Physical and Chemical Properties of Watermelon: A Comprehensive Review

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Abstract

Watermelon (Citrullus lanatus) is one of the world's most widely cultivated and consumed cucurbit crops, valued not only for its refreshing taste and high water content but also for its diverse nutritional and functional attributes. This review paper systematically examines the physical, morphological, chemical, and mechanical properties of watermelon, encompassing its fruit, flesh, rind, and seeds. Physical characterization of fruit reveals wide genotypic variation in weight (0.11–9.32 kg), diameter (5.5–27.8 cm), rind thickness (0.1–2.8 cm), soluble solids content (3.9-13.2%), and CIE L*a*b* flesh colour parameters. Seed engineering properties including geometric mean diameter, sphericity, bulk and true density, porosity, terminal velocity, and rupture force-are significantly influenced by moisture content and variety. Chemical composition analysis demonstrates that watermelon flesh is predominantly water (93–95%), with the rind being a comparatively richer source of carbohydrates, vitamin C, and dietary fibre. The mineral profile reveals iron as the most abundant element in the pulp, followed by magnesium, potassium, calcium, sodium, and zinc. Bioactive constituents, notably lycopene, beta-carotene, citrulline, and ascorbic acid, confer antioxidant, cardioprotective, and anti-inflammatory properties. Mechanical characterization of the flesh shows non-elastic, visco-plastic behaviour under static loading, with a Poisson's ratio far exceeding unity, highlighting its complex cellular architecture. These findings collectively underscore the multidimensional value of watermelon and its by-products-rind and seed-as underutilized sources of nutrition, nutraceuticals, and industrial raw materials. The review provides a consolidated scientific resource for researchers, food technologists, and agricultural engineers involved in watermelon processing, utilization, and value addition

Keywords: Citrullus lanatus, watermelon, physical properties, chemical composition, lycopene, citrulline, seed engineering, rind nutrition.

1. Introduction

Watermelon (Citrullus lanatus) is a major fruit crop within the Cucurbitaceae family, which also includes cucumber, melon, and squash (Dube et al.,2021). It is primarily cultivated in tropical and subtropical climates, where the plant grows as a trailing annual vine producing monoecious or andromonoecious flowers. The fruit comprises a firm rind, fleshy pulp, and seeds, with flesh colour ranging from pale yellow and orange to deep red depending on the cultivar (Bahari et al., 2012; Munisse et al., 2013). Nutritionally, watermelon is recognized for its abundance of vitamins A, B, C, and E, as well as minerals such as calcium, phosphorus, magnesium, and iron Bioactive compounds including lycopene, β-carotene, citrulline, and polyphenols enhance its antioxidant activity and contribute to protective roles against cardiovascular diseases, cancer, and oxidative stress (Edwards et al., 2003; Perkins-Veazie et al., 2007). Lycopene concentration in red-fleshed watermelon is reported to exceed that of tomato, with high bioavailability in humans (Edwards et al., 2003; Barnes et al., 2019). Flesh pigmentation is largely due to lycopene (red) and β-carotene (orange), while sweetness is derived from sugars such as sucrose, glucose, and fructose.

Beyond basic nutrition, watermelon is a source of functional compounds. Citrulline, a non-essential amino acid found in high concentration in the rind and flesh, plays a role in nitric oxide metabolism, thereby improving vascular function and reducing blood pressure (Gu et al., 2023; Song, 2020). Lycopene, a carotenoid pigment, has been extensively studied for its role in reducing oxidative stress and lowering the risk of prostate cancer (Edwards et al., 2003; Barnes et al., 2019). These biochemical properties make watermelon not only a refreshing fruit but also a candidate for nutraceutical development. Watermelon is consumed in multiple forms-fresh slices, fruit blends, beverages, candied rind, and edible seeds from specialized cultivars (Wehner, 2008). Processing yields approximately 55.3% juice, 31.5% rind, and 10.4% pomace (Oberoi & Sogi, 2017). While pulp and juice are widely utilized, seeds and rind are often discarded despite their nutritional potential. Seeds are rich in proteins and lipids, making them suitable for oil extraction and pharmaceutical applications. The rind, containing dietary fiber, can be processed into flour or candied products. Thus, watermelon is not only a refreshing fruit but also a source of raw material for value-added products.

Globally, watermelon production is estimated at nearly 29.6 million tonnes annually, contributing significantly to agricultural economies (Masih et al., 2021). In India, cultivation supports rural livelihoods and supplies raw material for food, cosmetic, and pharmaceutical industries.Globally, watermelon is among the most extensively consumed cucurbit crops, with China, Turkey, India and Brazil being the leading producers. In India, watermelon was cultivated on approximately 110 thousand hectares during 2021–2022, with a total production of about 3,225 thousand tonnes (Jagadeesh S. et al., 2024). Uttar Pradesh and Andhra Pradesh are the major watermelon-producing states, contributing significantly to national production. Owing to its high-water content and rich nutritional profile, watermelon plays an important role in human hydration, health and dietary intake, while also holding substantial economic importance in horticultural production systems.

Seeds are increasingly used for oil extraction and cosmetic formulations due to their protein and lipid content. The fruit provides essential nutrients such as vitamins A and C, linked to skin health and vision. Seed minerals may also aid in reducing harmful cholesterol and improving nutritional quality. Consumption of watermelon is associated with hydration, cardiovascular benefits, reduced oxidative stress, and potential protection against certain cancers. Ancient scholars such as Hippocrates and Dioscorides described its cooling and diuretic properties, underscoring its medicinal relevance. With ~93% water content and low levels of fat, sodium, and cholesterol, watermelon is considered ideal for hydration, functional food development, and healthy diets. Despite these benefits, utilization remains limited, as rind (about 30%) and seeds (around 2%) are often discarded. Both components, however, are rich in fiber, protein, fats, and minerals, and can be processed into flour, oil, and other value-added products (Oberoi & Sogi, 2017). Beyond nutritional and economic importance, watermelon also plays a role in cultural traditions and local economies. In many regions, watermelon festivals celebrate the fruit's harvest season, promoting agritourism and rural development. In traditional medicine, watermelon rind and seeds have been used for their cooling, diuretic, and anti-inflammatory properties. Modern research is now validating these uses, linking citrulline and lycopene to improved vascular function and reduced oxidative damage (Gu et al., 2023). Furthermore, watermelon's high-water content makes it an essential fruit in arid and semi-arid regions, where it serves as a natural source of hydration.

2.Physical and Morphological Properties of watermelon

Watermelon (Citrullus lanatus) exhibits considerable variation in its physical and morphological characteristics depending upon genotype and growing conditions. Coskun and Gulsen (2024) studied 96 watermelon genotypes and reported significant diversity in fruit size, shape, texture, and seed parameters.

The average fruit weight was 3.5 ± 0.06 kg, ranging from 0.11 kg to 9.32 kg. Fruit diameter and height averaged 18.4 ± 0.12 cm and 19 ± 0.14 cm, respectively. Rind thickness varied from 0.1 cm to 2.8 cm (mean 1.25 ± 0.02 cm). Fruit firmness showed a wide range (0.26-6.85 g) with a mean of 0.94 ± 0.02 g. Flesh colour parameters also displayed large variation using the CIE L∗a∗b∗ system. Seed characteristics were equally diverse. The number of seeds per fruit ranged from 65 to 935. (Coskun & Gulsen, 2024)

Table 1. Physical and pomological properties of watermelon fruits (Coskun & Gulsen, 2024)

Parameter	**Mean ± SE**	**Range**	**Unit**
Fruit Weight	3.5 ± 0.06	0.11 – 9.32	Kg
Fruit Diameter	18.4 ± 0.12	5.5 – 27.8	Cm
Fruit Height	19 ± 0.14	3.0 – 38.6	Cm
Rind Thickness	1.25 ± 0.02	0.1 – 2.8	Cm
Fruit Hardness	0.94 ± 0.02	0.26 – 6.85	G
Soluble Solids Content (SSC)	7.63 ± 0.07	3.9 – 13.2	%

Table 2. Fruit flesh colour and seed physical properties (Coskun & Gulsen, 2024)

Parameter	**Mean ± SE**	**Range**	**Unit**
Flesh Colour - L∗ L^* L∗	48.38 ± 0.42	9.37 – 94.85	-
Flesh Colour - a∗ a^* a∗	19.11 ± 0.49	−34.16 – 70.3	-
Flesh Colour - b∗ b^* b∗	2.52 ± 0.06	1.14 – 7.83	-
Seeds per Fruit	391.7 ± 8.5	65 – 935	seeds/fruit
Seed Length	12.88 ± 0.06	7.83 – 16.15	mm

Parameter	Mean ± SE	Range	Unit
Seed Width	6.7 ± 0.03	3.03 – 9.74	mm
Seed Thickness	2.61 ± 0.01	1.71 – 3.78	mm
100-Seed Weight	13.24 ± 0.19	4.13 – 21.16	g

The physical characteristics of watermelon, particularly the rind, play a crucial role in determining suitable parameters for mechanical peeling operations. In a study conducted on seedless F1 Hybrid watermelon, several key measurements were recorded to better understand the fruit's structure.The average rind thickness was found to be 1.46 ± 0.27 cm, ranging between 0.90 cm and 2.30 cm. Interestingly, the thickness did not follow any consistent pattern across different positions on the fruit. However, a clear positive relationship was observed between rind thickness and overall fruit size. Larger and heavier fruits tended to have thicker rinds, as evidenced by significant positive correlations with fruit weight, circumference, and diameter.The detailed physical properties of the F1 Hybrid watermelon used in the study are presented in Table 2. (Azman,.et al 2024)

Table 2. Physical properties of F1 Hybrid seedless watermelon (mean ± standard deviation).

Parameter	Value
Rind thickness (cm)	1.46 ± 0.27
Weight (kg)	6.75 ± 1.51
Circumference (cm)	69.39 ± 4.62
Length (cm)	27.33 ± 3.54
Diameter (cm)	20.96 ± 3.55

The study also determined that the rind-to-flesh ratio was approximately 49:100, while the flesh recovery stood at 60.83 ± 9.49%. Moisture analysis revealed notable differences between the outer green skin (89.31 ± 2.21%) and the inner white rind (94.83 ± 1.02%). This high moisture level in the white portion of the rind has important implications for its mechanical strength and behaviour during peeling.

2.1 Physical Properties of Watermelon Seeds

The physical characteristics of watermelon seeds are essential for agricultural engineering, particularly in the design of sowing, harvesting, processing, and storage equipment. These properties are strongly influenced by moisture content, which alters seed dimensions, density, porosity, and mechanical strength. At 6% dry basis moisture, the average seed length, width, and thickness were 10.8 mm, 6.8 mm, and 2.3 mm, respectively, with a geometric mean diameter of 5.5 mm and sphericity of 51.5% (Mohsenin, 1970). The 1000 seed weight was 94.10 g, and average seed volume was 0.13 cm^3. Bulk density decreased from 446.4 to 417.68 kg/m^3 as moisture increased, while true density rose from 639 to 732 kg/m^3, reflecting swelling and water absorption within seed tissues (Gupta & Das, 1997). Porosity increased from 30.79% to 45.46%, indicating greater void space between seeds at higher moisture levels (Paksoy & Aydın, 2004).

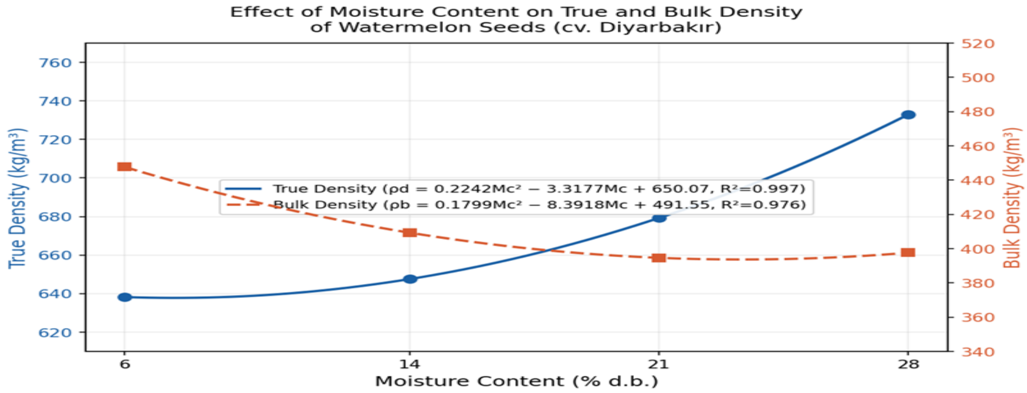

Figure 1: Effect of moisture content on true density and bulk density of watermelon seeds (cv. Diyarbakır). (Source: Paksoy et al., 2010)

Terminal velocity increased from 4.45 to 4.82 m/s, requiring stronger airflow for pneumatic conveying (Joshi et al., 1993). Rupture force decreased from 9.94 N to 2.52 N, showing that hydrated seeds are mechanically weaker and more prone to damage during handling (Aydın & Öğüt, 1992). Both sphericity and geometric mean diameter increased slightly with moisture, reflecting dimensional swelling (Koocheki et al., 2007). Moisture acts as a plasticizer in biological materials, reducing mechanical strength while increasing elasticity and volume. This dual effect explains why rupture force decreases but sphericity and projected area increase. Such knowledge is critical for designing threshing, conveying, and storage systems that minimize seed damage.

The high oil content positions watermelon seeds as a potential source for edible oil extraction, comparable to pumpkin and sunflower seeds (Gupta & Das, 1997; Joshi et al., 1993). Protein levels suggest utility in plant-based protein supplements, while minerals such as calcium and phosphorus contribute to bone health, and zinc and iron are essential for enzymatic and hematological functions. Razavi and Milani (2006) conducted a comprehensive study on the physical properties of watermelon seeds from three major Iranian commercial varieties - Sarakhsi, Kolaleh, and Red at moisture contents of 4.55%, 4.75%, and 5.02% (w.b.), respectively. The authors emphasized that watermelon (Citrullus vulgaris), belonging to the Cucurbitaceae family, is cultivated across tropical, semi-tropical, and arid regions worldwide. The seed holds significant nutritional importance, containing 31.9% protein, 57.1% fat, 8.2% fiber, and essential amino acids such as Leucine, Isoleucine, Tryptophan, and Valine. Razavi and Milani (2006) studied the geometrical, gravimetric, and frictional properties along with the angles of repose of watermelon seeds."

Geometrical Properties

Using a sample of 100 seeds per variety, the three principal dimensions - length (L), width (W), and thickness (T) were measured with a micrometer to an accuracy of 0.001 mm. Arithmetic mean diameter and geometric mean diameter were calculated using standard formulae given by Mohsenin (1970), while sphericity was computed using Mohsenin (1970) method. Results showed that the Red variety exhibited the greatest length (18.972 mm), width (10.72 mm), arithmetic mean diameter (10.894 mm), geometric mean diameter (8.456 mm), and surface area values among the three varieties. The Sarakhsi variety had the greatest thickness (3.107 mm), while Kolaleh recorded the highest sphericity by Mohsenin's method (0.513). Comparatively, the geometric mean diameter of Red watermelon seeds (10.894 mm) was found to be greater than that of sunflower seeds (5.39 mm), though the sphericity of sunflower seeds (57%) was considerably higher than all three watermelon varieties, indicating that watermelon seeds are more elongated and flattened in shape.

Gravimetric Properties

Seed volume and true density were determined using the liquid displacement method with toluene as the displacing fluid, chosen for its low surface tension and minimal absorption by seeds. Bulk density was measured by filling a container of known volume from a height of 150 mm, and porosity was derived from the ratio of bulk to true density. Among the three varieties, the Red variety had the largest volume (311.627 mm^3), the Kolaleh variety had the highest bulk density (527.265 kg/m^3) and true density (866.669 kg/m^3), while the Sarakhsi variety exhibited the greatest porosity (51.681%). When compared with other cucurbit seeds, the bulk density and true density of watermelon seeds were higher than those of squash seeds (350 kg/m^3 and 450 kg/m^3, respectively), but the true density of pumpkin seeds (1179 kg/m^3) was markedly higher than all three watermelon varieties.

Frictional Properties

The static coefficient of friction was evaluated on five surfaces: plywood, glass, fiberglass, rubber, and galvanized sheet metal. A fiberglass box filled with seeds was placed on a tilting surface, and the angle at which sliding began was recorded. Results showed that the static coefficient of friction was highest against rubber and lowest against glass across all varieties, with plywood intermediate. The friction coefficient of the Red variety ranged from 0.26 (glass) to 0.68 (rubber), Sarakhsi from 0.26 to 0.66, and Kolaleh from 0.31 to 0.56. When compared to other seeds, the friction coefficient of watermelon seeds was higher than that reported for lentil, sunflower, pumpkin, white lupine, and squash seeds, making surface material selection an important consideration in the design of handling and conveying systems.

Angles of Repose

The filling angle of repose was measured using a cylinder-and-cone method, while the funneling angle was measured using a box with a removable front panel. The filling angle of repose ranged from 27.09° to 32.38°, and the funneling angle ranged from 21.66° to 28.15° across the three varieties. The Red variety recorded the highest values in both cases, while Kolaleh had the lowest. In all varieties, the filling angle of repose was consistently higher than the funneling angle. Compared to other seeds, the repose angle of watermelon seeds was lower than pumpkin and squash seeds but higher than Locust Bean seeds.

2.2 Physical Properties of Watermelon Flesh

Determining the precise mechanical behaviour of agricultural produce under external forces remains a challenging task, particularly when the focus is on micro-level deformations within the elastic range. A study by Kawamura (1994) investigated how watermelon flesh responds to static compressive loads, aiming to understand its mechanical nature at a cellular level. The research was driven by a practical concern prevalent in Japan, where maintaining the structural integrity of watermelons during transport is critical, and where experienced growers rely on tapping sounds and vibrational cues to assess fruit quality. It was reasoned that such acoustic and vibrational responses are closely tied to the underlying mechanical properties of the fruit. Unlike the commonly used punching test, which deforms the tissue well beyond its elastic limit and into visco-elastic and cell-rupture zones, this investigation targeted the region of minimal deformation, where the material may behave in a near-elastic manner. The fruit was conceptualized as an assembly of interconnected micro cells, and understanding how forces propagate through this cellular network was considered essential for accurately characterizing the physical behaviour of the fruit.

Four ripeness categories were examined in this study, ranging from fruits harvested two weeks ahead of optimal maturity to those left on the vine one week beyond peak ripeness, along with two intermediate stages. Observations indicated a clear progression in physical characteristics with advancing maturity. The average horizontal dimension of the fruit grew from around 174.5 mm in the least mature group to nearly 278.5 mm in the overripe category, while the sweetness of the flesh, as reflected by sugar content, rose steadily from 5.9 to 12.6 across the four groups (Kawamura, 1994). When cylindrical flesh specimens were subjected to increasing static loads, it was found that deformations in both the axial and radial directions occurred simultaneously. Under light loading conditions, below roughly 0.05 N, the tissue recovered fully once the load was withdrawn, suggesting reversible elastic deformation. At a load of 0.0098 N, corresponding to a stress of approximately 7.8 Pa, radial and axial deformations of around 0.52 mm and 0.04 mm were recorded, respectively. As loading intensified beyond the 0.05 N threshold, the tissue no longer returned to its original dimensions after unloading, pointing to the onset of irreversible plastic deformation (Kawamura, 1994).

Strain calculations from the experimental data yielded a radial strain of 0.013 and a compressive strain of 0.00118, producing a Poisson's ratio of approximately 11.05. Since this value far exceeds unity, it contradicts the behaviour expected of a conventional elastic solid, confirming that watermelon flesh does not conform to standard elastic material assumptions. The overall deformation profile along the specimen's vertical axis followed a barrel-shaped pattern. Variations in the extent and distribution of radial deformation were also noted across different maturity levels, flesh sampling locations, and specimen conditions. Interestingly, the deformation patterns observed under concentrated loading were broadly consistent with those recorded under distributed loading conditions (Kawamura, 1994). Based on these findings, Kawamura (1994) concluded that watermelon flesh behaves as a non-elastic material under static compression, given that lateral expansion consistently outpaced axial compression, resulting in a Poisson's ratio well above the elastic threshold. The author emphasized that a deeper examination of micro cell mechanics would be necessary to fully account for this behaviour, since the mechanical response of the fruit is ultimately governed by the structural arrangement and interaction of its constituent cells. It was further proposed that linking the compressive behaviour of the flesh with its vibrational and acoustic responses, through the lens of cellular mechanics, could open pathways for developing reliable non-destructive methods to assess watermelon quality during handling and distribution.

Overall, watermelon flesh is a highly deformable biological material that exhibits elastic behaviour under very small loads and plastic deformation at higher loading levels. The unusually high Poisson's ratio and the predominance of radial deformation suggest that its mechanical behaviour is strongly influenced by the cellular structure of the tissue rather than by the characteristics of a homogeneous elastic material.

3. Chemical Properties of Watermelon (Citrullus lanatus)

The proximate chemical composition of watermelon highlights its importance as both a refreshing fruit and a nutrient-dense seed source. The flesh is primarily composed of high moisture, making it valuable for hydration, while protein and fat levels remain comparatively low. Ash content reflects the presence of essential minerals, and fiber contributes to digestive health. Carbohydrate levels vary among varieties, influencing the overall energy contribution of the fruit. In contrast, seeds demonstrate a richer nutrient profile, with substantial protein and fat dominated by beneficial unsaturated fatty acids that support cardiovascular health. Their high fiber content enhances dietary bulk, while carbohydrates and caloric values make them an important energy source. Seeds also serve as a plant-based protein alternative, complementing cereals and other foods in diets where protein deficiency is common. These findings emphasize the dual nutritional role of watermelon, with flesh serving as a hydrating antioxidant-rich food and seeds acting as concentrated sources of protein, fat, and fiber. Varietal differences further highlight the influence of genetic and environmental factors on nutrient distribution, underscoring the importance of cultivar selection in dietary planning.

3.1 Moisture Content

Moisture constitutes the most abundant component in C. lanatus, a characteristic shared with other members of the Cucurbitaceae family, which are inherently known for their high-water content. In freshly collected samples, moisture content has been recorded in the range of 93.65 ± 0.03% in the rind to 94.47 ± 0.04% in the pulp (Olayinka and Etejere, 2018). The pulp consistently exhibits higher moisture concentrations than the rind, a finding that aligns with established reports on fruit composition across the Cucurbitaceae family (Ozioma et al., 2013). The high moisture content renders these fruits effective thirst quenchers, particularly advantageous under hot and humid climatic conditions typical of sub-Saharan Africa. However, elevated moisture content simultaneously predisposes these fruits to rapid microbial deterioration when left unprocessed for extended durations (Ozioma et al., 2013). This observation has important implications for post-harvest management and the development of value-added products from watermelon. Comparison with Cucumis sativus, which exhibits slightly higher moisture levels of up to 96.79 ± 0.05%, further highlights that the latter may be more susceptible to spoilage under ambient conditions. From a dietary perspective, high moisture content is associated with low energy density, which supports the use of these fruits in calorie-controlled diets and weight reduction regimes (Ngoddy and Ihekoronye, 1985; Fila et al., 2013).

3.2 Proximate Composition

3.2.1 Carbohydrate and Energy Values

Carbohydrates in C. lanatus are present in higher concentrations in the rind (5.22 ± 0.06%) compared to the pulp (4.23 ± 0.12%) (Olayinka and Etejere, 2018). This pattern suggests that the rind, though typically discarded by consumers, represents a viable source of energy-yielding carbohydrate substrate. The potential use of the watermelon rind as feed supplement for livestock rearing has been proposed on account of this carbohydrate composition (Ngoddy and Ihekoronye, 1985; Olayinka and Etejere, 2013).

The calorific values derived from both the rind and pulp of C. lanatus are statistically comparable, ranging from approximately 20 to 24 kcal per 100 g. These values are lower than those reported for several other tropical fruits, including African star apple (162.58 ± 3.49 kcal), mango (63 kcal), orange (49 kcal), and pineapple (65 kcal), but are comparable to cooked pumpkin pulp at 20.93 kcal (Ngoddy and Ihekoronye, 1985; Fila et al., 2013). Furthermore, C. lanatus recorded higher carbohydrate and energy values than Cucumis sativus, and fruits low in carbohydrates and fat, such as cucumber, have been cited as suitable components of dietary regimens for diabetic and hypertensive patients who require low sugar and fat intake.

3.2.2 Protein Content

Protein concentrations in watermelon are generally modest, with values ranging between 0.34 ± 0.01% and 0.86 ± 0.02% across both fruit fractions (Olayinka and Etejere, 2018). In C. lanatus, protein content is higher in the pulp relative to the rind, a pattern that reflects the concentration of metabolically active tissue in the mesocarp. Across comparative analyses, C. sativus was found to contain higher overall protein levels than C. lanatus, with the exception of carbohydrate and energy values. Although the protein levels in these fruits are not sufficiently high to fulfil daily protein requirements independently, they may contribute meaningfully when consumed as part of a diversified diet. Protein values recorded in these fruits were higher than those documented for certain other tropical fruits such as Musa domestica and Carica papaya, though lower than those of Psidium guajava (Ozioma et al., 2013).

3.2.3 Crude Fibre and Ash

Crude fibre content in C. lanatus ranges from 0.23 ± 0.01% to 0.53 ± 0.02% and is consistently higher in the pulp than in the rind (Olayinka and Etejere, 2018). Dietary fibre plays a fundamental role in gastrointestinal health by facilitating peristaltic movement, and high fibre diets are known to accelerate metabolic processes necessary for normal growth and development (Bello et al., 2008; Atasie et al., 2009). Ash content, a proxy measure of total mineral matter, similarly shows slightly higher values in the pulp compared to the rind, suggesting that the mesocarp is a richer repository of inorganic constituents than the exocarp. Cucumis sativus was found to contain a greater proportion of both fibre and ash than C. lanatus, implying a superior roughage profile in cucumber.

3.2.4 Fat Content

The fat content of both C. lanatus and C. sativus is consistently low across all fractions, with values ranging from 0.13 ± 0.05% to 0.23 ± 0.02% in watermelon samples (Olayinka and Etejere, 2018). This is in agreement with the well-established observation that fruits generally contain upwards of 85% water on average and are therefore poor sources of fat (Ngoddy and Ihekoronye, 1985; Fila et al., 2013). The low-fat content of these fruits positions them as suitable components of weight-reduction diets. Although fat is highest in the pulp among all proximate constituents, its absolute concentration remains negligible from a dietary fat contribution standpoint.

4. Mineral Composition

4.1 Iron (Fe)

Among all minerals examined, iron exhibits the highest concentration in both the pulp and rind of C. lanatus, with the pulp recording the peak value of 0.242 ± 0.001 ppm (Olayinka and Etejere, 2018). Iron is nutritionally indispensable, particularly for pregnant women, nursing mothers, and infants, in whom iron deficiency is a primary aetiological factor of anaemia (Oluyemi et al., 2006). The relatively high iron content in the watermelon pulp is therefore of clinical significance and supports the inclusion of this fruit in dietary interventions targeting at-risk populations. In comparison, C. sativus pulp recorded the lowest iron value at 0.074 ± 0.001 ppm, indicating a clear superiority of C. lanatus as a dietary iron source. Among all mineral elements and across all parts investigated in both fruits, iron ranked highest in magnitude, followed in decreasing order by magnesium, potassium, calcium, sodium, and zinc (Olayinka and Etejere, 2018).

4.2 Magnesium (Mg) and Calcium (Ca)

Magnesium concentrations are higher in the pulp of C. lanatus (0.167 ± 0.006 ppm) compared to the rind (0.107 ± 0.008 ppm), and higher in C. lanatus overall when compared to C. sativus (Olayinka and Etejere, 2018). Magnesium serves as a cofactor for numerous enzymatic reactions, most notably those involving the sugar and protein kinase families that catalyse adenosine triphosphate (ATP)-dependent phosphorylation reactions (Rahul and Parimelazhagan, 2012). Its role in nerve relaxation and smooth blood circulation has also been well-documented (Muhammad et al., 2014). Calcium, which is essential for the regulation of muscle contraction, the transmission of nerve impulses, and bone mineralisation (Okwu and Emenike, 2006), is found in higher concentrations in the pulp of C. lanatus than in the rind, with values of 0.136 ± 0.004 ppm and 0.095 ± 0.002 ppm respectively (Olayinka and Etejere, 2018). These findings reinforce the nutritional case for consuming the whole fruit rather than merely discarding the rind.

4.3 Sodium (Na), Potassium (K), and Na/K Ratio

Sodium and potassium are critical intracellular and extracellular cations respectively, involved in the regulation of plasma volume, acid-base homeostasis, nerve conduction, and muscle contraction (Akpanyung, 2005). Their ratio (Na/K) in the body is of particular concern in the prevention and management of hypertension, with a Na/K ratio below unity being the recommended threshold (Daffodil et al., 2016). Consumption of C. lanatus and C. sativus would likely be beneficial in blood pressure regulation, as both fruits exhibit Na/K ratios less than one, consistent with dietary guidance for hypertensive individuals (FNB, 2005; Daffodil et al., 2016). Potassium concentration in the pulp of C. lanatus is 0.158 ± 0.008 ppm, higher than in the rind (0.114 ± 0.006 ppm), suggesting the pulp's advantage as a source of this mineral (Olayinka and Etejere, 2018).

4.4 Zinc (Zn)

Zinc is present in the smallest concentrations among the minerals quantified in both C. lanatus and C. sativus, with values ranging from 0.058 to 0.086 ppm in watermelon samples (Olayinka and Etejere, 2018). Despite these low levels, zinc should not be considered nutritionally inconsequential; it is an essential element involved in protein and nucleic acid synthesis, and plays an important role in normal growth and immune function (Abitogun et al., 2010). Notably, C. sativus contains higher zinc concentrations than C. lanatus, making cucumber a relatively superior source of this micronutrient among the two fruits studied. Both fruits, however, recorded the lowest zinc levels among all minerals assessed.

5. Vitamin C (Ascorbic Acid) Content

One of the most noteworthy findings pertaining to the chemical composition of C. lanatus is the distribution of vitamin C (ascorbic acid) between the rind and the pulp. The rind of both C. lanatus and C. sativus contains significantly higher concentrations of vitamin C compared to their respective pulp fractions. In C. lanatus, vitamin C in the rind was measured at 5.32 ± 0.02 mg/100 g compared to 2.27 ± 0.03 mg/100 g in the pulp, while C. sativus exhibited values of 4.74 ± 0.07 mg/100 g and 2.81 ± 0.08 mg/100 g in the rind and pulp respectively (Olayinka and Etejere, 2018). There was no statistically significant difference in vitamin C content between the two fruit species. Vitamin C is a water-soluble antioxidant vitamin that plays a pivotal role in a wide range of biological processes including collagen synthesis, immune function, and protection against oxidative stress (Abitogun et al., 2010). The higher concentration of ascorbic acid in the rind suggests that the rind possesses significant antioxidant (free radical scavenging) capacity. This is particularly relevant given that the watermelon rind is traditionally discarded, representing a substantial loss of bioactive nutrients. The findings therefore advocate strongly for the utilisation of the rind in food processing, pharmaceutical preparations, and nutraceutical development.

6. pH and Titratable Acidity

The pH values recorded for C. lanatus ranged from 5.07 ± 0.08 in the pulp to 5.18 ± 0.06 in the rind, reflecting a mildly acidic character (Olayinka and Etejere, 2018). Titratable acidity values for both fruit species were consistently low, which is a direct consequence of their mildly acidic pH. These low acidity profiles serve as reliable indicators of fruit maturity at the time of harvest (Olayinka and Etejere, 2018). The acidic conditions prevailing within the fruit matrix are also relevant from a food preservation standpoint, as mildly acidic environments can help retard the growth of certain spoilage microorganisms.

7. Nutritional Significance and Dietary Implications

The cumulative nutritional profile of C. lanatus makes it a fruit of substantial dietary significance, particularly in populations characterised by high carbohydrate intake and micronutrient deficiencies. Both the rind and pulp of the fruit serve as good sources of vital nutrients that may be used to supplement the diets of populations that are high in carbohydrates and deficient in vitamins and minerals (Olayinka and Etejere, 2018). The rind offers a rich source of carbohydrates, proteins, vitamin C, and certain minerals, suggesting its utility beyond simple waste material. The presence of citrulline in the fruit has been associated with improvements in vascular function and the management of erectile dysfunction, while its lycopene content has been linked to the protection against prostate and oral cancers (Gwana et al., 2014). The antioxidant compounds, including both vitamin C and lycopene, collectively reduce oxidative stress, which is implicated in the pathogenesis of chronic diseases including cardiovascular disease, kidney stones, and age-related bone loss (Gwana et al., 2014). Additionally, the beta-carotene content and amino acid profile of watermelon contribute to its diuretic properties and its role in the prevention of heart disease.

From a public health perspective, the low Na/K ratio in C. lanatus suggests that regular consumption could contribute to blood pressure regulation, thereby mitigating the cardiovascular disease burden in affected populations (FNB, 2005; Daffodil et al., 2016). The magnesium content, in conjunction with its enzymatic roles, further supports cardiovascular health through smooth muscle relaxation and efficient circulation (Muhammad et al., 2014). Furthermore, the low fat and caloric values of watermelon recommend its inclusion in dietary plans designed for diabetic and obese individuals requiring low-energy-dense food sources.

4. Conclusion

This review comprehensively documents the physical, morphological, chemical, and mechanical properties of watermelon (Citrullus lanatus). The fruit exhibits wide genotypic variability, with weight ranging from 0.11 to 9.32 kg, rind thickness from 0.1 to 2.8 cm, and soluble solids content from 3.9 to 13.2%, making cultivar selection critical for fresh market and processing applications. Seed engineering properties such as bulk density, porosity, terminal velocity, and rupture force are strongly moisturedependent, with friction being highest against rubber and lowest against glass — findings essential for processing machinery design. The flesh behaves as a non-elastic, visco-plastic material under static compression, with a Poisson's ratio of approximately 11.05, confirming that its mechanical response is governed by cellular micro-architecture. Chemically, the pulp is predominantly water (93–95%), while the rind though routinely discarded is a superior source of carbohydrates, vitamin C (5.32 mg/100 g), and dietary fibre, warranting its valorization in food and nutraceutical industries. The mineral profile is led by iron, followed by magnesium, potassium, calcium, sodium, and zinc, and a low Na/K ratio supports watermelon's role in cardiovascular health and blood pressure regulation. Bioactive compounds including lycopene, citrulline, beta-carotene, and polyphenols collectively confer antioxidant, anti-inflammatory, and anti-carcinogenic properties. Future research should prioritize integrated utilization of the fruit, rind, and seed to minimize post-harvest waste and maximize value addition across food technology and public health domains.

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References
1. Abitogun, A.S., Ashogbon, A.O. and Borokin, F.B. (2010). Nutritional and chemical compositions of ripe and unripe Vitex glandifolia. Journal of Research in National Development, 8(1), 1–5.
2. Akpanyung, E.O. (2005). Proximate and mineral composition of bouillon cubes produced in Nigeria. Pakistan Journal of Nutrition, 4, 327–329.
3. Alaekwe, I.O. and Mojekwu, O.E. (2013). Proximate composition and utilization of Napoleona imperialis fruits. Journal of Natural Sciences Research, 3(6), 160–165.
4. Atasie, V.N., Akinhanmi, T.F. and Ojiodu, C.C. (2009). Proximate analysis and physico-chemical properties of groundnut (Arachis hypogaea L.). Pakistan Journal of Nutrition, 8, 194–197.
5. Aydin, C. and Öğüt, H. (1992). Determination of deformation energy in some biological materials. National Symposium on Mechanizations in Agriculture, Samsun, Turkey, 254–264.
6. Bahari, M., Rafii, M.Y., Saleh, G.B. and Latif, M.A. (2012). Combining ability analysis in complete diallel cross of watermelon (Citrullus lanatus (Thunb.) Matsum. & Nakai). Scientific World Journal, 2012, 1–6.
7. Barnes, G., Crowe-White, K. and Ellis, A. (2019). Watermelon juice supplementation yields varying responses in serum lycopene levels. Current Developments in Nutrition, 3, nzz031-OR29.
8. Bello, M.O., Falade, O.S., Adewusi, S.R. and Olawole, N.O. (2008). Studies on the chemical compositions and antinutrients of some lesser-known Nigeria fruits. African Journal of Biotechnology, 7, 3972–3979.
9. Coskun, O.F. and Gulsen, O. (2024). Molecular, morphological and phytochemical characterization of some watermelon (Citrullus lanatus L.) genotypes. Horticultural Science, 51(3).
10. Daffodil, E.D., Tresina, P.S. and Mohan, V.R. (2016). Nutritional and antinutritional assessment of Mucuna pruriens (L) DC var. utilid (Wall ex. Wight). International Food Research Journal, 23(4), 1501–1513.

11. Dimari, G.A. and Hati, S.S. (2010). Vitamin C composition and mineral content of some Nigerian packaged juice drinks. Journal of the Life and Physical Sciences, 3(2), 129–134.
12. Dosumu, O.O., Oluwaniyi, O.O., Awolola, G.V. and Okunola, M.V. (2009). Stability studies and mineral concentration of some Nigeria packed fruits juices, concentrate and local beverages. African Journal of Food Science, 3(3), 82–85.
13. Dube, J., Ddamulira, G. and Maphosa, M. (2021). Watermelon production in Africa: challenges and opportunities. International Journal of Vegetable Science, 27(3), 211–219.
14. Edwards, A.J., Vinyard, B.T., Wiley, E.R., Brown, E.D., Collins, J.K., Perkins-Veazie, P., Baker, R.A. and Clevidence, B.A. (2003). Consumption of watermelon juice increases plasma concentrations of lycopene and β-carotene in humans. The Journal of Nutrition, 133(4), 1043–1050.
15. Ekpete, O.A., Marcus, A.C. and Osi, V. (2013). Proximate and mineral composition of some Nigerian fruits. British Journal of Applied Science and Technology, 3(4), 1447–1454.
16. Fila, W.A., Itam, E.H., Johnson, J.T., Odey, M.O., Effiong, E.E., Dasofunjo, K. and Ambo, E.E. (2013). Comparative proximate compositions of watermelon Citrullus lanatus, squash Cucurbita pepo L. and rambutan Nephelium lappaceum. International Journal of Science and Technology, 2(1), 81–88.
17. Food and Nutrition Board (2005). Dietary Reference Intake for Energy, Carbohydrate, Fibre, Fat, Fatty Acids, Cholesterol, Protein and Amino Acid. The National Academic Press, Washington D.C.
18. Goda, M. (2007). Diversity of Local Genetic Resources of Watermelon Citrullus lanatus (Thunb.) Matsum and Nakai in Sudan. MSc thesis, Uppsala University.
19. Gu, I., Balogun, O., Brownmiller, C., Kang, H.W. and Lee, S.O. (2023). Bioavailability of citrulline in watermelon flesh, rind, and skin using a human intestinal epithelial Caco-2 cell model. Applied Sciences, 13(8), 4882.
20. Gupta, R.K. and Das, S.K. (1997). Physical properties of sunflower seeds. Journal of Agricultural Engineering Research, 66, 1–8.
21. Gwana, A.M., Bako, M.M., Bagudu, B.Y., Sadiq, A.B. and Abdullahi, M.M. (2014). Determinations of phytochemical, vitamin, mineral and proximate compositions of varieties of watermelon seeds cultivated in Borno State, North-Eastern Nigeria. International Journal of Nutrition and Food Sciences, 3(4), 238–245.
22. Jagadeesh, S., Dhillon, A., Bajwan, A., Pawar, N. and Malik, D.P. (2024). Assessing the economic viability of watermelon cultivation in Haryana and Karnataka, India: a comparative analysis. Journal of Experimental Agriculture International, 46, 379–386.
23. Joshi, D.C., Das, S.K. and Mukherjee, R.K. (1993). Physical properties of pumpkin seeds. Journal of Agricultural Engineering Research, 54, 219–229.
24. Kawamura, T. (1994). Physical property of watermelon: compressive characteristics of flesh of watermelon at static loading. International Agrophysics, 8(3).
25. Koocheki, A., Razavi, S.M.A., Milani, E., Monghadam, T.M., Alamatiyan, S. and Izadkhah, S. (2007). Physical properties of watermelon seed as a function of moisture content and variety. International Agrophysics, 21, 349–359.
26. Masih, A., Kaur, M. and Singh, B. (2021). Watermelon (Citrullus lanatus): a comprehensive review. International Journal of All Research Education and Scientific Methods, 9(5), 3628–3645.
27. Mohsenin, N.N. (1970). Physical Properties of Plant and Animal Materials. Gordon and Breach Science Publishers, New York.

28. Muhammad, A., Sallem, U., Sharmsur, R., Zia, U. and Muhammad, A. (2014). Comparison of different types of watermelon and their important nutrients. Journal of Biology, Agriculture and Healthcare, 4(14), 59–65.
29. Munisse, P., Jensen, B.D. and Andersen, S.B. (2013). Genetic differentiation of watermelon landraces in Mozambique using microsatellite markers. African Journal of Biotechnology, 12, 5513–5521.
30. Ngoddy, P.O. and Ihekeronye, A.I. (1985). Integrated Food Science and Technology. Macmillan Publisher Limited, London.
31. Oberoi, D.P.S. and Sogi, D.S. (2017). Utilization of watermelon pulp for lycopene extraction by response surface methodology. Food Chemistry, 232, 316–321.
32. Okwu, D.E. and Emenike, I.N. (2006). Evaluation of the phytonutrients and vitamin C content of citrus fruits. International Journal of Molecular Medicine and Advance Sciences, 2, 1–6.
33. Olayinka, B.U. and Etejere, E.O. (2013). Influence of weed management strategies on proximate composition of two varieties of groundnut (Arachis hypogaea L.). Annals Food Science and Technology, 14(2), 286–293.
34. Olayinka, B.U. and Etejere, E.O. (2018). Proximate and chemical compositions of watermelon (Citrullus lanatus Thunb.) Matsum and Nakai cv Red and cucumber (Cucumis sativus L. cv Pipino). International Food Research Journal, 25(3), 1060–1066.
35. Oluyemi, E.A., Akinlua, A.A., Adenuga, A.A. and Adebayo, M.B. (2006). Mineral contents of some commonly consumed Nigeria foods. Science Focus, 11(1), 153–157.
36. Onibon, V.O., Abulude, F.O. and Lawal, L.O. (2007). Nutritional and anti-nutritional composition of some Nigerian fruits. International Journal of Molecular Medicine and Advance Sciences, 5(2), 120–122.
37. Ozioma, A.D., Onisogen, S.E. and Ebirien, P.F. (2013). Proximate and mineral composition of some Nigerian fruits. British Journal of Applied Science and Technology, 3(4), 1447–1454.
38. Paksoy, M. and Aydin, C. (2004). Some physical properties of edible squash (Cucurbita pepo L.) seeds. Journal of Food Engineering, 65, 225–231.
39. Pamplona-Roger, G.D. (2008). Healthy Foods. Editorial Safeliz S.L., San Fernando de Henares, Madrid.
40. Perkins-Veazie, P., Collins, J.K., Clevidence, B. and Wu, G. (2007). Watermelons and health. Acta Horticulturae, 731, 121.
41. Perkins-Veazie, P., Beaulieu, J.C. and Siddiq, M. (2012). Watermelon, cantaloupe and honeydew. In: Tropical and Subtropical Fruits: Postharvest Physiology, Processing and Packaging, 549–568.
42. Rahul, C. and Parimelazhagan, T. (2012). Nutritional assessment of Monochoria vaginalis, a wild edible vegetable supplement to the human diet. International Journal of Vegetable Science, 18, 199–207.
43. Razavi, S.M.A. and Milani, E. (2006). Some physical properties of the watermelon seeds. African Journal of Agricultural Research, 1(3), 65–69.
44. Rolls, B.J., Ello-Martin, J.A. and Johill, B.C. (2004). What can intervention studies tell us about the relationship between fruit and vegetable consumption and weight management? Nutrition Reviews, 62, 1–17.
45. Song, Q. (2020). Metabolic and Transcriptional Regulation of Citrulline in Watermelon. Doctoral dissertation.

46. Wehner, T.C. (2008). Watermelon. In: Vegetables I: Asteraceae, Brassicaceae, Chenopodicaceae, and Cucurbitaceae. Springer, New York, 381–418.
47. World Health Organization and Food and Agriculture Organization (2003). Diet, Nutrition and the Prevention of Chronic Diseases. Report of a Joint WHO/FAO Expert Consultation. WHO, Geneva.