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Nutraceutical and pharmacological insights into watermelon (*Citrullus lanatus* L.) phytochemicals

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Abstract

Watermelon (*Citrullus lanatus* L.) is a widely consumed fruit renowned for its high-water content, sweet and refreshing flavor and rich profile of bioactive compounds, including carotenoids (lycopene and β-carotene), non-protein amino acids (citrulline), phenolics, flavonoids and vitamins. These phytochemicals confer potent antioxidant, anti-inflammatory, neuroprotective, cardiovascular, digestive and metabolic health benefits, positioning watermelon as a functional fruit with significant nutraceutical potential. However, watermelon is highly perishable due to its soft, succulent pulp, elevated moisture content, rapid respiration rate and susceptibility to microbial spoilage, enzymatic degradation and oxidative stress. Consequently, postharvest losses and quality deterioration remain major challenges, affecting both nutritional and functional properties.This review provides a comprehensive synthesis of the phytochemical composition, postharvest challenges and preservation strategies in watermelon, highlighting the biochemical, physiological and molecular mechanisms that govern quality retention. The review discusses key postharvest interventions, including temperature management, modified and controlled atmospheres, edible coatings, chemical and natural antioxidants and non-thermal technologies such as UV-C irradiation, ozone treatment and pulsed light. It further elaborates on biochemical parameters commonly assessed in postharvest studies, including lycopene, β-carotene, citrulline, phenolic and flavonoid contents, vitamin C, sugar composition, titratable acidity, antioxidant activity, enzymatic activity, moisture content, firmness andcolor. These parameters serve as critical indicators of fruit quality, shelf-life and functional potential. Mechanistic insights into phytochemical degradation reveal that oxidative stress, enzymatic browning, microbial activity, water loss and temperature fluctuations are primary factors influencing the stability of bioactive compounds. Conversely, integrated postharvest strategiescombining controlled atmospheres, antioxidant treatments, edible coatings and low-temperature storageeffectively mitigate degradation, preserving both sensory and nutritional qualities. Additionally, this review highlights the health-promoting properties of watermelon, including neuroprotective effects *via* modulation of reactive oxygen species and anti-inflammatory pathways, cardiovascular benefits through citrulline-mediated nitric oxide synthesis, digestive support by prebiotic-like actions of phenolics and systemic antioxidant activity.Future perspectives emphasize the importance of advanced omics approaches, bioavailability and functional efficacy studies, valorization of by-products (rind and seeds), climate-adaptive storage strategies and the development of functional foods and nutraceutical products.

1. Introduction

Watermelon (*Citrullus lanatus* L.) is a widely cultivated fruit belonging to the family Cucurbitaceae, renowned for its refreshing taste, high water content and diverse health-promoting compounds. The fruit is primarily consumed as fresh pulp or juice but is also processed into jams, powders and other value-added products, expanding its application in both the food and nutraceutical industries. Watermelon not only provides hydration and essential nutrients but also contains an array of bioactive phytochemicals, including carotenoids, phenolic acids, flavonoids, amino acids such as citrulline and polysaccharides, which collectively contribute to its functional and therapeutic potential. Botanically, watermelon is an annual, trailing vine characterized by pinnately lobed leaves, yellow monoecious flowers and globose to oblong fruits that vary in size, shape, rind color and pulp pigmentation (Sangeetha *et al*., 2023). The fruit consists of three primary anatomical components: the rind, which forms the protective exocarp and mesocarp layers; the pulp, or endocarp, which is the edible portion rich in sugars, carotenoids and phenolics; and the seeds, which contain proteins, lipids and amino acids, including citrulline. The pulp is the primary source of functional compounds in red-fleshed cultivars, whereas the rind, although less consumed,

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contains bioactive compounds that can be utilized in extracts or processed products. Seeds, in addition to their nutrient content, contribute minor phytochemicals and are increasingly explored for their antioxidant and protein-rich extracts. Watermelon cultivation thrives in sandy loam soils with good drainage and requires warm climatic conditions. Its growth cycle ranges from 80 to 120 days, depending on cultivar, climate and agronomic practices. Fruits are highly perishable, emphasizing the importance of understanding postharvest handling and bioactive compound stability to maintain quality and therapeutic properties (Dube *et al*., 2021).

Figure: Watermelon plant with fruits

From a nutritional perspective, watermelon is composed predominantly of water (approximately 90-92%), making it a low-calorie, hydrating fruit. The carbohydrate content consists mainly of natural sugars such as glucose, fructose and sucrose, which provide energy while maintaining palatability. Additionally, watermelon contains dietary fiber, vitamins and minerals, including vitamins A and C, potassium and magnesium. Beyond these conventional nutrients, watermelon is rich in bioactive phytochemicals that are increasingly recognized for their health-promoting properties. Lycopene, the primary carotenoid responsible for the red color of the pulp, functions as a potent antioxidant, protecting cells from oxidative stress and damage. β-Carotene, phytoene and phytofluene, though present in lower concentrations, contribute to antioxidant activity and serve as precursors for vitamin A biosynthesis. Flavonoids such as quercetin, kaempferol and rutin, as well as phenolic acids including ferulic acid and caffeic acid, play crucial roles in neutralizing reactive oxygen species, modulating inflammatory responses and reducing the risk of chronic diseases. Citrulline, a non-essential amino acid abundant in the rind and present in the pulp, is metabolized into arginine, enhancing nitric oxide production and supporting cardiovascular health, vascular function and muscle recovery (Asfaw *et al*., 2021). The synergy of these bioactive compounds contributes to the fruit's status as a functional food and nutraceutical candidate.Globally, watermelon is one of the most cultivated horticultural crops, with annual production exceeding 100 million tons. Asia, Africa and the Americas are the primary production regions, with India being a major contributor. Beyond fresh consumption, the fruit is increasingly utilized in processed forms, including juices, concentrates, powders and nutraceutical formulations. Industrial applications of watermelon extend to cosmetic, pharmaceutical and dietary supplement sectors, primarily due to its bioactive compounds and antioxidant potential. The expansion of value-added products has heightened interest in the detailed characterization of watermelon phytochemicals, their stability and their health benefits (Asfaw, 2022).

Despite extensive research, literature on watermelon's phytochemical composition and pharmacological effects remains fragmented, often focusing on individual bioactive compounds or specific health outcomes (Campos *et al*., 2019). A comprehensive analysis integrating the fruit's phytochemical profile, pharmacological properties and factors affecting bioactive content is lacking, particularly for cultivars like PKM 1, which are widely cultivated for commercial and functional purposes. This review seeks to fill this gap by providing an in-depth discussion of watermelon's bioactive compounds, health-promoting properties and potential applications in functional foods and nutraceuticals. Emphasis is placed on carotenoids, phenolic compounds, flavonoids, citrulline, vitamins and other bioactives, along with their mechanisms of action, factors influencing accumulation and implications for human health. This review aims to provide a comprehensive and scientifically rigorous synthesis of current knowledge on watermelon's phytochemical composition, pharmacological properties and applications, serving as a foundation for future research, clinical studies and industrial utilization.

2. Phytochemical composition of watermelon

Watermelon is not only valued for its high-water content and sweet flavor but also for its wide range of bioactive phytochemicals that contribute to its health-promoting properties. Phytochemicals are secondary metabolites produced by plants, which serve protective functions in the plant and provide multiple therapeutic benefits to humans (Table 1). These compounds are found in varying concentrations across the fruit's different anatomical partsthe pulp, rind and seeds. The pulp is the primary edible portion and is rich in carotenoids, flavonoids, phenolic compounds and vitamins, whereas the rind and seeds, though less consumed, contain concentrated levels of amino acids, citrulline and other bioactives with potential functional uses in nutraceuticals, functional foods and even pharmaceuticals (Nadeem *et al*., 2022).

2.1 Carotenoids

Carotenoids are fat-soluble pigments responsible for the characteristic red, orange and yellow coloration of watermelon. Lycopene is the dominant carotenoid in red-fleshed watermelon, giving the pulp its vibrant color. Lycopene has been extensively studied for its antioxidant properties, including its ability to quench singlet oxygen, scavenge free radicals and protect lipids, proteins and DNA from oxidative damage. Other carotenoids such as β-carotene, phytoene and phytofluene are also present, albeit in smaller quantities. These carotenoids not only contribute to antioxidant activity but also act as precursors for vitamin A biosynthesis, supporting eye health, immune function and cellular integrity. The synthesis and accumulation of carotenoids in watermelon are influenced by fruit maturity, genotype, environmental conditions and cultivation practices (Sola *et al*., 2019). Full ripening generally corresponds to the peak lycopene content. Factors such as sunlight exposure, soil fertility, irrigation and temperature also significantly modulate carotenoid biosynthesis. Additionally, postharvest storage conditions, such as temperature and duration, affect carotenoid stability, with optimal handling required to preserve their bioactivity.

Table 1: Major phytochemical constituents of watermelon and their functional properties (Jaroszewska *et al*., 2023)

Class of compound	Phytochemicals present	Properties
Carotenoids	Lycopene, β-carotene, phytoene, phytofluene, lutein	Antioxidant, anticancer, eye health and reduces cardiovascular risks
Phenolic compounds	Flavonoids (quercetin, kaempferol, myricetin), acids (caffeic acid, gallic acid, ferulic acid, phenolic p-coumaric acid, chlorogenic acid)	Antioxidant, anti-inflammatory and antimicrobial
Amino acid derivatives	Citrulline, arginine	Precursor for nitric oxide, improves cardiovascular function and reduces fatigue
Triterpenoids andsterols	Cucurbitacins, phytosterols (β-sitosterol, campesterol, stigmasterol)	Anti-inflammatory, anticancer and cholesterol-lowering
Alkaloids	Minor alkaloid fractions (not abundant)	Antimicrobial and protective roles
Vitamins	Vitamin C, vitamin A (from β-carotene), vitamin B-complex (niacin, riboflavin, folate, pyridoxine)	Antioxidant, immune-boosting and metabolic functions
Minerals	Potassium, magnesium, calcium, phosphorus	Electrolyte balance and enzyme function
Other bioactives	Saponins, tannins (in seeds and rind)	Antioxidant, antimicrobial andantiobesity

2.2 Phenolic compounds and flavonoids

Phenolic compounds and flavonoids are important water-soluble phytochemicals that contribute to the antioxidant, anti-inflammatory and cardioprotective properties of watermelon. Phenolic acids such as ferulic acid, gallic acid, p-coumaric acid and caffeic acid are widely present and contribute to neutralizing reactive oxygen species and metal chelation. Flavonoids, including quercetin, kaempferol and rutin, are involved in cellular signaling pathways, reducing inflammation and regulating apoptosis, thereby offering protection against chronic diseases such as cancer and cardiovascular disorders.These compounds are distributed unevenly in the fruit (Nkonna *et al*., 2022). The rind often contains higher concentrations of phenolics and flavonoids than the pulp, which is significant given that the rind is typically discarded as waste. This presents opportunities for developing functional products from watermelon by-products. The stability and bioavailability of these compounds can be affected by processing methods such as drying, juicing and heat treatments. Understanding these factors is crucial to maximize the retention of functional properties in processed watermelon products.

2.3 Amino acids and citrulline

Watermelon is particularly notable for its high citrulline content, a non-essential amino acid predominantly found in the rind but also present in the pulp. Citrulline is a precursor for arginine, which plays a crucial role in nitric oxide synthesis. Nitric oxide is essential for vasodilation, cardiovascular health and immune function. Citrulline also exhibits antioxidant and anti-inflammatory effects and is linked to improved muscle recovery and reduced exercise-induced fatigue. The content of citrulline is influenced by fruit maturity, environmental factors and plant physiology, with higher concentrations often observed in fully ripened fruits and in the outer rind tissues (Jaroszewska *et al*., 2023).

2.4 Vitamins and minerals

Watermelon is a significant source of essential vitamins and minerals. Vitamin C, a water-soluble vitamin, contributes to antioxidant activity and immune support, while provitamin A carotenoids act as a source of vitamin A, critical for vision and epithelial tissue maintenance. Mineral elements such as potassium and magnesium support electrolyte balance, cardiovascular health and enzymatic functions (Sajjad *et al*., 2020). Together, these nutrients complement the antioxidant and bioactive properties of carotenoids and phenolics, making watermelon a valuable functional food.

2.5 Polysaccharides and other bioactive compounds

In addition to carotenoids, phenolics and amino acids, watermelon contains polysaccharides and other bioactive compounds that contribute to its health benefits. Polysaccharides derived from watermelon pulp and rind have been reported to exhibit immunomodulatory effects, supporting immune cell function and enhancing host defense mechanisms. Minor compounds such as triterpenes, sterols and volatile compounds contribute to the fruit's aroma, flavor and potential pharmacological properties. The combined presence of these phytochemicals contributes to a multifaceted profile of bioactivity, enhancing watermelon's therapeutic potential (Acharya *et al*., 2021).

2.6 Synergistic effects and functional implications

The diverse phytochemical composition of watermelon allows for synergistic interactions among its constituents. For example, lycopene and phenolics work together to enhance antioxidant capacity, while citrulline supports cardiovascular function alongside other micro-nutrients. This synergy amplifies the fruit's therapeutic potential, including anti-inflammatory, cardioprotective, anticancer and metabolic health benefits. Understanding these interactions is important for both dietary consumption and the development of functional products that harness the full potential of watermelon bioactives.Watermelon exhibits a complex and diverse array of phytochemicals including carotenoids, phenolic compounds, flavonoids, citrulline, vitamins, minerals, polysaccharides and other minor bioactives (Eke *et al*., 2021). These compounds contribute not only to the fruit's sensory properties but also to its functional and therapeutic benefits. The distribution, stability and interactions of these compounds are critical for optimizing health-promoting effects, both in fresh consumption and in processed forms. The subsequent section will focus on the pharmacological and therapeutic properties of these phytochemicals and their implications for human health.

3. Pharmacological and therapeutic properties of watermelon

Watermelon is increasingly recognized for its wide-ranging pharmacological activities, largely due to the synergistic action of its bioactive compounds including carotenoids, phenolics, flavonoids, citrulline, vitamins, minerals and polysaccharides. These compounds contribute to antioxidant, anti-inflammatory, cardioprotective, neuroprotective, metabolic, digestive, renal, reproductive and dermatological health. The multifaceted effects of watermelon are primarily attributed to the interactions between its phytochemicals and their influence on cellular signaling pathways, enzyme activity and gene expression (Arawande *et al*., 2024).

3.1 Antioxidant activity and molecular mechanisms

The antioxidant potential of watermelon is largely derived from lycopene, β-carotene, phenolics and flavonoids. Lycopene neutralizes singlet oxygen and scavenges free radicals such as superoxide and hydroxyl radicals. Its conjugated double bonds facilitate electron donation, protecting lipids, proteins and nucleic acids from oxidative stress. β-carotene complements this activity by serving as a precursor for vitamin A, supporting epithelial integrity and immune function.Phenolic compounds such as ferulic acid, gallic acid and caffeic acid act via hydrogen atom donation, metal chelation and regulation of antioxidant enzyme systems including superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx). Flavonoids such as quercetin and kaempferol stabilize reactive oxygen species, modulate the Nrf2/ARE pathway and reduce NF-κB-mediated oxidative stress responses (Benmeziane *et al*., 2023). The combined action of these phytochemicals provides a potent, multi-targeted defense against cellular damage, contributing to the prevention of chronic diseases like cardiovascular disorders, neurodegenerative conditions and cancer.

3.2 Anti-inflammatory effects and pathway modulation

Inflammation underlies many chronic health conditions. Watermelon bioactives exhibit anti-inflammatory effects through multiple molecular pathways. Lycopene inhibits NF-κB and AP-1 signaling, reducing the expression of pro-inflammatory cytokines such as TNF-α, IL-6 and IL-1β. Flavonoids inhibit cyclooxygenase (COX) and lipoxygenase (LOX) enzymes, limiting the production of prostaglandins and leukotrienes. Citrulline, via arginine metabolism, enhances nitric oxide production, which modulates vascular inflammation and oxidative stress. Collectively, these compounds mitigate chronic inflammation, lowering the risk of cardiovascular disease, diabetes and cancer.

3.3 Cardioprotective effects

Citrulline in watermelon is converted to arginine, a substrate for nitric oxide synthase (NOS), producing nitric oxide (NO). NO induces vasodilation, reduces arterial stiffness, inhibits platelet aggregation and improves endothelial function. Lycopene prevents oxidation of LDL cholesterol, a major factor in atherosclerosis, while phenolics and flavonoids reduce oxidative stress in the vascular system (Maoto *et al*., 2019). Together, these actions contribute to blood pressure regulation, improved lipid profiles and reduced risk of cardiovascular events.

3.4 Metabolic, antidiabetic and antiobesity effects

Watermelon supports metabolic health and weight management through multiple mechanisms. Its high water content and low glycemic index make it ideal for controlling calorie intake. Citrulline enhances fatty acid oxidation and reduces adiposity. Polyphenols and flavonoids improve insulin sensitivity by modulating key enzymes such as glucokinase, glucose-6-phosphatase and AMPK signaling pathways. These actions help regulate blood glucose levels, reduce insulin resistance and improve lipid metabolism, making watermelon a functional dietary component for managing obesity, metabolic syndrome and type 2 diabetes (Manivannan *et al*., 2020).

3.5 Anticancer properties and molecular targets

Watermelon's anticancer potential is largely attributed to lycopene, flavonoids and phenolics. Lycopene inhibits cancer cell proliferation by modulating PI3K/Akt, MAPK and Wnt/β-catenin signaling pathways. It also induces apoptosis by activating caspases and increasing p53 expression. Flavonoids inhibit angiogenesis and tumor growth via downregulation of VEGF and MMPs. Phenolics protect DNA from oxidative damage and regulate epigenetic markers involved in tumor suppression (Kataria *et al*., 2023). These compounds may synergistically reduce the risk of various cancers, including prostate, colon and breast cancers.

3.6 Neuroprotective effects

Watermelon bioactives protect neurons and cognitive function through antioxidant and anti-inflammatory mechanisms. Lycopene and flavonoids reduce oxidative stress and neuroinflammation by scavenging ROS and inhibiting microglial activation. Citrulline improves cerebral blood flow through NO-mediated vasodilation, enhancing oxygen and nutrient delivery to neurons. Polyphenols regulate Nrf2/ARE and NF-κB pathways, increasing antioxidant defenses and reducing neuronal apoptosis. These effects suggest potential in preventing cognitive decline, Alzheimer's disease and Parkinson's disease (Enemor*et al*., 2019).

3.7 Digestive health and gut microbiota modulation

Watermelon contributes to digestive health via water content, soluble fiber and bioactive compounds. Soluble fiber supports bowel regularity, while polyphenols and flavonoids act as prebiotics, promoting beneficial gut bacteria and suppressing pathogenic strains. Citrulline may support nitrogen metabolism and intestinal barrier function. The combined effect enhances nutrient absorption, gut integrity and overall gastrointestinal health (Nissar *et al*., 2025).

3.8 Hepatoprotective effects

Watermelon exhibits liver-protective effects through antioxidant and anti-inflammatory mechanisms. Lycopene and phenolics reduce hepatic lipid peroxidation, enhance glutathione levels and modulate detoxifying enzymes. Citrulline improves nitrogen metabolism and may aid in reducing ammonia accumulation. These actions help prevent liver damage induced by oxidative stress, alcohol, or toxins (Agboola *et al*., 2024).

3.9 Renal health and electrolyte balance

The high water content, potassium and magnesium in watermelon maintain hydration and electrolyte balance. Citrulline-mediated NO production improves renal blood flow, supports diuresis and enhances toxin elimination. The fruit's bioactives collectively reduce oxidative stress in renal tissues, supporting kidney function and reducing the risk of nephrotoxicity (Ayubi *et al*., 2024).

3.10 Antifatigue and physical performance

Citrulline plays a key role in reducing fatigue and enhancing physical performance. By increasing arginine and nitric oxide levels, it improves blood flow, nutrient delivery and waste removal in muscles. Antioxidant phytochemicals further reduce exercise-induced oxidative stress, supporting recovery and endurance (Anitha *et al*., 2025).

3.11 Reproductive health

Watermelon bioactives, particularly citrulline and arginine, support male reproductive health by enhancing nitric oxide synthesis, improving penile blood flow and potentially aiding in erectile function. Antioxidants reduce oxidative stress in reproductive tissues, protecting sperm DNA integrity and supporting fertility (Maoto *et al*., 2019).

3.12 Skin protection and antiaging

Watermelon contributes to skin health via lycopene, β-carotene and vitamin C. Lycopene neutralizes ROS generated by UV exposure, while vitamin C enhances collagen biosynthesis, maintains skin elasticity and protects against photoaging. Flavonoids provide additional antioxidant protection, reducing inflammation and preventing cellular senescence (Naddem *et al*., 2022).

3.13 Synergistic and multi-target effects

The diverse phytochemicals in watermelon act synergistically, targeting multiple biological pathways simultaneously. Lycopene, citrulline, flavonoids, phenolics, vitamins and minerals collectively enhance antioxidant defenses, reduce inflammation, support cardiovascular and neurovascular health, regulate metabolism, promote renal and liver function, improve skin health and modulate immunity. This synergy underscores the importance of consuming the whole fruit for maximal therapeutic benefits, rather than relying on isolated compounds.Watermelon demonstrates a broad spectrum of pharmacological properties, including antioxidant, anti-inflammatory, cardioprotective, anticancer, neuroprotective, hepatoprotective, renoprotective, metabolic, reproductive, digestive, antifatigue and skin-protective effects (Sola *et al*., 2019). The mechanisms involve modulation of oxidative stress, inflammation, cellular signaling pathways, enzyme activity and gut microbiota, making watermelon a valuable functional food with multifaceted health benefits.

4. Postharvest treatments and effects on phytochemical stability and shelf-life of watermelon

Watermelon is a highly perishable fruit with a short postharvest shelf-life due to its high water content, soft pulp, susceptibility to mechanical injury, microbial spoilage and rapid metabolic deterioration. The biochemical composition of watermelon, particularly bioactive compounds such as lycopene, citrulline, phenolics, flavonoids, vitamins and minerals, is highly sensitive to postharvest handling and storage conditions. The preservation of watermelon quality and functional properties is crucial for reducing economic losses, maintaining nutritional value and ensuring availability to consumers. Several postharvest treatments, ranging from temperature management to chemical, physical and non-thermal interventions, have been employed to enhance shelf-life, inhibit microbial growth and stabilize bioactive compounds (Acharya *et al*., 2021). These treatments act individually or synergistically to maintain the fruit's biochemical integrity, delay senescence and minimize postharvest losses.

4.1 Importance of postharvest management

Effective postharvest management is critical for minimizing physical, physiological and biochemical losses in watermelon. The fruit's soft, high-moisture pulp is prone to microbial attack and enzymatic deterioration, which can result in discoloration, off-flavors, loss of firmness and degradation of functional compounds. In addition to maintaining visual appeal and taste, postharvest management is essential for preserving bioactive compounds such as lycopene, citrulline and flavonoids, which are responsible for antioxidant, anti-inflammatory and cardioprotective properties. Delayed handling, improper transport, or inadequate storage conditions can lead to accelerated respiration and transpiration, causing sugar depletion, loss of aroma and enhanced oxidative stress (Mohamad *et al*., 2022). The biochemical quality of watermelon is strongly correlated with storage conditions; therefore, implementing appropriate postharvest strategies ensures that the fruit retains its nutritional and functional properties during distribution and marketing.

4.2 Temperature management

Temperature is the most critical factor affecting watermelon shelf-life and phytochemical stability. Cold storage at 5-10°C is effective in reducing respiration rate, enzymatic activity, water loss and microbial proliferation. Low-temperature storage slows the degradation of heat-sensitive compounds such as vitamin C, lycopene and phenolics, thereby preserving the fruit's antioxidant capacity. However, watermelon is highly sensitive to chilling injury below 5°C, which can manifest as pitting, water-soaked lesions, browning and increased susceptibility to decay. Room temperature storage, although convenient for short-term handling, accelerates biochemical deterioration, leading to significant losses of lycopene and citrulline within 3-5 days. Stepwise cooling, intermittent cold storage, or dynamic temperature management has been investigated to minimize chilling stress while retaining phytochemical stability. These strategies allow respiration to slow without inducing cellular damage, maintaining both fruit quality and functional properties (Quandoh *et al*., 2025).

4.3 Modified atmosphere and controlled atmosphere storage

Modified atmosphere packaging (MAP) and controlled atmosphere (CA) storage are widely used postharvest techniques to extend watermelon shelf-life. By altering the concentrations of oxygen and carbon dioxide, these methods reduce metabolic activity and delay senescence. Low oxygen levels suppress respiration and oxidative reactions, while elevated carbon dioxide inhibits ethylene production and microbial growth. Studies have shown that MAP with 3-5% O_2 and 5-10% CO_2 can significantly preserve lycopene and phenolic content while extending shelf-life by 2-3 weeks. Similarly, CA storage under precise oxygen and carbon dioxide control prevents oxidative degradation, maintains firmness and sugar content and stabilizes antioxidant compounds (Navida *et al*., 2022). These technologies are particularly effective in maintaining the functional and sensory quality of watermelon during long-distance transportation and prolonged storage.

4.4 Edible coatings

Edible coatings derived from natural polymers such as chitosan, alginate, starch and whey protein form semi-permeable films on the watermelon surface, reducing water loss, gas exchange and microbial contamination. Chitosan coatings, in particular, exhibit intrinsic antimicrobial activity while enhancing antioxidant enzyme activity in the fruit, thereby stabilizing lycopene, flavonoids and vitamin C. Alginate coatings combined with antioxidants or essential oils provide additional protection against oxidative stress and microbial decay (Innocent and Matenda, 2018). Edible coatings can also be formulated to deliver bioactive compounds gradually, enhancing the fruit's functional properties. The application of such coatings has been shown to extend shelf-life by reducing softening, minimizing color loss and maintaining overall fruit quality.

4.5 Chemical treatments

Chemical treatments are widely used to maintain postharvest quality of watermelon. Natural antioxidants such as ascorbic acid, citric acid and plant extracts inhibit enzymatic oxidation of carotenoids, phenolics and vitamin C. Calcium chloride treatments enhance cell wall stability by crosslinking pectin and cellulose, reducing softening and tissue breakdown. Antimicrobial treatments with natural extracts or safe chemical solutions reduce microbial load, inhibit fungal growth and prevent decay (Prajapati *et al*., 2021). These treatments not only preserve visual and textural quality but also stabilize functional compounds, maintaining the fruit's bioactive profile during storage.

4.6 Irradiation and non-thermal treatments

Non-thermal treatments such as UV-C irradiation, pulsed light and ozone exposure have gained attention for postharvest preservation. Low-dose UV-C induces stress-mediated accumulation of phenolics and flavonoids, enhancing antioxidant capacity while inhibiting microbial proliferation. Pulsed light and ozone treatments reduce surface microbial populations without the detrimental effects associated with heat-based interventions. These methods maintain sensory attributes, firmness andcolor while preserving thermolabile bioactive compounds. UV-C and other non-thermal treatments are especially valuable for extending shelf-life in organically grown or minimally processed watermelon, where chemical usage is restricted (Nadeem *et al*., 2022).

4.7 Watermelon rind and seed preservation

Although the pulp is primarily consumed, watermelon rind and seeds are rich in citrulline, phenolics, amino acids and oils, with significant functional and nutraceutical potential. Postharvest preservation strategies such as blanching, drying, vacuum packaging and low-temperature storage are effective in maintaining these bioactive compounds. Proper handling of rind and seeds not only contributes to zero-waste initiatives but also creates opportunities for value-added products, including citrulline-rich supplements, functional flours and oils for health-promoting applications (Artés-Hernández *et al*., 2021). Utilizing these by-products ensures the full exploitation of watermelon's nutritional and functional potential.

4.8 Effects of postharvest treatments on phytochemical stability

The retention of bioactive compounds in watermelon is highly dependent on the type of postharvest treatment employed. Cold storage slows enzymatic degradation and oxidation of carotenoids and vitamin C. MAP and CA storage limit oxygen exposure, preserving lycopene and phenolics. Edible coatings protect against water loss and oxidative stress, while chemical treatments and natural antioxidants inhibit enzymatic browning and microbial decay. Non-thermal interventions like UV-C and ozone can further enhance phenolic content by inducing stress-related biosynthesis (Bose *et al*., 2019). A combination of these treatments is often required to achieve optimal retention of phytochemicals, ensuring both the nutritional and therapeutic quality of watermelon throughout storage.

4.9 Integration of postharvest strategies

Synergistic postharvest approaches maximize shelf-life and functional quality. Combining cold storage with MAP or CA packaging slows respiration, reduces microbial proliferation and stabilizes antioxidant compounds. Edible coatings applied in conjunction with antioxidant dips provide additional protection against oxidative stress and moisture loss. UV-C irradiation followed by controlled temperature storage can induce phenolic accumulation while inhibiting spoilage. Integrated postharvest management strategies are essential for maintaining fruit quality during distribution, enabling longer storage durations without compromising biochemical or sensory attributes (Tlili *et al*., 2022).

5. Postharvest biochemical attributes of watermelon

Assessment of watermelon quality during postharvest storage relies heavily on the evaluation of both physicochemical and biochemical parameters. These measurements provide insight into the nutritional, functional and sensory attributes of the fruit, as well as the efficacy of various postharvest treatments in preserving its bioactive compounds. The major parameters that have been widely studied in watermelon postharvest research include carotenoids, amino acids, phenolic compounds, antioxidant activity, sugars, organic acids, enzymatic activity, water content and microbial load. Each of these parameters is sensitive to storage conditions and postharvest interventions and their careful monitoring allows for a comprehensive understanding of fruit quality (Hu *et al*., 2022).

Lycopene is the principal carotenoid in watermelon and the primary contributor to its red color and antioxidant potential. Several studies have demonstrated that lycopene content is highly susceptible to temperature fluctuations, oxygen exposure and light during storage. Low-temperature storage and modified atmosphere conditions have been shown to slow its degradation, thereby maintaining both visual and nutritional quality (Candir *et al*., 2021). Lycopene's stability is also influenced by oxidative reactions mediated by reactive oxygen species (ROS) and enzymatic activity, making it a key indicator of postharvest quality preservation. β-Carotene and other carotenoids complement lycopene in contributing to antioxidant activity and vitamin A content. Their degradation during storage can affect not only nutritional value but also color and flavor. Literature indicates that postharvest treatments such as edible coatings, antioxidant dips and controlled atmosphere storage help mitigate carotenoid loss by reducing oxidative stress and slowing metabolic activity. Studies using high-performance liquid chromatography (HPLC) have confirmed the retention of these compounds under optimized postharvest conditions. Citrulline, a non-protein amino acid unique to watermelon, is recognized for its cardiovascular and metabolic benefits. It is water-soluble and prone to leaching and enzymatic degradation during storage. Research has shown that citrulline retention is enhanced under low-temperature storage, in combination with coatings or modified atmospheres that reduce transpiration and oxidative reactions (Mohamad *et al*., 2022). Citrulline content is therefore a useful biomarker for evaluating the nutritional and functional quality of watermelon in postharvest studies. Phenolic compounds and flavonoids are major contributors to the antioxidant and anti-inflammatory properties of watermelon. Total phenolic content (TPC) and total flavonoid content (TFC) are frequently measured to assess the efficacy of postharvest treatments. Studies have demonstrated that UV-C irradiation, edible coatings and modified atmosphere storage can preserve or even enhance these compounds by inducing stress-related biosynthesis. Preservation of phenolics and flavonoids is critical for maintaining both health-promoting properties and fruit stability during storage (Silva *et al*., 2022).

Enzymatic activity, including polyphenol oxidase (PPO), peroxidase (POD) and catalase (CAT), plays a critical role in postharvest fruit quality. PPO and POD are involved in enzymatic browning and oxidative reactions, while CAT contributes to ROS detoxification. Monitoring these enzymes allows researchers to understand the biochemical basis of quality deterioration and the effectiveness of treatments such as coatings, antioxidants, or temperature control in stabilizing phytochemicals (Devi *et al*., 2020). Moisture content and water activity are essential parameters influencing microbial growth, texture and shelf-life. Water loss during storage can accelerate senescence and affect firmness, color and biochemical stability. Treatments that reduce transpiration, such as edible coatings or modified atmospheres, have been shown to maintain moisture levels and water activity, thereby preserving both structural and functional quality (Jonathar *et al*., 2025). Firmness and textural properties, while primarily physical attributes, are closely linked to biochemical changes such as pectin degradation and cell wall softening. Texture analysis provides indirect information about enzymatic activity, water loss and postharvest treatment efficacy (Yaseem *et al*., 2025). A comprehensive assessment of watermelon postharvest quality requires a combination of biochemical, physicochemical and functional parameters. Lycopene, β-carotene, citrulline, phenolics, flavonoids, vitamin C, sugars, acidity, antioxidant activity, enzymatic activity, moisture, firmness, microbial load andcolor together provide a holistic understanding of the fruit's quality and the effectiveness of postharvest treatments (Adepoju and Ologan, 2021). Monitoring these parameters enables the development of integrated postharvest management strategies aimed at minimizing losses, extending shelf-life and preserving the therapeutic and nutritional value of watermelon.

6. Mechanisms of phytochemical degradation and preservation in watermelon during postharvest storage

The stability of bioactive compounds in watermelon is influenced by a combination of biochemical, enzymatic and environmental factors during postharvest storage. Lycopene, β-carotene, citrulline, phenolics, flavonoids and vitamin C are particularly sensitive to oxidative stress, enzymatic activity, light, temperature fluctuations and microbial spoilage. Understanding the mechanisms underlying degradation and preservation is essential for designing effective postharvest interventions that maintain nutritional and functional quality (Xu *et al*., 2019).

6.1 Oxidative degradation of carotenoids and phenolics

Carotenoids such as lycopene and β-carotene are highly susceptible to oxidation, which is accelerated by exposure to oxygen, light and elevated temperatures. Reactive oxygen species (ROS), including superoxide anions, hydroxyl radicals and hydrogen peroxide, can attack double bonds in carotenoids, leading to structural breakdown and loss of color and antioxidant activity. Phenolic compounds are also vulnerable to oxidative polymerization catalyzed by polyphenol oxidase (PPO) and peroxidase (POD), resulting in browning, loss of bioactivity and diminished health benefits (Darre *et al*., 2022). Antioxidant enzymes such as catalase (CAT) and superoxide dismutase (SOD) play protective roles, but their activity can decline under stress or prolonged storage, exacerbating phytochemical degradation.

6.2 Enzymatic browning and hydrolysis

Polyphenol oxidase catalyzes the oxidation of phenolics to quinones, which polymerize into brown pigments, affecting both visual quality and functional properties. Similarly, pectinases, cellulases and other hydrolytic enzymes degrade cell wall components, leading to softening and increased susceptibility of carotenoids and flavonoids to oxidative damage. The activity of these enzymes is influenced by temperature, pH and storage duration, highlighting the importance of interventions such as low-temperature storage, pH regulation and enzyme inhibitors (Lecholocholo *et al*., 2022).

6.3 Water loss and transpiration effects

Postharvest water loss accelerates biochemical degradation by concentrating solutes, increasing enzymatic activity and creating stress conditions that promote oxidation. Moisture reduction can also disrupt cellular compartmentalization, allowing oxidative enzymes to come into contact with carotenoids and phenolics. Treatments that reduce transpiration, including edible coatings and controlled atmospheres, help mitigate these effects by maintaining cellular integrity and slowing oxidative processes (Rastgoo *et al*., 2024).

6.4 Microbial-induced degradation

Microorganisms such as fungi and bacteria contribute to postharvest losses by secreting enzymes that degrade cell walls and bioactive compounds. Microbial metabolism can generate reactive oxygen species and secondary metabolites that accelerate carotenoid oxidation and phenolic breakdown. Chemical or natural antimicrobial treatments, as well as modified atmosphere storage, help control microbial growth, indirectly preserving phytochemical stability (Panghal *et al*., 2018).

6.5 Role of temperature in phytochemical preservation

Temperature directly affects the kinetic rate of enzymatic reactions and oxidative processes. Low-temperature storage slows respiration, enzymatic activity and ROS generation, thereby preserving carotenoids, phenolics and vitamin C. However, chilling injury at suboptimal low temperatures can disrupt cellular membranes, leading to leakage of bioactive compounds and accelerated degradation. Stepwise cooling and dynamic temperature management have been shown to minimize these adverse effects (Shinga *et al*., 2025).

6.6 Implications for functional properties

The stability of phytochemicals directly impacts the health-promoting and functional properties of watermelon. Lycopene, citrulline, phenolics, flavonoids and vitamin C contribute to antioxidant activity, cardiovascular benefits, anti-inflammatory effects and metabolic regulation. Understanding and mitigating the mechanisms of postharvest degradation ensures that these therapeutic properties are retained, thereby enhancing the fruit's value for both consumption and nutraceutical applications.Understanding the biochemical and enzymatic mechanisms that govern phytochemical stability in watermelon is essential for effective postharvest management. Strategies that minimize oxidative stress, inhibit detrimental enzymes, control microbial growth and preserve cellular integrity collectively contribute to the retention of color, firmness, bioactive compounds and antioxidant activity (Rastgon *et al*., 2024). Mechanistic insights provide the foundation for developing integrated, scientifically informed postharvest treatments that maintain both nutritional and functional quality, supporting broader applications in food systems, functional foods and nutraceutical industries.

7. Health benefits of watermelon phytochemicals

Watermelon (*C. lanatus*) is not only a refreshing fruit but also a rich source of bioactive compounds, including lycopene, β-carotene, citrulline, phenolics, flavonoids and vitamins, which contribute to multiple health-promoting effects. Preservation of these phytochemicals through effective postharvest management is critical to maintaining the fruit's functional properties (Jibril *et al*., 2019). Extensive research has documented the therapeutic potential of watermelon bioactive, particularly in neuroprotection, digestive health, cardiovascular regulation, metabolic modulation and antioxidant defence.

7.1 Neuroprotective benefits

Phytochemicals in watermelon, especially carotenoids and polyphenols, exhibit neuroprotective properties through their antioxidant, anti-inflammatory and antiapoptotic activities. Lycopene, a potent antioxidant, scavenges reactive oxygen species (ROS) and reduces oxidative stress in neuronal cells, protecting against neurodegenerative diseases such as Alzheimer's and Parkinson's disease. Phenolic compounds and flavonoids modulate signalling pathways, including nuclear factor erythroid 2-related factor 2 (Nrf2) and nuclear factor kappa B (NF-κB), enhancing endogenous antioxidant defences and reducing neuroinflammation. Citrulline contributes indirectly by improving nitric oxide (NO) bioavailability, enhancing cerebral blood flow and supporting neuronal function (Asfaw, 2022). Studies in animal models have demonstrated that dietary intake of watermelon extracts mitigates cognitive decline, reduces neuronal apoptosis and enhances synaptic plasticity.

7.2 Digestive and gut health benefits

Watermelon phytochemicals and dietary fibers play a role in promoting gastrointestinal health. Phenolics and flavonoids exert prebiotic-like effects, supporting beneficial gut microbiota and modulating gut-associated immune responses. Citrulline contributes to the urea cycle and ammonia detoxification, indirectly supporting digestive function. Watermelon consumption has been associated with improved bowel regularity, reduction of intestinal oxidative stress and attenuation of inflammation in the gut mucosa (Casacchia *et al*., 2020). Bioactive compounds in watermelon also inhibit pathogenic bacterial growth, contributing to a balanced gut microbiome and enhanced nutrient absorption.

7.3 Cardiovascular and metabolic benefits

Citrulline, as a precursor of arginine, enhances nitric oxide synthesis, leading to vasodilation, improved endothelial function and blood pressure regulation. Lycopene and flavonoids further support cardiovascular health by reducing oxidative stress, lipid peroxidation and inflammation in vascular tissues. Studies have shown that watermelon supplementation can improve lipid profiles, reduce atherosclerotic risk and lower markers of metabolic syndrome. The synergistic effects of carotenoids, polyphenols and citrulline contribute to enhanced insulin sensitivity, glucose regulation and overall metabolic homeostasis (Eke *et al*., 2021).

7.4 Antioxidant and anti-inflammatory effects

The antioxidant activity of watermelon is primarily attributed to the combined action of lycopene, β-carotene, vitamin C, phenolics and flavonoids. These compounds neutralize free radicals, reduce oxidative stress and prevent cellular damage. Flavonoids and phenolics also modulate inflammatory pathways by downregulating NF-κB and cyclooxygenase (COX) enzymes, reducing the production of pro-inflammatory cytokines. Regular consumption of watermelon or retention of its bioactives postharvest can contribute to systemic antioxidant protection, mitigating chronic oxidative and inflammatory conditions (Bamidele *et al*., 2021).

7.5 Functional food and nutraceutical applications

The retention of watermelon bioactives postharvest enables the development of functional foods, dietary supplements and nutraceutical products. Extracts rich in citrulline, lycopene and phenolics can be incorporated into beverages, powders, or capsules, offering targeted health benefits such as cardiovascular protection, cognitive support, digestive health and antioxidant supplementation (Balogun *et al*., 2024). Effective postharvest strategies, including cold storage, modified atmospheres, edible coatings and antioxidant treatments, are critical to preserving these compounds during processing and storage.Watermelon phytochemicals confer a wide range of health benefits, including neuroprotection, digestive support, cardiovascular and metabolic regulation and antioxidant and anti-inflammatory effects (Linda *et al*., 2022). Maintaining these bioactive compounds through optimized postharvest treatments is essential to maximize functional value. Integrating knowledge of phytochemical mechanisms with practical postharvest strategies allows the production of high-quality watermelon that supports health promotion, functional food development and nutraceutical applications.

8. Future directions

Despite substantial progress in postharvest management and phytochemical research in watermelon (*C. lanatus*), several knowledge gaps and opportunities remain for enhancing shelf-life, nutritional quality and functional properties. Future research should focus on integrating advanced technologies, mechanistic insights and translational applications to optimize the retention of bioactive compounds and maximize health benefits. Innovations such as nano-coatings, antioxidant-enriched edible films, smart packaging with real-time monitoring and controlled-atmosphere systems offer promising approaches for extending shelf-life and preserving sensitive bioactives like lycopene, citrulline and vitamin C. Future research should employ integrated evaluation systems combining biochemical, physicochemical, sensory and microbiological parameters. Standardized protocols, predictive modeling and machine learning approaches can optimize storage conditions and anticipate quality changes, enabling effective supply chain management.With global climate change affecting storage environments, research should focus on adaptive strategies that mitigate temperature fluctuations, humidity variability and stress-induced phytochemical degradation. Breeding or selecting cultivars with enhanced postharvest stability will be essential in combination with climate-adapted storage technologies. Postharvest research should aim to maximize the retention of bioactives linked to specific health benefits, enabling the development of functional foods, beverages and nutraceuticals. Aligning postharvest management with consumer health priorities will increase both market value and dietary impact.

9. Conclusion

Watermelon is a nutritionally and functionally rich fruit whose bioactive compounds, including lycopene, citrulline, phenolics, flavonoids and vitamins, are highly sensitive to postharvest conditions. Effective postharvest managementincluding temperature control, modified atmosphere storage, edible coatings, antioxidant treatments and non-thermal interventionsis critical for preserving phytochemical integrity, antioxidant capacity and sensory quality. Mechanistic understanding of oxidative, enzymatic and microbial pathways informs the development of integrated strategies to maintain fruit quality. Preservation of these bioactives ensures that watermelon continues to provide neuroprotective, cardiovascular, digestive and antioxidant benefits. Furthermore, the valorization of by-products and the application of emerging technologies can enhance both nutritional and economic outcomes. In summary, optimized postharvest practices, informed by biochemical and mechanistic studies, have the potential to significantly reduce postharvest losses, extend shelf-life and deliver high-quality, health-promoting water-melon to consumers. Continued research integrating technological innovation, functional evaluation and sustainability considerations will strengthen watermelon's role in functional foods and nutraceutical applications.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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