus fertilization would primarily affect the biochemical and antioxidant composition of citron watermelon tissues, while changes in rind physico-mechanical properties would mainly depend on postharvest storage duration rather than phosphorus nutrition.

This study is the first to integrate the effects of phosphorus fertilization and postharvest storage duration on the physico-mechanical behavior of the rind and the biochemical composition of the pulp in citron watermelon (*Citrullus lanatus* var. *citroides*). Unlike previous studies that examined fruit quality attributes or mechanical properties separately, this research integrates engineering-oriented mechanical

characterization (cutting and multi-diameter puncture responses) with biochemical assessments (total phenolic and flavonoid content, total antioxidant activity, and chlorophyll content) using a factorial experimental design. This approach provides quantitative reference data linking nutrient management and storage conditions to biomass processing performance and functional biochemical quality.

Therefore, this study evaluated the combined effects of five phosphorus doses (0, 4, 8, 12, and 16 kg da^{-1}, equivalent to 0, 40, 80, 120, and 160 kg ha^{-1}) and three storage durations (fresh, one month, and two months) on the physical and mechanical properties of citron watermelons. Parameters assessed included fruit weight, dimensional characteristics, rolling angles, color attributes, puncture resistance measured with 6-, 8-, and 12-mm probes, and cutting force measured with a standardized blade. The goal of this research was to generate mechanical data relevant to engineering to support storage planning and the development of efficient systems for cutting, peeling, separating, and reducing the size of citron watermelon rind as a bioresource.

EXPERIMENTAL

Material

The experiment was arranged using a randomized complete block design (RCBD) with three replications. The experiment was conducted from June to October 2024 in the Isparta Province, Türkiye. Climatic conditions during the growing period were characterized using meteorological data obtained from the Turkish State Meteorological Service (2024). Table 1 presents both long-term averages (1929 to 2024) and 2024 seasonal values to describe the environmental conditions under which the experiment was performed.

During the 2024 growing period, total precipitation (73.0 mm) was considerably lower than the long-term average (121 mm), while the mean air temperature (23.4 °C) was higher than the long-term average (19.9 °C). These relatively warm and dry conditions required supplemental drip irrigation to maintain adequate soil moisture and prevent water deficit stress.

Table 1. Climatic Characteristics of the Study Area (Isparta province, Türkiye) during the Growing Period (June–October) and Long-term Averages (1929–2024)

Month	Precipitation (mm) 1929–2024	Precipitation (mm) 2024	Temp. (°C) 1929–2024	Temp. (°C) 2024	Relative Humidity (%) 1929–2024	Relative Humidity (%) 2024
June	35.4	4.7	20.0	27.1	42.0	36.8
July	15.8	36.7	23.5	26.6	40.0	45.7
August	13.9	4.0	23.4	26.5	38.0	40.7
September	18.7	27.2	19.0	21.4	41.4	55.5
October	37.1	0.4	13.5	16.0	61.0	49.2
Total	**120.9**	**73.0**	—	—	—	—
Mean	—	—	**19.9**	**23.4**	**44.5**	**45.6**

In the experimental field, 16-mm polyethylene drip irrigation laterals equipped with inline emitters spaced at 20 cm intervals were installed along each row and used throughout the growing period. Water was applied at a constant rate of 4.05 mm h^{-1} (equivalent to 4.05 t da^{-1} h^{-1} or 40.5 m^3 ha^{-1} h^{-1}). Eleven irrigation events were performed between June 26 and September 26, 2024. The duration of each irrigation event ranged from 2 to 8 hours, depending on the crop's water requirements and soil moisture conditions. The total seasonal irrigation amount was 180.23 mm (equivalent to 180.23 t da^{-1} or 1,802.3 m^3 ha^{-1}). The highest single irrigation depth (28.35 mm; 28.35 t da^{-1}; 283.5 m^3 ha^{-1}) was applied on 8 July 2024 (7 h), whereas the lowest amount (10.13 mm; 10.13 t da^{-1}; 101.3 m^3 ha^{-1}) was applied on 2 August 2024 (2.5 h). Irrigation scheduling was adjusted according to soil moisture status to prevent water deficit and maintain optimal vegetative and reproductive development.

Within each block, five phosphorus (P) doses (0, 4, 8, 12, and 16 kg da^{-1}) were randomly assigned. Phosphorus was applied in the form of triple superphosphate (TSP; $Ca(H_2PO_4)_2 \cdot H_2O$, containing 43 to 44% P_2O_5). The fruits (Fig. 1) were harvested at physiological maturity and stored for three durations: Fresh (H1), one month (H2), and two months (H3), all under ambient conditions of 25 ± 2 °C and 55% to 60% relative humidity.

A total of 180 uniform fruits were used for postharvest analyses. For each combination of phosphorus dose and storage duration, 12 fruits were randomly sampled (n = 12), resulting in 5 × 3 × 12 = 180 experimental units. Each fruit served as an experimental unit in all analyses.

Fig. 1. Watermelon fruit (*Citrullus lanatus*) used in the experiment

For mechanical testing, fruits were subsampled from the original experimental units. For each storage duration (H1 to H3), fruits were proportionally selected from all phosphorus treatments to maintain the representation of the RCBD. Within each storage duration, fruits were randomly selected across phosphorus doses to avoid bias associated with fertilizer treatments.

Methods

Determination of moisture content

The moisture content of the citron watermelon rind was determined using the oven-drying method. Representative samples of the rind were cut into small pieces and weighed

to determine the initial mass. The samples were then dried in a forced-air oven at 105 ± 2 °C until they reached a constant weight. The moisture content was calculated on a wet basis (w.b.) as the percentage loss in mass relative to the initial sample weight. All measurements were performed in triplicate for each storage duration.

Determination of physical properties

The fruit's dimensions, including its length (L) and two perpendicular diameters (D_1 and D_2), were measured with a digital caliper with an accuracy of ±0.01 mm. The fruit's weight was determined using a high-precision electronic balance with a sensitivity of ±0.01 g.

The geometric mean diameter (D_g) and sphericity (Φ) were calculated using the following equations:

$$D_g = (L \times D_1 \times D_2)^{1/3} \quad (1)$$

$$\phi = \frac{D_g}{L} x(100) \quad (2)$$

In these equations, D_g is the geometric mean diameter (mm), L is the fruit length (mm), and D_1 and D_2 are the two perpendicular diameters (mm). These parameters offer a more complete picture of fruit shape and are often employed in agricultural engineering to assess suitability for mechanical handling and processing (Mohsenin 1986).

The fruit color was measured separately from the green and yellow regions of the rind. These regions were taken from opposite sides of the equatorial zone. The average of these readings was used in the statistical analysis. Measurements were performed using a Minolta CR-400 chromameter (Konica Minolta, Osaka, Japan). Color parameters were recorded as L^*, a^*, and b^* values according to the CIELab color space. In this space, L^* represents brightness (0 = black, 100 = white); a^* indicates the red–green axis (positive = red, negative = green); and b^* represents the yellow–blue axis (positive = yellow, negative = blue) (Doymaz 2015). Each measurement was performed in triplicate at each sampling location to ensure reliability.

Determination of rolling angle

The horizontal and vertical rolling angles of the fruits were measured using an adjustable inclined plane made of galvanized sheet metal. Individual fruits were placed on the plane, and the inclination was gradually increased until the fruit began to roll. A digital inclinometer with a precision of ±0.1° was used to record the angle at which each fruit began to roll.

Mechanical testing

Mechanical tests were performed using a Lloyd Instruments Plus Texture Analyzer (Bognor Regis, UK), which was equipped with a 500 N load cell (Fig. 2). Puncture tests were conducted using cylindrical probes with diameters of 6, 8, and 12 mm to characterize rind penetration behavior. Each fruit was tested at a constant probe speed of 3.3 mm s^{-1}. The probe was driven perpendicular to the rind until the puncture or failure point was reached, at which point the force-deformation curve ended.

Cutting tests were performed using a stainless-steel blade mounted on the texture analyzer. The blade had a straight cutting edge that was 2 mm thick. Tests were conducted at a constant crosshead speed of 4.2 mm s^{-1}. To ensure stable contact, each fruit was positioned on the test platform, and cutting was performed perpendicular to the rind surface

at the equatorial region of the fruit. The blade penetrated the rind until complete fracture occurred.

Force-deformation data were recorded continuously during both puncture and cutting tests using Nexygen Plus software (version 4.1). The following parameters were obtained from the force-deformation curves: Maximum force (N), deformation at maximum force (mm), work or energy (J), stiffness (N mm^{-1}), and load at break (N). This testing procedure follows the standard force-deformation methodology commonly used to characterize tissue firmness under controlled loading conditions (Aydın and Ögüt 1992; Marakoğlu *et al*. 2005; Yılmaz and Gökduman 2020).

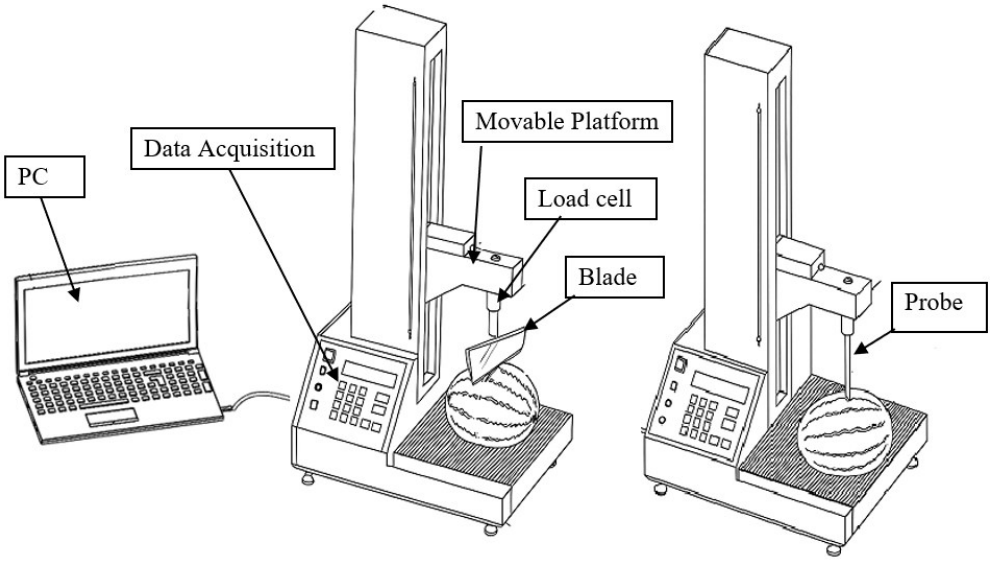

Fig. 2. Texture analyzer setup used for cutting and puncture tests

A total of 30 fruits were used for cutting tests, with a standardized cut applied to each fruit using a stainless-steel blade. For the puncture tests, 30 fruits were analyzed for each probe diameter (6, 8, and 12 mm), resulting in 90 puncture measurements in total. To avoid pseudo-replication, fruits used for cutting and puncture tests were selected independently from the overall sample pool, and each fruit was treated as a single experimental unit. Each fruit was treated as a single experimental unit in all mechanical tests. When multiple measurements were obtained from the same fruit, the mean value was used for statistical analysis.

For the cutting test, force-displacement curves were recorded continuously. Deformation (mm) was defined as the crosshead or blade displacement at the fracture point, which corresponded to the "extension at break" output provided by the Nexygen Plus software. Cutting stiffness (N mm^{-1}) was calculated as the slope of the linear elastic region of the force-displacement curve prior to fracture. Cutting work (J) was determined by numerically integrating the force-displacement curve up to the fracture point.

Determination of total phenolic content

Total phenolic content (TPC) was determined using the Folin–Ciocalteu reagent according to the method described by Singleton and Rossi (1965). Homogenized fruit puree was extracted in a solution of acetone, water, and acetic acid (70:29.5:0.5, v/v/v) for 1 h in test tubes. Following extraction, the Folin–Ciocalteu reagent was added to the extract and mixed with distilled water, and the mixture was allowed to stand for 8 min. Subsequently,

7% Na_2CO_3 solution was added. After incubation for 2 h, during which a bluish coloration developed, the absorbance of the solution was measured at 750 nm using a spectrophotometer. Total phenolic content was expressed as milligrams of gallic acid equivalents per gram of sample (mg GAE/ 100g).

Determination of total flavonoid content

Total flavonoid content (TFC) was determined following the method described by Jia *et al*. (1999). Briefly, 1 mL of each sample extract was mixed with 0.3 mL of 5% $NaNO_2$ solution and thoroughly vortexed. After 5 min of incubation, 0.3 mL of 10% $AlCl_3$ solution was added. The mixture was incubated for an additional 6 min, followed by the addition of 2 mL of 1 M NaOH and gentle mixing. After standing for 2 min, 4 mL of distilled water was added to the final mixture, and absorbance was measured at 510 nm using a spectrophotometer. Total flavonoid content was expressed as milligrams of catechin equivalents per 100 g of sample (mg catechin/100 g FW).

Determination of total antioxidant capacity

Total antioxidant capacity was determined using the DPPH (1,1-diphenyl-2-picrylhydrazyl) radical scavenging assay as described by Kumaran and Karunakaran (2006). Briefly, 2 g of each sample was homogenized in 20 mL of 80% ethanol and incubated at -20 °C for 2 h. The homogenate was then centrifuged at 2000 rpm for 5 min, and the supernatant was collected for analysis. An aliquot of 100 µL of the supernatant was mixed with 2 mL of 0.1 mM DPPH solution prepared in methanol. After incubation in the dark for 30 min, absorbance was measured at 517 nm against methanol as a blank. Total antioxidant capacity was expressed as percentage inhibition and as mg per 100 g of sample.

Determination of chlorophyll content

Chlorophyll content (mg/g FW) was determined according to the method described by Zhang and Huang (2013). Briefly, 0.1 g of fresh sample was homogenized in 100% N,N-dimethylformamide (DMF). The homogenate was centrifuged at 10,000 × g for 10 min, and the absorbance of the supernatant was measured at 664 and 647 nm using a spectrophotometer. Chlorophyll a, chlorophyll b, and total chlorophyll (a + b) contents were calculated using Eqs. 1-3 as proposed by Inskeep and Bloom (1985), as modified by Aono *et al*. (1993) and Sibley *et al*. (1996):

$$\text{Chlorophyll a} = 12.7 \times A_{664} - 2.79 \times A_{647} \quad (1)$$

$$\text{Chlorophyll b} = 20.7 \times A_{647} - 4.62 \times A_{664} \quad (2)$$

$$\text{Total chlorophyll (a + b)} = 17.90 \times A_{647} + 8.08 \times A_{664} \quad (3)$$

Statistical Analysis

All data were analyzed using SPSS software (version 26.0, IBM Corp., Armonk, NY, USA). The experiment was conducted using a randomized complete block design (RCBD), in which three blocks were treated as random effects and phosphorus dose (five levels) and storage duration (three levels) were considered fixed factors.

Initially, the data were analyzed using a two-way analysis of variance (ANOVA) within a general linear model (GLM). Phosphorus dose and storage duration were considered fixed factors, and block was considered a random effect. The main effects of phosphorus dose and storage duration, as well as their interaction (P × storage), were tested

for all measured parameters. A two-way ANOVA was appropriate because the experimental design involved two independent factors-phosphorus dose and storage duration-and their potential interaction. This allowed for the simultaneous evaluation of both the main effects and the interaction effect.

However, since the phosphorus dose and phosphorus-dose × storage-duration interaction were not statistically significant for any response variable ($P > 0.05$), the results are primarily presented with respect to storage duration to improve clarity and focus. However, the full factorial structure of the experiment was retained during statistical testing.

RESULTS AND DISCUSSION

A two-way ANOVA revealed that storage duration significantly affected several physico-mechanical properties. However, phosphorus dose and its interaction with storage duration were not significant for any measured parameter ($P > 0.05$). The moisture content of citron watermelon fruits declined progressively throughout the storage period. The initial moisture content of freshly harvested fruits was 96%, decreasing to 88% after one month and 80% after two months of ambient storage. This reduction is primarily attributed to water loss through transpiration and respiration during storage. Such a decline is typical of fleshy fruits kept under non-refrigerated conditions. Although all phosphorus treatments showed a similar downward trend, no statistically significant differences in moisture retention were observed among the fertilizer levels. Furthermore, moisture-dependent changes in physical and handling properties have been reported for melons and egusi seeds, where reductions in moisture content significantly influence bulk density, porosity, and other engineering parameters critical for postharvest operations (Bande *et al*. 2012; Obi and Offorha 2015; Jahun and Babajide 2024).

Fruit weight and dimensional characteristics

Phosphorus fertilization did not significantly affect fruit weight or dimensions ($P > 0.05$). Fruit weight ranged from 5,340 g (4 kg da^{-1}) to 7,490 g (0 kg da^{-1}), and fruit length ranged from 32.5 to 37.1 cm. There was no consistent trend in diameter values, and the geometric mean diameter ranged from 21.8 to 24.4 cm. Sphericity values (63.5% to 68.1%) indicated stable fruit morphology across phosphorus doses (Table 2).

Table 2. Effect of Phosphorus Doses on the Weight and Dimensions of Citron Watermelon Fruit

Phosphorus Dose (kg da^{-1})	Fruit Weight (g)	Length (cm)	Diameter-1 (cm)	Diameter-2 (cm)	Geometric Mean Diameter (cm)	Sphericity (%)
0	7487.72	37.11	19.50	20.11	24.41	65.79
4	5340.06	32.50	17.56	18.11	21.78	67.02
8	5879.39	35.41	18.11	17.75	22.49	63.53
12	5471.22	32.54	17.97	17.99	21.91	67.34
16	6925.83	35.33	19.50	20.17	24.04	68.05

The control treatment (0 kg da^{-1}) produced the heaviest fruit (7,490 g) and the largest geometric mean diameter (24.4 cm). The 4 kg da^{-1} treatment produced the lightest fruit. Although sphericity increased slightly with higher phosphorus doses, this trend was not statistically significant. According to Mohsenin (1986), these traits are important for mechanized handling and postharvest operations.

There was minor numerical variation in rolling angles across phosphorus treatments, with no statistically significant differences ($P > 0.05$) (Table 3). Horizontal rolling angles ranged from 8.72° to 10.78°, while vertical angles decreased slightly with increasing phosphorus doses, though there was no consistent trend. These results suggest that rolling behavior is primarily governed by intrinsic morphological traits rather than by the level of fertilization, which is consistent with previous reports on fruit geometry and mass distribution (Buyanov and Voronyuk 1985; Bahnasawy *et al*. 2004).

Table 3. Effects of Phosphorus Levels on Citron Watermelon Rolling Angles

Phosphorus Dose (kg da^{-1})	Horizontal Rolling Angle (°)	Vertical Rolling Angle (°)
0	10.78	17.67
4	9.33	17.67
8	8.72	17.33
12	9.44	16.56
16	10.0	15.33

The rolling angle is a critical parameter in designing sorting, grading, and conveyor-based handling systems. Fruits with lower rolling angles transition more readily between conveyor elements, rotate more easily on rollers, and maintain a predictable orientation during mechanical transport. These features enhance automation efficiency. Since the application of phosphorus did not significantly modify these geometric properties, the observed rolling behavior primarily reflects the natural structural symmetry of citron watermelon fruits. This stability in rolling response is advantageous for engineering applications because it indicates that fruits will consistently rotate the same way, regardless of field-level phosphorus management.

Color parameters (L^*, a^*, b^*, C^*, and $h°$) were not significantly affected by phosphorus doses (0 to 16 kg da^{-1}) at any storage duration ($P > 0.05$), suggesting that phosphorus fertilization did not impact rind color (Table 4).

Table 4. Interaction Effects of Phosphorus Doses (0 to 16 kg da^{-1}) and Storage Durations

Phosphorus Dose (kg da^{-1})	*L** (mean ± SD)	*a** (mean ± SD)	*b** (mean ± SD)	*C** (mean ± SD)	*h*° (mean ± SD)
H1 (fresh harvest)					
0	61.06 ± 2.87	-7.42 ± 1.17	25.70 ± 1.89	27.07 ± 1.92	106.33 ± 2.64
4	63.22 ± 1.15	-7.40 ± 1.26	27.93 ± 1.68	29.25 ± 1.67	105.00 ± 1.67
8	63.78 ± 2.48	-7.51 ± 2.21	27.77 ± 1.51	29.14 ± 1.98	105.50 ± 2.90
12	63.39 ± 2.58	-7.67 ± 1.05	27.35 ± 1.47	28.81 ± 1.48	105.80 ± 1.84
16	63.59 ± 2.62	-7.55 ± 1.79	26.80 ± 1.14	28.05 ± 1.13	103.42 ± 7.74
H2 (1 month)					
0	62.58 ± 4.47	-8.04 ± 1.91	29.03 ± 4.85	30.43 ± 4.45	105.99 ± 4.42
4	62.35 ± 5.58	-7.79 ± 1.49	29.11 ± 3.28	30.36 ± 2.91	105.17 ± 4.02
8	62.93 ± 5.32	-7.59 ± 2.47	29.87 ± 4.53	31.06 ± 4.24	104.64 ± 4.83
12	63.27 ± 4.83	-6.99 ± 3.41	30.39 ± 6.77	31.55 ± 6.21	104.06 ± 7.02
16	63.46 ± 3.68	-8.54 ± 1.36	27.83 ± 1.02	29.24 ± 1.21	106.97 ± 2.18
H3 (2 months)					
0	67.74 ± 3.35	-6.48 ± 2.25	31.20 ± 4.25	32.09 ± 3.85	101.96 ± 4.55
4	68.05 ± 3.35	-7.00 ± 2.17	32.24 ± 3.63	33.24 ± 3.35	102.54 ± 4.26
8	65.56 ± 3.78	-8.13 ± 1.45	29.25 ± 2.85	30.49 ± 2.85	105.24 ± 2.50
12	67.23 ± 2.05	-7.48 ± 1.24	30.02 ± 0.90	31.14 ± 0.68	103.70 ± 2.64
16	67.74 ± 3.35	-8.07 ± 1.01	29.38 ± 3.13	30.60 ± 3.02	105.47 ± 2.31

(H1 = Fresh, H2 = 1 month, H3 = 2 months) on rind; and color parameters (L, a, b*, C*, h°)

In contrast, storage duration produced clear and systematic changes in all color attributes. *L** values increased from H1 to H3, reflecting the rind surface's progressive lightning. Similarly, the *a** values became less negative with storage, indicating a reduction in green intensity. Meanwhile, the *b** and *C** values increased, demonstrating greater yellowness and chromaticity at later stages. The hue angle (*h*°) showed a slight decreasing trend from H1 to H3; however, these differences were not statistically significant ($P > 0.05$).

These results show that rind color development in citron watermelon was primarily governed by postharvest physiological changes associated with storage rather than phosphorus application. The observed color transitions (higher *L**, *a**, *b**, *C**, and lower h°) align with typical chlorophyll degradation and pigment conversion processes reported for Cucurbitaceae species during postharvest maturation.

In contrast, storage duration was found to have a significant influence, as summarized in Table 5.

Table 5. Effect of Storage Duration on Rind Color Parameters of Citron Watermelon

Storage Duration	*L** (mean±SD)	*a** (mean ± SD)	*b** (mean ± SD)	*C** (mean ± SD)	*h*° (mean ± SD)
H1 (Fresh)	62.99 ± 2.32^{b}	-7.50 ± 1.32^{a}	27.09 ± 1.58^{c}	28.44 ± 1.65^{c}	105.20 ± 3.59^{a}
H2 (1 month)	62.92 ± 4.12^{b}	-7.79 ± 1.98^{a}	29.22 ± 3.90^{a}	30.51 ± 3.59^{a}	105.37 ± 4.13^{a}
H3 (2 months)	66.45 ± 3.20^{a}	-7.43 ± 1.54^{a}	30.42 ± 2.77^{a}	31.51 ± 2.59^{a}	103.78 ± 3.09^{a}

**Different lowercase letters within the same column indicate statistically significant differences among storage durations according to Tukey's HSD test ($P \leq 0.05$).

The *L** values increased significantly with storage duration. Fruits stored for two months (H3) exhibited the highest lightness ($L^* = 66.45 \pm 3.20$, Group A), while H1 and H2 showed significantly lower values ($L^* = 62.99 \pm 2.32$ and $L^* = 62.92 \pm 4.12$, Group

B). This upward trend indicates progressive surface lightning during storage and is consistent with earlier reports suggesting that prolonged storage enhances lightness due to moisture loss, tissue dehydration, and chlorophyll degradation (Perkins-Veazie and Collins 2004; Ngwepe *et al*. 2019).

The *a** values remained negative throughout the storage period (from –7.8 to –7.4) and did not differ significantly among H1, H2, and H3 ($P > 0.05$). These results suggest that green tones persisted in the rind during storage. In contrast, both the *b** and *C** values increased markedly after storage. Fresh fruit (H1) exhibited the lowest *b** value (27.09 ± 1.58), while fruit stored for two months (H3) exhibited the highest value (30.42 ± 2.77). A similar increase was observed for chroma (*C**), rising from 28.44 ± 1.65 (H1) to 31.51 ± 2.59 (H3). These enhancements in yellowness and chromaticity reflect the development of stronger yellow tones and greater color saturation over time. Similar increases in *b** and *C** have been reported for dessert watermelons and are primarily associated with carotenoid accumulation and chlorophyll degradation during storage (Nagal *et al*. 2012).

The hue angle (*h*°) did not change significantly across storage durations (103.8° to 105.4°, $P > 0.05$), suggesting that the green-yellow balance of the rind remained consistent. This finding is consistent with previous observations that the hue angle is less sensitive to storage-related changes in chroma and lightness (Ali *et al*. 2017; Wang *et al*. 2024). Taken together, these results demonstrate that storage duration rather than phosphorus fertilization plays a primary role in influencing the color development of citron watermelon rinds. This has important implications for assessing postharvest quality and consumer acceptability.

Since phosphorus fertilization did not significantly impact any cutting-related parameters ($P > 0.05$), all evaluations were based solely on storage duration (Table 6). Cutting force increased from 294.95 ± 52.89 N at harvest (H1) to 318.88 ± 96.23 N after two months of storage (H3). H3 formed a statistically distinct group ($P \leq 0.05$). This increase indicates greater resistance to blade penetration following prolonged storage.

Table 6. Effect of Storage Duration on Cutting Properties of Citron Watermelon Rind

	Cutting Force (N)	Work (J)	Deformation (mm)	Stiffness (N mm^{-1})	Cutting Strength (N mm^{-2})
H1 (Fresh)	294.95±52.89^{b}	2.92±1.75^{a}	50.00±0.76^{b}	25.51±5.24^{a}	0.010±0.004^{a}
H2 (1month)	301.31±54.19^{b}	2.73±1.82^{a}	50.15±0.04^{b}	23.36±7.55^{a}	0.011±0.005^{a}
H3 (2 months)	318.88±96.23^{a}	2.81±1.50^{a}	62.19±9.83^{a}	26.21±6.00^{a}	0.012±0.004^{a}

*Different lowercase letters within the same column indicate statistically significant differences among storage durations according to Tukey's HSD test ($P \leq 0.05$).

The pronounced increase in deformation observed at H3 may be attributed to storage-related moisture loss, which reduces tissue turgor and alters textural and viscoelastic properties of fruit tissues (Gidado *et al*. 2024). Similar moisture-dependent mechanical responses involving an initial phase of moisture redistribution, followed by progressive moisture loss and increased structural rigidity, have been widely reported in cucurbit tissues and other biological materials (Eissa *et al*. 2010; Aremu *et al*. 2014; Satimehin and Akaayar 2017; Eboibi and Uguru 2018; Oyerinde *et al*. 2020). Comparable effects of moisture content on deformation behavior and penetration resistance have also been documented in chickpea and egusi melon seeds (Eissa *et al*. 2010; Satimehin and Akaayar 2017).

As shown in Table 6, work values (2.73 to 2.92 J) did not differ significantly, indicating stable overall energy requirements for cutting during storage. However, deformation increased markedly at H3 (62.19 ± 9.83 mm), reflecting greater displacement under blade loading.

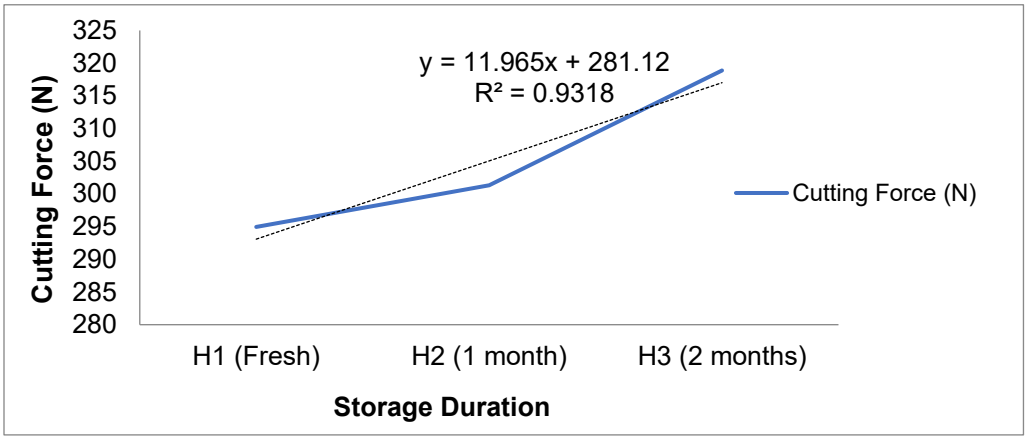

Fig. 3. Effect of storage duration on the cutting force of citron watermelon fruits

Meanwhile, stiffness and cutting strength remained statistically unchanged, demonstrating that fracture-related mechanical parameters were largely preserved. Consistent with these findings, cutting force increased linearly with storage duration (R^2 = 0.93; Fig. 3). From an engineering perspective, these quantified cutting force values serve as reference thresholds when designing blade geometry and slicing components. The higher cutting force required at H3 indicates that long-stored fruits require increased penetration loads, whereas fresh fruits can be processed with lower mechanical input, improving overall energy efficiency.

Puncture tests using 6-, 8-, and 12-mm probes revealed that phosphorus fertilization did not significantly impact any puncture-related parameter ($P > 0.05$). Consequently, the evaluation concentrated on storage duration. Penetration resistance was primarily determined by the intrinsic structure and thickness of the rind (Azman *et al*. 2024). Storage duration significantly affected deformation for the 6-mm probe, while puncture force, work, stiffness, and load at break did not differ ($P > 0.05$) (Table 7).

Table 7. Effect of Storage Duration on Mechanical Parameters of Citron Watermelon Rind (6 mm Probe)

	Puncture Force (N)	Work (J)	Deformation (mm)	Stiffness (N mm^{-1})	Load at Break (N)
H1 (Fresh)	152.56±22.04^a	0.84±0.30^a	33.98±13.94^a	28.52±11.26^a	87.17±22.80^a
H2 (1month)	145.65±17.58^a	0.83±0.31^a	23.39±8.75^b	27.38±8.76^a	78.71±25.67^a
H3 (2 months)	164.63±36.07^a	0.81±0.33^a	22.22±7.87^b	33.52±7.71^a	86.65±32.21^a

*Different lowercase letters within the same column indicate statistically significant differences among storage durations according to Tukey's HSD test ($P \leq 0.05$).

Puncture force values showed only slight numerical variation, ranging from 152.56 ± 22.04 N at harvest (H1) to 164.63 ± 36.07 N after two months of storage (H3). Conversely, deformation decreased markedly from 33.98 ± 13.94 mm at harvest (H1) to

22.22 ± 7.87 mm after two months of storage (H3), indicating reduced rind flexibility during prolonged storage. Similar patterns were observed for the 8-mm probe: deformation declined significantly with storage time, while puncture force, work, stiffness, and load-at-break values remained stable (Table 8).

Table 8. Effect of Storage Duration on Mechanical Parameters of Citron Watermelon Rind (8 mm Probe)

	Puncture Force (N)	Work (J)	Deformation (mm)	Stiffness (N mm^{-1})	Load at Break (N)
H1 (Fresh)	217.79 ± 32.83^{a}	1.81 ± 0.75^{a}	40.34 ± 19.12^{a}	19.13 ± 11.66^{a}	132.68 ± 38.97^{a}
H2 (1month)	200.75 ± 33.25^{a}	1.47 ± 0.60^{a}	26.29 ± 8.44^{b}	26.14 ± 9.18^{a}	102.32 ± 39.11^{a}
H3 (2 months)	240.78 ± 57.11^{a}	2.08 ± 1.36^{a}	27.45 ± 10.30^{b}	31.28 ± 10.63^{a}	135.99 ± 80.22^{a}

*Different lowercase letters within the same column indicate statistically significant differences among storage durations according to Tukey's HSD test ($P \leq 0.05$).

Deformation decreased significantly for the 8-mm probe from 40.34 ± 19.12 mm at harvest (H1) to 26.29 ± 8.44 mm and 27.45 ± 10.30 mm after one (H2) and two (H3) months of storage, respectively ($P \leq 0.05$). Meanwhile, puncture force (201 to 241 N), work, stiffness, and load-at-break values remained statistically unchanged.

For the 12-mm probe, storage duration significantly affected deformation and stiffness, though it did not impact puncture force, work, or load at break (Table 9). Deformation decreased from 44.39 ± 20.05 mm in freshly harvested fruit (H1) to 30.17 ± 6.43 mm after two months of storage (H3). However, stiffness only increased significantly at H3. These results suggest that prolonged storage primarily reduces the deformation capacity of citron watermelon rind while having a minimal effect on maximum penetration resistance.

Table 9. Effect of Storage Duration on Mechanical Parameters of Citron Watermelon Rind (12 mm Probe)

	Puncture Force (N)	Work (J)	Deformation (mm)	Stiffness (N mm^{-1})	Load at break (N)
H1 (Fresh)	342.31±55.85^{a}	4.41±1.47^{a}	44.39±20.05^{a}	33.71±10.29^{a}	196.91±81.20^{a}
H2 (1month)	339.35±58.61^{a}	4.17±1.41^{a}	32.81±10.49^{b}	34.35±12.32^{ab}	182.29±86.80^{a}
H3 (2 months)	340.75±45.29^{a}	3.98±0.92^{a}	30.17±6.43^{b}	36.09±8.27^{b}	182.97±91.01^{a}

*Different lowercase letters within the same column indicate statistically significant differences among storage durations according to Tukey's HSD test ($P \leq 0.05$).

The puncture force differed significantly with probe size ($P \leq 0.05$). The 12-mm probe consistently produced the highest forces, followed by the 8-mm and 6-mm probes. In contrast, storage duration caused only minor variations in puncture force, and there were no statistically significant differences among H1, H2, and H3 (Fig. 4). These results confirm that probe diameter, rather than storage duration, dominates in governing penetration resistance (Li *et al*. 2023).

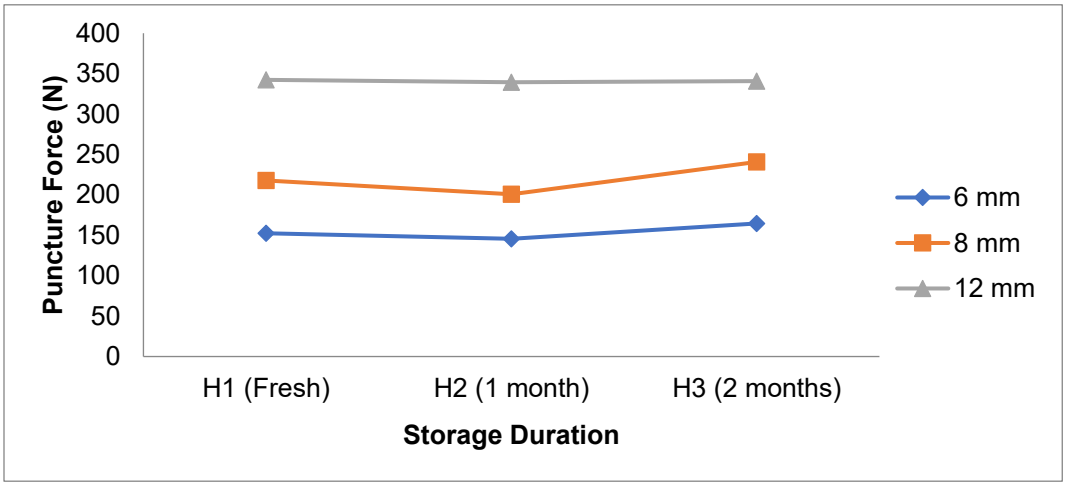

Fig. 4. Interaction effect of probe diameter (6, 8, and 12 mm) and storage duration (H1-H3) on puncture force of citron watermelon rind.

These results demonstrated that ambient storage primarily altered the viscoelastic response of citron watermelon rind by reducing its deformability. Meanwhile, penetration force and fracture-related properties remained largely stable. The quantified effects of probe diameter and deformation behavior provide practical reference values for designing cutting, peeling, and separation systems, as well as for defining allowable penetration forces in postharvest handling and processing equipment (Balasubramanian *et al*. 2012; Jahun and Babajide 2024).

A statistically significant and consistent increase in total phenolic content (TPC) and total flavonoid content (TFC), total antioxidant activity (TA), and chlorophyll content was observed with increasing phosphorus doses (Fig. 5). The lowest TPC and TFC values were recorded in the control treatment (0 kg/da), whereas a marked increase was evident particularly beyond the 8 kg/da phosphorus application, with the highest values obtained at 16 kg/da. This trend suggests that phosphorus stimulated the phenylpropanoid pathway, thereby promoting the biosynthesis of phenolic and flavonoid compounds. Considering the critical role of phenolic compounds in antioxidant defense, stress tolerance, and secondary metabolite production in plants, the observed enhancement in TPC and TFC indicates that increasing phosphorus doses strengthened the biochemical defense capacity of the plant. The consistent and significant increase observed in TPC and TFC with increasing phosphorus doses clearly demonstrated the stimulatory effect of this nutrient on secondary metabolism. Similarly, fertilization studies conducted on watermelon (*Citrullus lanatus*), melon (*Cucumis melo*), and other members of the Cucurbitaceae family have reported that moderate to high phosphorus applications enhance the accumulation of phenolic and flavonoid compounds (Martuscelli *et al*. 2016; He *et al*. 2022; Sekhar 2025). The central role of phosphorus in cellular energy metabolism (ATP, NADPH) indirectly promotes the activity of key enzymes associated with the phenylpropanoid pathway, such as phenylalanine ammonia-lyase (PAL), thereby stimulating the biosynthesis of phenolic compounds (Zhang and Liu 2015). In this context, the pronounced increase in TPC and TFC observed beyond the 12 and 16 kg/da phosphorus application suggests that the plant has entered a metabolically more active phase of secondary metabolite production. The reporting of similar trends across different plant species further supports the regulatory role of phosphorus in secondary metabolite synthesis (Shinde *et al*. 2024).

Total antioxidant activity (TA) values also exhibited an increasing trend in parallel with phosphorus doses. The lowest antioxidant activity was observed in control treatment, whereas the highest values were obtained under the 16 kg/da phosphorus application. The concomitant increase in TA values with rising TPC and TFC indicates that antioxidant capacity was largely derived from phenolic and flavonoid compounds. This finding suggests that phosphorus nutrition exerted a strong, albeit indirect, influence on mechanisms associated with oxidative stress. Phenolic and flavonoid compounds are known to play a critical role in antioxidant defense, stress tolerance, and adaptive mechanisms in plants (Kumar *et al*. 2023). Previous studies have reported that adequate phosphorus nutrition contributes to the suppression of oxidative stress in plants and limits cellular damage caused by reactive oxygen species (ROS) (Mohammadi vd. 2021). In the present study, the increase in total antioxidant activity (TA) in parallel with elevated TPC and TFC further confirms that antioxidant capacity is predominantly associated with phenolic and flavonoid compounds. Similarly, studies conducted on various vegetable and fruit species have demonstrated that phosphorus applications enhance antioxidant activity, an effect directly linked to the accumulation of secondary metabolites (Poiroux-Gonord *et al*. 2010; Swallah *et al*. 2020). The highest TA value recorded at the 16 kg/da phosphorus dose indicates that higher phosphorus levels strengthen the plant's capacity to cope with oxidative stress. Overall, these results highlight the indirect yet pronounced regulatory role of phosphorus nutrition in the antioxidant defense system of plants.

An evaluation of photosynthetic pigments revealed that chlorophyll a (Chl a), chlorophyll b (Chl b), and total chlorophyll (Chl a+b) contents increased in response to increasing phosphorus doses. Notably, a pronounced increase in Chl a and Chl a+b contents was observed under the 12 and 16 kg/da phosphorus applications. Considering the fundamental role of phosphorus in ATP synthesis, energy transfer, and chloroplast function, this increase is likely associated with enhanced photosynthetic activity. Although the increase in Chl b content was relatively limited, its consistent trend indicates that light-harvesting complexes responded positively to phosphorus application. From the perspective of photosynthetic pigments, the observed increases in Chl a, Chl b, and total (Chl a+b) further support the beneficial effect of phosphorus nutrition on photosynthetic capacity. Phosphorus plays a crucial role in chloroplast membrane integrity, energy transfer, and carbon fixation processes; accordingly, numerous studies have emphasized that adequate and balanced phosphorus supply promotes chlorophyll synthesis (Malhotra *et al*. 2018; Khan *et al*. 2023; Misra *et al*. 2024). The increases in Chl a and total Chl a+b contents recorded at the 12 and 16 kg/da phosphorus doses suggest improved photosystem efficiency and more effective utilization of light energy. The more limited yet stable increase in Chl b content indicates that light-harvesting complexes were sensitive to phosphorus nutrition and exhibit an adaptive response. These findings are consistent with previous reports demonstrating that phosphorus-enhanced photosynthetic pigment synthesis contributes to improved plant growth and increased biochemical production capacity (Zhang *et al*. 2025).

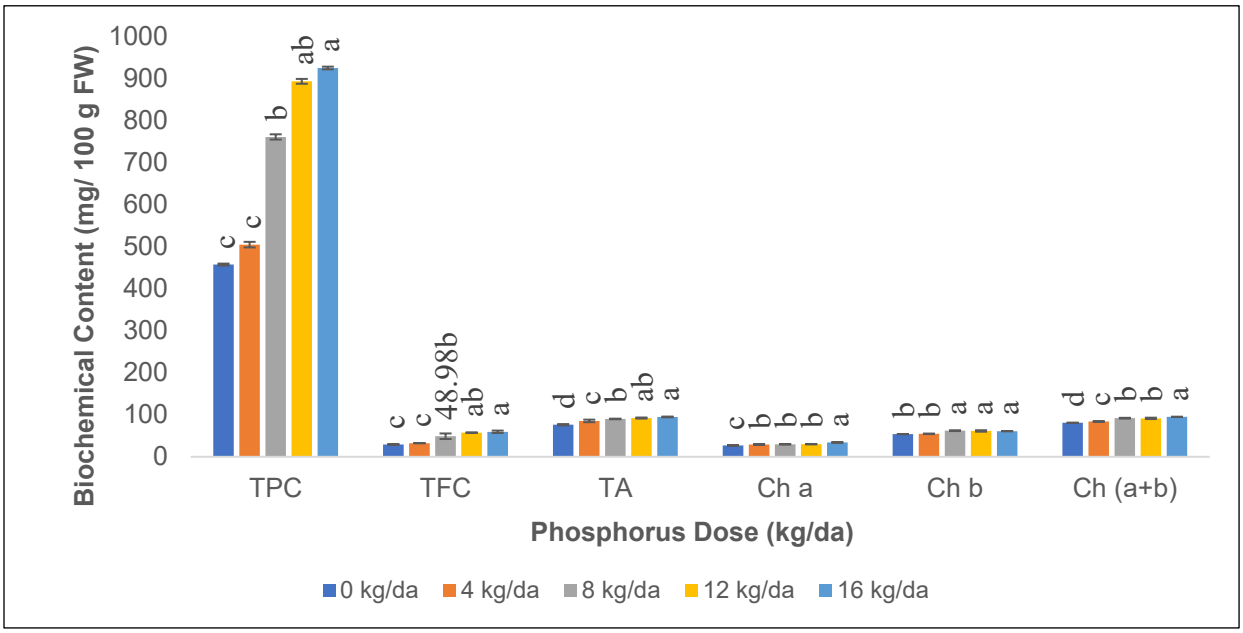

Fig. 5. Response of biochemical parameters of *C. lanatus* var. *citroides* to increasing phosphorus doses (TPC: Total phenolic content, TFC; Total flavonoid content, TA: Total antioxidant, Ch: Chlorophyll)

Future research should focus on evaluating controlled storage environments and integrating both mechanical behavior and biochemical stability data into predictive models for postharvest handling and processing equipment, with the aim of improving fruit quality retention and enhancing the utilization potential of this underexploited cucurbit species.

CONCLUSIONS

1. The results demonstrated that phosphorus fertilization (0 to 16 kg da) did not significantly affect the physico-mechanical properties of citron watermelon rind, indicating that this species was largely insensitive to phosphorus with respect to rind-related traits such as size, color attributes, firmness, and mechanical characteristics related to cutting and puncturing. In contrast, phosphorus application had a pronounced effect on biochemical composition, as increasing phosphorus doses significantly enhanced total phenolic content, total flavonoid content, total antioxidant activity, and chlorophyll (a, b, and a+b) levels. These findings suggest that phosphorus nutrition primarily regulates secondary metabolism and antioxidant potential rather than structural or mechanical properties of the rind tissue.

2. Storage duration, however, significantly influenced several quality-related physical and mechanical parameters. After two months of ambient storage, fruits exhibited reduced rind moisture content along with notable increases in L^*, b^*, and chroma values, which are consistent with pigment degradation and compositional changes commonly reported in watermelon fruits during postharvest storage. Storage also led to a significant reduction in deformation capacity, indicating alterations in tissue elasticity and viscoelastic behavior, although puncture force, work, and fracture-related properties remained statistically unchanged.

3. Overall, postharvest storage conditions exerted a stronger influence on the physical and mechanical properties of citron watermelon than phosphorus fertilization, whereas phosphorus application was the dominant factor affecting biochemical quality and antioxidant capacity.

4. Quantified parameters such as deformability, stiffness, puncture force, cutting energy, and antioxidant-related biochemical indices provide essential reference values for the design and optimization of cutting, peeling, handling, and processing systems in engineering applications. The preservation of fracture-related strength during storage further suggests that citron watermelon maintains sufficient rind integrity for long-distance transport and extended shelf life.

List of Abbreviations

ANOVA	Analysis of variance
*C**	Chroma
CIELAB	Commission Internationale de l'Éclairage Lab* color space
D_1, *D*	Perpendicular fruit diameters
D_g	Geometric mean diameter
H1	Fresh harvest (no storage)
H2	One month of storage
H3	Two months of storage
h°	Hue angle
*L**	Lightness
*a**	Red–green color coordinate
*b**	Yellow–blue color coordinate
N	Newton
P	Phosphorus
RCBD	Randomized complete block design
RH	Relative humidity
SD	Standard deviation
TA	Total antioxidant activity
TFC	Total flavonoid content
TPC	Total phenolic content
TPS	Triple superphosphate
Φ	Sphericity

REFERENCES CITED

Ali, M. M., Hashim, N., Bejo, S. K., and Shamsudin, R. (2017). "Quality evaluation of watermelon using laser-induced backscattering imaging during storage," *Postharvest Biology and Technology* 123, 51-59. https://doi.org/10.1016/j.postharvbio.2016.08.010

Aono, M., Kubo, A., Saji, H., Tanaka, K., and Kondo, N. (1993). "Enhanced tolerance to photooxidative stress of transgenic *Nicotiana tabacum* with high chloroplastic glutathione reductase activity," *Plant and Cell Physiology* 34(1), 129-135.

Aremu, A. K., Ademuwagun, A. A., and Ogunlade, C. A. (2014). "Effects of moisture content and loading orientation on some mechanical properties of the African oil bean seed (*Pentaclethra macrophylla* Benth.)," *African Journal of Agricultural Research* 9, 3504-3510.

Asoiro, F. U., Simeon, M. I., and Ezugwu, I. C. (2018). "Aerodynamic and thermal properties of melon (*Citrullus lanatus*) seeds under varying drying temperatures for separation from shells and processing," *Arid Zone Journal of Engineering, Technology and Environment* 14(SP.i4), 149-160.

Azman, W. M. F. B. W., Shahar, A., Azizan, S. A., and Rahim, A. A. (2024). "Physical and mechanical properties of watermelon rind," *Advances in Agricultural and Food Research Journal* 5(2), article a0000318. https://doi.org/10.36877/aafrj.a0000318

Bahnasawy, A. H., El-Haddad, Z. A., El-Ansary, M. Y., and Sorour, H. M. (2004). "Physical and mechanical properties of some Egyptian onion cultivars," *Journal of Food Engineering* 62, 255-261. https://doi.org/10.1016/S0260-8774(03)00238-3

Balasubramanian, S., Singh, K. K., and Kumar, R. (2012). "Physical properties of coriander seeds at different moisture contents," *International Agrophysics* 26(4), 419-425. https://doi.org/10.2478/v10247-012-0059-x

Bande, Y. M., Adam, N. M., Azmi, Y., and Jamarei, O. (2012). "Variation of physical properties of egusi melon (*Citrullus colocynthis* L.) seeds and kernels with moisture content," *International Journal of Basic and Applied Sciences* 12, 65-74.

Benmeziane, F., and Derradji. (2023). "Composition, bioactive potential and food applications of watermelon (*Citrullus lanatus*) seeds – A review," *Journal of Food Measurement and Characterization* 17(5), 5045-5061. https://doi.org/10.1007/s11694-023-02012-5

Buyanov, A. I., and Voronyuk, B. A. (1985). *Physical and Mechanical Properties of Plants, Fertilizers and Soils*. Amerind Publishing Co., New Delhi, India, pp. 15-97.

Coşkun, Ö. F., Toprak, S., and Mavi, K. (2025). "Genetic diversity and association mapping for salinity tolerance in watermelon (*Citrullus lanatus* L.)," *Journal of Crop Health* 77(2), article 01141. https://doi.org/10.1007/s10343-025-01141-9

Dane, F., and Liu, J. (2007). "Diversity and origin of cultivated and citron type watermelon (*Citrullus lanatus*)," *Genetic Resources and Crop Evolution* 54, 1255-1265. https://doi.org/10.1007/s10722-006-9107-3

Doymaz, İ. (2015). "Infrared drying kinetics and quality characteristics of carrot slices," *Journal of Food Processing and Preservation* 39, 2738-2745. https://doi.org/10.1111/jfpp.12524

Dumitru, M. G., and Tutunea, D. (2017). "Extraction and determination of physico-chemical properties of oil from watermelon seeds (*Citrullus lanatus* L.) for use in internal combustion engines," *Revista de Chimie* 68, 2676-2681. https://doi.org/10.37358/RC.17.11.5952

Eboibi, O., and Uguru, H. (2018). "Effect of moisture content on the mechanical properties of cucumber fruit," *International Journal of Scientific and Engineering Research* 9, 671-678.

Eissa, A. H. A., Mohamed, M. A., Moustafa, H., and Alghannam, A. R. O. (2010). "Moisture-dependent physical and mechanical properties of chickpea seeds," *International Journal of Agricultural and Biological Engineering* 3, 80-93.

Gidado, M. J., Gunny, A. A. N., Gopinath, S. C., Ali, A., Wongs-Aree, C., and Salleh, N. H. M. (2024). "Challenges of postharvest water loss in fruits: Mechanisms, influencing factors, and effective control strategies – A comprehensive review," *Journal of Agriculture and Food Research* 17, article 101249. https://doi.org/10.1016/j.jafr.2024.101249

He, S., Zhao, Y., Liu, C., Li, Z., Zhang, Z., Li, B., and Tang, X. (2022). "An exploration into the relationship between mineral elements (nitrogen and phosphorus) and nutritional quality in soil-watermelon (*Citrullus lanatus*) system," *Journal of Analytical Science and Technology* 13(1), article 48. https://doi.org/10.1186/s40543-022-00357-y

Inskeep, W. P., and Bloom, P. R. (1985). "Extinction coefficients of chlorophyll a and b in N, N-dimethylformamide and 80% acetone," *Plant Physiology* 77(2), 483-485. https://doi.org/10.1104/pp.77.2.483

Jahun, R. F., and Babajide, T. U. (2024). "Comparative investigation of some engineering properties of melon seed varieties in Nigeria (*Citrullus lanatus* Bara and Serewe)," *Nigerian Defense Academy Journal of Military Science and Interdisciplinary Studies* 2, 22-28.

Jia, Z.-S., Tang, M.-C., and Wu, J.-M. (1999). "The determination of flavonoid contents in mulberry and their scavenging effects on superoxide radicals," *Food Chemistry* 64 (4), 555-559. https://doi.org/10.1016/S0308-8146(98)00102-2

Khan, A., Vijay, R., Singaravelu, D. L., Sanjay, M. R., Siengchin, S., and Jawaid, M. (2022). "Extraction and characterization of natural fibers from *Citrullus lanatus* climber," *Journal of Natural Fibers* 19, 621-629. https://doi.org/10.1080/15440478.2020.1758281

Kumar, K., Debnath, P., Singh, S., and Kumar, N. (2023). "An overview of plant phenolics and their involvement in abiotic stress tolerance," *Stresses* 3(3), 570-585. https://doi.org/10.3390/stresses3030040

Kumaran, A., Joel Karunakaran, R. (2006). "Antioxidant activities of the methanol extract of *Cardiospermum halicacabum*," *Pharmaceutical Biology* 44 (2), 146-151. https://doi.org/10.1080/13880200600596302

Levi, A., Thomas, C., Joobeur, T., Zhang, X., and Davis, A. (2002). "A genetic linkage map for watermelon derived from a testcross population (*Citrullus lanatus* var. *citroides* × *C. lanatus* var. *lanatus*) × *Citrullus colocynthis*," *Theoretical and Applied Genetics* 105, 555-563. https://doi.org/10.1007/s00122-001-0860-6

Li, M., He, L., Yue, D., Wang, B., and Li, J. (2023). "Fracture mechanism and separation conditions of pineapple fruit-stem and calibration of physical characteristic parameters," *International Journal of Agricultural and Biological Engineering* 16, 248-259. https://doi.org/10.25165/j.ijabe.20231605.8079

Malhotra, H., Vandana, Sharma, S., and Pandey, R. (2018). "Phosphorus nutrition: plant growth in response to deficiency and excess," in: *Plant Nutrients and Abiotic Stress Tolerance*, pp. 171-190. Springer, Singapore. https://doi.org/10.1007/978-981-10-9044-8_7

Mandizvo, T., Odindo, A. O., and Mashilo, J. (2021). "Citron watermelon potential to improve crop diversification and reduce negative impacts of climate change," *Sustainability* 13(4), article 2269. https://doi.org/10.3390/su13042269

Marakoğlu, T., Arslan, D., and Özcan, M. (2005). "Proximate composition and technological properties of fresh blackthorn (*Prunus spinosa* L. subsp. *dasyphylla*) fruits," *Journal of Food Engineering* 68, 137-142. https://doi.org/10.1016/j.jfoodeng.2004.05.024

Martuscelli, M., Di Mattia, C., Stagnari, F., Speca, S., Pisante, M., and Mastrocola, D. (2016)." Influence of phosphorus management on melon (*Cucumis melo* L.) fruit quality," *Journal of the Science of Food and Agriculture* 96(8), 2715-2722. https://doi.org/10.1002/jsfa.7390

Mohammadi, M. A., Cheng, Y., Aslam, M., Jakada, B. H., Wai, M. H., Ye, K., and Qin, Y. (2021). "ROS and oxidative response systems in plants under biotic and abiotic stresses: revisiting the crucial role of phosphite triggered plants defense response," *Frontiers in Microbiology*, 12, article 631318. https://doi.org/10.3389/fmicb.2021.631318

Mohsenin, N. N. (1986). *Physical Properties of Plant and Animal Materials*. Gordon and Breach Science Publishers, New York, USA.

Mushtaq, M., Sultana, B., Bhatti, H. N., and Asgher, M. (2014). "Optimization of enzyme-assisted revalorization of sweet lime (*Citrus limetta* Risso) peel into phenolic antioxidants," *BioResources* 9(4), 6153-6165. https://doi.org/10.15376/biores.9.4. 6153-6165

Nagal, S., Kaur, C., Choudhary, H., Singh, J., Singh, B. B., and Singh, K. N. (2012). "Lycopene content, antioxidant capacity and colour attributes of selected watermelon (*Citrullus lanatus*) cultivars grown in India," *International Journal of Food Sciences and Nutrition* 63, 996-1000. https://doi.org/10.3109/09637486.2012.694848

Ngwepe, R. M., Mashilo, J., and Shimelis, H. (2019). "Progress in genetic improvement of citron watermelon (*Citrullus lanatus* var. *citroides*): A review," *Genetic Resources and Crop Evolution* 66, 735-758. https://doi.org/10.1007/s10722-018-0724-4

Obi, O. F., and Offorha, L. C. (2015). "Moisture-dependent physical properties of melon (*Citrullus colocynthis*) seed and kernel relevant in bulk handling," *Cogent Food and Agriculture* 1(1), article 1020743. https://doi.org/10.1080/23311932.2015.1020743

Olubi, O., Felix-Minnaar, J., and Jideani, V. A. (2024). "Nutritional profiling of underutilised *Citrullus lanatus* mucosospermus seed flour," *Applied Sciences* 14, article 3709. https://doi.org/10.3390/app14093709

Oyerinde, A. S., Sedara, A. M., Oladimeji, S. T., Ezenwogene, R. C., Akinsanya, O. M., and Ogunlade, C. A. (2020). "Mechanical properties of two varieties of melon (*Colocynthis citrullus*)," *New York Science Journal* 13, 33-42.

Perkins-Veazie, P., and Collins, J. K. (2004). "Flesh quality and lycopene stability of fresh-cut watermelon," *Postharvest Biology and Technology* 31, 159-166. https://doi.org/10.1016/j.postharvbio.2003.08.005

Ramirez, A. H. M., Jhala, A. J., and Singh, M. (2014). "Factors affecting germination of citronmelon (*Citrullus lanatus* var. *citroides*)," *Weed Science* 62, 45-50. https://doi.org/10.1614/WS-D-13-00041.1

Ravichandran, G., Ramasamy, K., Kalidas, S., Jayamani, M., Mausam, K., Palanisamy, S., Ma, Q., and Al-Farraj, S. A. (2025). "Effect of sal wood and babool sawdust fillers on the mechanical properties of snake grass fiber-reinforced polyester composites," *BioResources* 20(4), 8674-8694. https://doi.org/10.15376/biores.20.4. 8674-894

Salehi, B., Quispe, C., Sharifi-Rad, J., Giri, L., Suyal, R., Jugran, A. K., Zucca, P., Rescigno, A., Peddio, S., Bobis, O. *et al*. (2021). "Antioxidant potential of family Cucurbitaceae with special emphasis on *Cucurbita* genus: A key to alleviate oxidative stress-mediated disorders," *Phytotherapy Research* 35(7), 3533-3557. https://doi.org/10.1002/ptr.7045

Satimehin, A. A., and Akaayar, M. (2017). "Determination of selected moisture-dependent physical and frictional properties of shelled egusi melon (*Citrullus lanatus*)," *FUOYE Journal of Engineering and Technology* 2(1), 1-6. https://doi.org/10.46792/fuoyejet.v2i1.112

Sekhar, V. (2025). "Maximizing watermelon (*Citrullus lanatus* Thunb.) growth, yield and quality through synergistic use of biofertilizers and inorganic nutrients," *Plant Archives* 25(1), 2264-2274. https://doi.org/10.51470/PLANTARCHIVES.2025.v25.supplement-1.312

Shinde, M., Khan, V., Umar, S., and Iqbal, N. (2024). "Salicylic acid with phosphorus strengthens antioxidative system, secondary metabolite accumulation, and limited resource enrichment to enhance photosynthesis under drought in mustard," *Journal of Soil Science and Plant Nutrition* 24(1), 956-974. https://doi.org/10.1007/s42729-023-01599-4

Singleton, V. L., and Rossi, J. A. (1965). "Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents," *American Journal of Enology and Viticulture* 16 (3), 144-158. https://doi.org/10.5344/ajev.1965.16.3.144

Suárez-Hernández, A. M., Grimaldo-Juárez, O., Ceceña-Durán, C., Vázquez-Angulo, J. C., Carrazco-Peña, L. D., and Avendaño-Reyes, L. (2022). "Influence of seed and fruit characteristics of *Lagenaria siceraria* on production and quality of grafted watermelon," *Horticulturae* 8, article 242. https://doi.org/10.3390/horticulturae8030242

Swallah, M. S., Sun, H., Affoh, R., Fu, H., and Yu, H. (2020). "Antioxidant potential overviews of secondary metabolites (polyphenols) in fruits," *International Journal of Food Science* 2020(1), article 9081686. https://doi.org/10.1155/2020/9081686

Thies, J. A., and Levi, A. (2007). "Characterization of watermelon (*Citrullus lanatus* var. *citroides*) germplasm for resistance to root-knot nematodes," *HortScience* 42, 1530-1533. https://doi.org/10.21273/HORTSCI.42.7.1530

Tokgöz, H., Gölükcü, M., Toker, R., and Turgut, D. Y. (2015). "Effects of grafting and harvesting time on some physical and chemical parameters of watermelon (*Citrullus lanatus*)," *GIDA* 40, 263-270. https://doi.org/10.15237/gida.GD15011

Turkish State Meteorological Service (2024). "Climatic data for Isparta province (June-October 2024)," Ministry of Environment, Urbanization and Climate Change, Ankara, Türkiye

Wang, H., Cui, J., Bao, R., Zhang, H., Zhao, Z., and Chen, X. (2024). "Research progress on the effects of postharvest storage methods on melon quality," *PeerJ* 12, article e17800. https://doi.org/10.7717/peerj.17800

Yılmaz, D., and Gökduman, M. E. (2014). "Physical-mechanical properties of *Origanum onites* at different moisture contents," *Journal of Essential Oil Bearing Plants* 17, 1023-1033. https://doi.org/10.1080/0972060X.2014.890082

Yilmaz, D., and Gokduman, M. E. (2020). "Effects of different harvesting times on physico-mechanical properties of sour cherry (*Prunus cerasus* L.)," *Erwerbs-Obstbau* 62, 335-340. https://doi.org/10.1007/s10341-020-00506-w

Zhang, X., and Liu, C. J. (2015). "Multifaceted regulations of gateway enzyme phenylalanine ammonia-lyase in the biosynthesis of phenylpropanoids," *Molecular Plant* 8(1), 17-27. https://doi.org/10.1016/j.molp.2014.11.001

Zhang, Y., Li, Y., Liu, J., Duan, J., He, L., Hou, G., Wang, Y., Feng, W., Wang, C., and Guo, T. (2025). "Phosphorus application enhances floret development and grain formation, stabilizing wheat yield under drought stress through improved photosynthetic performance and nutrient accumulation," *Journal of Integrative Agriculture* 2025, article 38. https://doi.org/10.1016/j.jia.2025.11.038

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