



# Pre and postharvest determinants of quality in hydroponically grown lettuce. A review

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**Abstract:** Hydroponic lettuce production has increased rapidly due to its efficient use of water, nutrients, and space, as well as its ability to consistently produce high-quality lettuce. However, hydroponically grown lettuce remains highly perishable, and maintaining quality after harvest is a significant challenge. This review summarizes the key pre and postharvest factors affecting the quality of hydroponically grown lettuce, including appearance, texture, flavor, nutritional composition, and shelf life. Preharvest factors such as nutrient management, water quality, environmental conditions, cultivar selection, and plant growth regulators influence structural and physiological characteristics at harvest. These characteristics interact with postharvest conditions, including temperature, relative humidity, handling practices, ethylene exposure, and microbial activity, to determine storage performance. Compared with soil-grown lettuce, hydroponically grown lettuce may differ in hydration, although postharvest recommendations are often generalized from conventional systems. This review highlights existing knowledge gaps and emphasizes the need for integrated, hydroponic-specific strategies to improve quality retention and shelf life.

## 1. Introduction

Hydroponic lettuce production has experienced rapid growth due to its efficient use of water, nutrients, and space, making it a crucial system for meeting the growing demand for fresh and high-quality leafy vegetables (Debangshi, 2021). Lettuce (*Lactuca sativa* L.) is valued for its crisp texture, appealing appearance, and nutritional benefits; however, it remains one of the most perishable vegetables (Adhikari, 2025). Lettuce undergoes rapid physiological changes after harvest, such as wilting, browning, tissue softening, and nutrient degradation due to transpiration and respiration, which reduce its shelf life and marketability (Yang *et al.*, 2024). Therefore, understanding the factors that influence postharvest quality is essential for maintaining freshness and reducing losses throughout the supply chain. Hydroponic production can enhance lettuce quality by providing optimal nutrient availability, optimum growth

conditions, and reduced soilborne contamination (Jan *et al.*, 2020). Preharvest factors such as nutrient solution composition, environmental stress, and water quality, combined with postharvest factors including temperature, humidity, ethylene exposure, and handling practices, strongly influence visual quality, texture, flavor, and nutrient stability (Damerum *et al.*, 2020). However, research on harvest and postharvest behavior of hydroponic lettuce remains limited compared to that of soil-grown lettuce. While several factors affecting lettuce quality have been investigated, gaps remain in understanding their combined effects under hydroponic production systems. This review summarizes current knowledge on the quality of hydroponic lettuce and factors affecting postharvest performance, identifies key research gaps, and outlines future directions to improve the quality of hydroponically grown lettuce.

## 2. Methodology

This narrative review was synthesized based on peer-reviewed literature retrieved from Google Scholar, ScienceDirect, and Web of Science, covering studies published between 2000 and 2025. Keywords related to hydroponic lettuce, postharvest quality, shelf life, and controlled environment agriculture were used. Studies focusing on hydroponically grown lettuce were prioritized. Soil-grown lettuce was included only when hydroponic-specific evidence was limited and used for comparative interpretation. Non-peer-reviewed articles and studies unrelated to the review focus were excluded. The selected literature was qualitatively analyzed to identify key factors influencing the quality and shelf life of hydroponically grown lettuce.

## 3. Key postharvest quality attributes of lettuce

Quality refers to the characteristics or attributes that determine the value and suitability of food for human consumption (Kader, 1983). In lettuce, quality is defined by key attributes including appearance, texture, flavor, and nutritional composition, which are essential for freshness, marketability, and consumer acceptance (Kader, 2002 b; Ahmed *et al.*, 2024). These quality attributes are influenced by cultivar selection, preharvest growing conditions,

harvesting practices, and postharvest handling, and together they serve as important indicators of shelf life and overall product stability (Damerum *et al.*, 2020).

### Appearance

Visual appearance is a primary determinant of consumer acceptance of lettuce and strongly influences purchase decisions. Freshness is commonly associated with a vibrant green color and leaves free of blemishes, discoloration, or decay. Mechanical damage during harvesting and processing, including shredding, tearing, and bruising, negatively affects visual quality and often results in immediate consumer rejection (Rico *et al.*, 2007). Visual quality of romaine lettuce is frequently assessed using a 5-to-9-point rating scale developed by Kader *et al.* (1973), which integrates parameters such as firmness, decay, discoloration, wilting, and other visible defects. In addition to physical injury, factors such as microbial contamination and wound-induced responses can further compromise visual quality. Chlorophyll degradation is a significant contributor to yellowing leaves and a decline in green color intensity, resulting in reduced visual appeal during storage (Toivonen and Brummell, 2008). Color plays a critical role in food selection, preference, and overall consumer satisfaction, influencing sensory perception and acceptance (Clydesdale, 1993). During storage, biochemical processes such as enzymatic browning and pigment degradation alter lettuce coloration, thereby accelerating quality deterioration (Ihl *et al.*, 2003; Rico *et al.*, 2007). Conversely, controlled light exposure during storage has been shown to maintain or enhance chlorophyll content, thereby improving visual quality and delaying senescence in lettuce leaves (Kasim and Kasim, 2017). However, storage under continuous illumination may raise product temperature, accelerating respiration and water loss, resulting in a negative impact on lettuce's shelf life. Even a slight increase in storage temperature can substantially elevate respiration rate due to the temperature sensitivity of plant metabolic processes. Although LED lighting systems generate less radiant heat than conventional light sources and have relatively cool surfaces (Sena *et al.*, 2024), localized heat accumulation may still occur in enclosed systems. Perera *et al.* (2022) reported that LED lighting is an excellent alternative for preserving fresh vegetables; however, it must be integrated with adequate

cooling and air circulation to prevent unintended thermal stress. Therefore, illuminated storage should be engineered carefully to balance chlorophyll retention and metabolic stability. This highlights a critical trade-off between maintaining visual quality and physiological stability, underscoring the need for integrated light-temperature management strategies. Most studies focus on evaluating visual quality using a scoring system developed for soil-grown lettuce, which may not fully record the changes specific to hydroponically grown lettuce.

### Texture

Leaf texture, defined by firmness and juiciness, is a critical component of postharvest quality and strongly influences consumer preference. Firmness is primarily determined by leaf anatomical characteristics, including cell wall thickness, cell size, cell-to-cell adhesion, and turgor pressure (Toivonen and Brummell, 2008). Due to its high surface area, lettuce is particularly sensitive to water loss, facilitating rapid moisture exchange and accelerating dehydration during storage (WUR, 2025). Excessive water loss during storage disrupts cellular integrity, leading to tissue softening and a decline in textural quality (Lee and Chandra, 2018). Additionally, factors such as initial leaf firmness, storage temperature, and mechanical stress during handling and transportation significantly contribute to texture degradation and moisture loss (Zhang *et al.*, 2023; Shezi *et al.*, 2024). Conversely, elevated calcium concentrations in plant tissues have been shown to strengthen cell walls and delay softening, thereby helping to maintain textural quality during postharvest storage (Kader, 2002 b). Calcium plays a critical role in cell wall structure by interacting with pectin to form calcium pectate, which stabilizes the cell wall and middle lamella (Sahin *et al.*, 2025). Calcium uptake and distribution within plants are largely driven by tissue transpiration and the rate of  $\text{Ca}^{2+}$  absorption (McLaughlin and Wimmer, 1999; Yang and Jie, 2005). High humidity in a greenhouse, especially during winter, can reduce transpiration, limiting calcium transportation to rapidly growing tissue and increasing the risk of calcium deficiency symptoms. Calcium deficiency primarily affects young leaves, leading to disorders such as tip burn in lettuce, which appear as brown necrotic lesions along the edges of younger leaves. Similarly, calcium deficiency reduces water and nutrient absorption, leading to a loss of turgor pressure and a softer leaf

texture (Sahin *et al.*, 2025). Although several studies link texture degradation to water loss and calcium availability, the influence of hydroponic nutrient management and root-zone conditions on the stability of postharvest texture remains less well understood.

### Flavor

Flavor is a complex sensory attribute resulting from the integration of taste, aroma, texture, and temperature, and it may also be influenced by the visual appearance of food (Touzani and Sclafani, 2017). Although flavor is a critical component of overall product quality and consumer satisfaction, it often receives less attention than visual attributes and can deteriorate before visible signs of spoilage become apparent (Damerum *et al.*, 2020). In lettuce, flavor is largely influenced by the balance of sugars and bitter compounds. Glucose contributes to sweetness and positively affects consumer preference, whereas bitterness negatively impacts acceptability (Chadwick *et al.*, 2016). During storage, ongoing respiratory metabolism degrades sugars and organic acids, resulting in a gradual decline in flavor quality over the shelf life period (Saltveit, 2015).

### Nutritional content

Lettuce is widely consumed due to its low-calorie content and favorable nutritional profile, which contribute to a healthy diet (Kim *et al.*, 2016). The principal nutritional components of fresh lettuce are summarized in Table 1.

These values may vary depending on cultivar, growing conditions, and environmental factors. In addition to primary nutrients, lettuce contains a diverse range of bioactive compounds, including polyphenols such as chicoric acid and chlorogenic acid, as well as anthocyanins, quercetin, and kaempferol derivatives (Nicolle *et al.*, 2004; Llorach *et al.*, 2008; Damerum *et al.*, 2015). These phytonutrients have been linked to various health benefits, including a reduced risk of cancer, obesity, and cardiovascular and neurological disorders (Martin, 2013; Cory *et al.*, 2018). Rather than acting solely as direct antioxidants, many phytochemicals enhance endogenous antioxidant defense systems through cellular signaling pathways. For example, quercetin has been shown to activate the Sestrin-2-AMPK-mTOR signaling pathway *in vitro* models, thereby contributing to the suppression of colon cancer cell growth (Kim *et al.*, 2013; Bjørklund and

Table 1 - Nutritional composition of fresh lettuce (per 100 g fresh weight)

| Component category               | Nutrient                          | Amount (per 100 g FW) |
|----------------------------------|-----------------------------------|-----------------------|
| Moisture                         | Water                             | 94.3 g                |
| Macronutrients                   | Carbohydrates                     | 4.06 g                |
|                                  | Protein                           | 0.98 g                |
|                                  | Lipids                            | 0.30 g                |
|                                  | Potassium                         | 260 mg                |
| Minerals                         | Calcium                           | 28 mg                 |
|                                  | Phosphorus                        | 23 mg                 |
|                                  | Magnesium                         | 12 mg                 |
|                                  | Vitamin A                         | 8710 IU               |
| Vitamins and bioactive compounds | $\beta$ -carotene                 | 5230 $\mu$ g          |
|                                  | Lutein + Zeaxanthin               | 23,120 $\mu$ g        |
|                                  | Folate                            | 136 $\mu$ g           |
|                                  | Vitamin K                         | 102 $\mu$ g           |
|                                  | Vitamin E ( $\alpha$ -tocopherol) | 0.14 mg               |

Values for moisture, macronutrients, and minerals are available at USDA-ARS, 2022; values for vitamins and bioactive compounds at USDA-ARS, 2019.

Chirumbolo, 2017). From a nutritional perspective, consuming raw lettuce is preferable, as thermal processing, such as boiling, can significantly reduce levels of heat-sensitive phytochemicals, including chlorogenic acid (Clifford, 2000). Although the nutritional composition at harvest has been widely documented, relatively few integrative studies have examined nutrient retention and postharvest stability, especially in a hydroponic system under commercial storage conditions. Therefore, further research is needed to determine how hydroponic nutrient management, light regimes, and storage conditions interact to influence the stability of vitamins and phytochemicals throughout the postharvest supply chain.

#### 4. Factors affecting postharvest quality of hydroponically grown lettuce

The postharvest quality of lettuce is influenced by both preharvest and postharvest factors from production to consumption. As pre and postharvest factors operate in an interconnected manner, a system-based perspective is important to understand quality development. Figure 1 presents a conceptual model linking preharvest practices to structural and physiological status at harvest, postharvest processes, and ultimate quality outcomes.

#### *Preharvest factors*

Production systems, such as hydroponics and soil-grown methods, can impact the postharvest quality of lettuce. Hydroponically grown lettuce can influence hydration and structural integrity due to the constant availability of water and nutrients; however, it has been reported to be more sensitive to weight loss, which decreases its shelf life compared to lettuce grown in soil (Manzocco *et al.*, 2011). This may be due to the higher initial moisture content in the leaves, which makes them more prone to moisture loss during storage. However, hydroponic lettuce, when harvested with its root, helps to maintain freshness during storage (Suo *et al.*, 2021). Furthermore, Pace *et al.* (2018) reported that soilless-grown multi-leaf lettuce exhibited improved microbial stability and lower ammonium accumulation during storage than soil-grown lettuce. Water quality plays a crucial role in a hydroponic system as it can directly impact crop growth, nutrient uptake, and overall crop health. Poor water quality may be contaminated with microbes, which can cross-contaminate edible lettuce leaves during production, leading to spoilage or disease outbreaks (Dankwa *et al.*, 2019). Optimizing the yield and nutritional quality of lettuce in a hydroponic system can be achieved through effective nutrient management. Excessive nitrogen (N) application leads to higher nitrate accumulation in lettuce tissue,

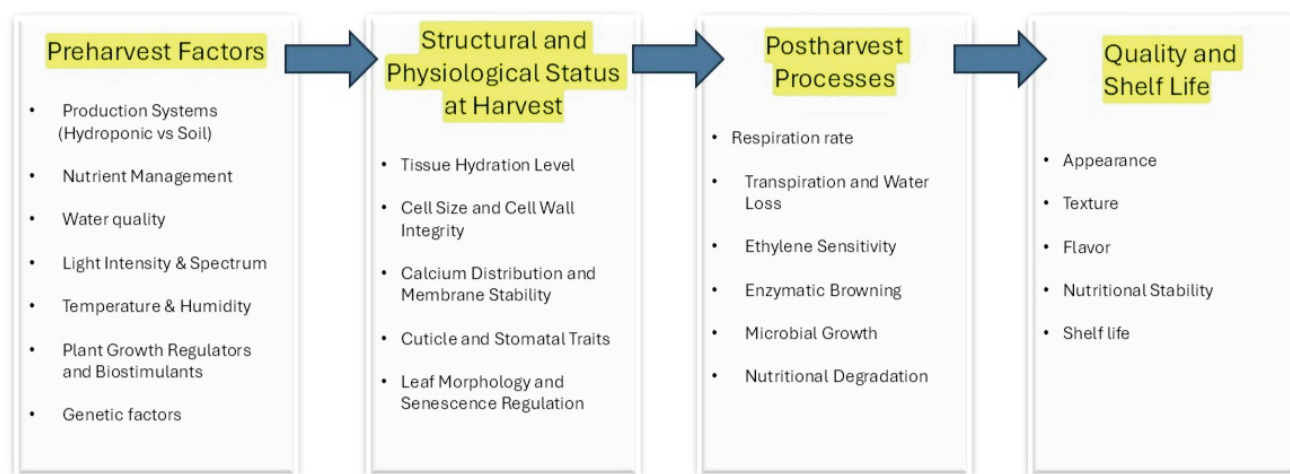


Fig. 1 - Conceptual framework illustrates how preharvest factors in hydroponic production systems influence structural and physiological characteristics at harvest, which regulate postharvest processes and ultimately determine quality attributes and shelf life of lettuce.

resulting in storage disorders, increased susceptibility to physiological damage, and a greater risk of postharvest decay (Hoque *et al.*, 2010). Nevertheless, replacing the nutrient solution with water 72 hours before harvest reduces nitrate accumulation by 63% in leafy greens, thereby improving lettuce quality (Ruangrak *et al.*, 2023). Low level of nitrate ( $\text{NO}_3$ ) application during production can increase soluble sugar and Vitamin C (Resh, 2016; Guo *et al.*, 2019). Moreover, the application of calcium chloride ( $\text{CaCl}_2$ ), known for preventing calcium deficiencies, also enhances chlorophyll levels during storage (Perucka *et al.*, 2014). Therefore, a balanced nutrient formula is recommended to maintain the yield, nutritional value, and extended shelf life by ensuring proper nutrient uptake (Bar-Yosef *et al.*, 2009).

Plant growth regulators and biostimulants applied during production can influence the postharvest quality and shelf life of hydroponically grown lettuce. For instance, the application of gibberellic acid ( $\text{GA}_3$ ) at a concentration of  $10^{-6} \text{ mol L}^{-1}$  in the nutrient solution has been shown to delay senescence, reduce nitrate accumulation, and maintain overall quality in lettuce during storage (Miceli *et al.*, 2019). As a plant growth regulator,  $\text{GA}_3$  plays a crucial role in regulating physiological processes associated with leaf expansion and senescence, thereby indirectly influencing postharvest performance. In addition to plant growth regulators, biostimulants derived from natural sources have gained increasing attention for

their role in improving lettuce quality. For example, the application of the seaweed-based bio-stimulant *Ecklonia maxima* in nutrient solutions has been reported to enhance yield and quality attributes at harvest, including biomass accumulation, leaf expansion, stomatal conductance, water-use efficiency, and nitrogen-use efficiency (Miceli *et al.*, 2021). These improvements in plant physiological status at harvest may contribute to enhanced postharvest quality and shelf life. Genetic factors are also crucial for postharvest and shelf life. Research by Chase *et al.* (2024) found that genetic markers, such as senescence-associated genes (SAGs) and transcription factors (e.g., WRKY, NAC, JAZ), linked to leaf morphology can prolong lettuce shelf life. Modifications to the lettuce cell wall improved texture and reduced water loss, both of which are essential for extending shelf life. For example, the addition of silicon ( $84 \text{ mg L}^{-1}$ ) to nutrient solutions during the growing period enhances growth and development, reduces water loss, and consequently results in greater firmness during storage at  $8 \pm 2^\circ\text{C}$  for 16 days (Mattiuz *et al.*, 2015). Neves *et al.* (2020) reported similar findings when silicon was applied directly to leaves in the form of calcium silicate at  $4 \text{ mg L}^{-1}$ , promotes growth and development and reduces postharvest weight loss. Harvesting time is another crucial factor that can impact postharvest quality. Harvesting too early or too late can result in suboptimal quality, leading to increased postharvest

loss (Alemu and Oanh, 2024). Environmental conditions, such as air temperature, affect the growth of hydroponic lettuce during production (Holmes *et al.*, 2019; Liu *et al.*, 2020). Temperatures above 28°C induce heat stress, leading to bolting, increased leaf latex, and bitter leaves (Holmes *et al.*, 2019; Liu *et al.*, 2020). Under controlled-environment conditions, higher light intensities (270 and 470  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) applied during 6-7 days before harvest significantly increase carbohydrates, vitamin C, and shelf life, especially at 469  $\mu\text{mol m}^{-2} \text{s}^{-1}$  (Min *et al.*, 2021). The study used red-white LEDs, with only light intensity varied rather than the spectrum. Therefore, the improvements were due to the higher light intensity rather than specific red, blue, or green wavelengths. Overall, while individual preharvest factors have been studied, their combined effects on postharvest quality are poorly understood.

#### Postharvest factors

Low temperatures are crucial for maintaining lettuce postharvest quality, as they reduce respiration (Watada and Qi, 1999). High temperatures increase respiration, which involves breaking down complex molecules, such as starch, sugars, and organic acids, into simpler molecules ( $\text{CO}_2$  and  $\text{H}_2\text{O}$ ), producing energy and intermediates essential for cellular maintenance (Watada and Qi, 1999; Kader, 2002 a). Similarly, relative humidity (RH) is another critical factor for maintaining postharvest quality during storage. Relative humidity affects the transpiration rate by altering the moisture gradient between plant tissue and the surrounding air (Saltveit, 2016). Therefore, maintaining an optimal relative humidity level (95-98%) is necessary to minimize moisture loss and extend shelf life (Agüero *et al.*, 2011). Transpiration occurs when moisture is lost through stomatal openings, resulting in wilting and a decline in texture, pigment, and quality during storage (Kramer and Boyer, 1995; Agüero *et al.*, 2011; Mansfield, 2012).

Using an appropriate harvesting tool is crucial to reducing mechanical damage. Harvesting lettuce with sharp-edge blades can reduce physical damage, while harvesting with blunt blades can increase cellular damage, loss of cell sap, and accelerate browning (Bolin *et al.*, 1977).

Ethylene exposure during storage triggers enzymatic discoloration, tissue deterioration, wilting, and senescence, while elevated carbon dioxide ( $\text{CO}_2$ )

levels can lead to brown staining, ultimately reducing the quality and shelf life of lettuce (Damerum *et al.*, 2020). Microorganisms, including pathogenic and saprophytic bacteria or fungi, are primary contributors to causing postharvest quality loss, as their growth alters lettuce's color, texture, and taste, making it unmarketable (Lugtenberg *et al.*, 2017; Myszka *et al.*, 2017). High temperatures favor bacterial growth. For example, the Shiga toxin-producing strain *E. coli* O157:H7 grows faster at 12°C than at 5°C (Luo *et al.*, 2010). Microbial metabolism increases respiration rates, leading to moisture loss, spoilage, and quality degradation during storage (Simko and Hayes, 2018). Lettuce surface-to-volume ratio, tissue damage, and chemical composition may further influence microbial proliferation (Kramer and Boyer, 1995; Mansfield, 2012). Hydroponically grown lettuce differs in hydration and nutrient status, which may alter postharvest handling responses. Most postharvest handling techniques are based on soil-grown lettuce, underscoring the need for further research on the storage and handling of hydroponically grown lettuce.

## 5. Discussion and Conclusions

The studies examined in this review suggest that postharvest quality in hydroponically grown lettuce is largely influenced by conditions established before harvest. Although storage temperature and relative humidity remain critical, structural and physiological traits developed during cultivation appear to determine postharvest responses. The continuous supply of water and nutrients in hydroponic systems promotes rapid vegetative growth and high tissue hydration (Manzocco *et al.*, 2011), resulting in desirable visual freshness and crisp texture at harvest. However, accelerated cell expansion under these conditions may reduce structural reinforcement, potentially producing tissues that are highly hydrated (Toivonen and Brummell, 2008). Following harvest, these tissues may be more susceptible to moisture loss if storage conditions are inadequate. This mechanism may help explain postharvest weight loss in hydroponically grown lettuce compared with soil-grown systems, although direct comparative evidence remains limited.

Nutrient management plays an important role in determining structural stability. Nitrogen enhances

vegetative growth, yet excessive availability may increase nitrate accumulation and alter tissue composition, which can influence postharvest storage behavior (Hoque *et al.*, 2010; Guo *et al.*, 2019). In contrast, adequate calcium supports cell wall integrity and membrane stability, contributing to firmness and delayed senescence (Sahin *et al.*, 2025). These contrasting roles highlight a potential trade-off between maximizing vegetative growth and enhancing postharvest durability. Optimizing hydroponic production, therefore, requires balancing nitrogen-driven productivity with an adequate supply of calcium to maintain structural resilience. Preharvest light management also appears to influence storage performance. Increased light exposure before harvest can stimulate carbohydrate and antioxidant accumulation (Min *et al.*, 2021), which may improve tolerance to oxidative stress during storage. However, higher metabolic activity may simultaneously elevate respiration rates, particularly if accompanied by temperature increases (Kader and Saltveit, 2002). These observations indicate that improving a single quality trait does not always lead to longer shelf life. Another important consideration is that most existing postharvest recommendations were developed using a conventional production system (Kader, 2002 a). Given the differences in hydration status and nutrient supply under hydroponic cultivation, it is reasonable to question whether conventional postharvest recommendations are fully transferable. Hydroponic lettuce may require more precise humidity control and rapid cooling to minimize water loss and physiological deterioration. Overall, the available evidence supports a more integrated perspective in which preharvest management decisions shape structural characteristics, metabolic status, and stress responses, ultimately determining postharvest behavior. Future research should focus on coordinated preharvest-to-postharvest studies that evaluate how production strategies can be adjusted to enhance resilience during storage, rather than treating cultivation and storage as independent phases.

This review demonstrates that lettuce quality is influenced by both preharvest factors, including production systems, nutrient management, environmental conditions, and the use of plant growth regulators and biostimulants, as well as postharvest factors such as temperature, relative

humidity, handling practices, ethylene exposure, and microbial activity. Although extensive research on lettuce exists, information specific to hydroponically grown systems remains limited and fragmented. Most studies focus on individual factors, and postharvest recommendations are often based on soil-grown lettuce, even though hydroponic lettuce differs in tissue hydration. Future studies should formulate and test clear hypotheses on how hydroponic nutrient management, light regimes, and environmental controls influence structural traits at harvest and, ultimately, determine postharvest stability and shelf life.

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## References

- ADHIKARI S., 2025 - *Evaluate the postharvest quality of romaine lettuce grown in a UV-treated hydroponic system*. - MS Report, Kansas State University, Olathe, USA, pp. 85.
- AGÜERO M.V., PONCE A.G., MOREIRA M.R., ROURA S.I., 2011 - *Lettuce quality loss under conditions that favor the wilting phenomenon*. - *Postharvest Biol. Technol.*, 59(2): 124-131.
- AHMED N., ZHANG B., CHACHAR Z., LI J., XIAO G., WANG Q., HAYAT F., DENG L., NAREJO M.N., BOZDAR B., TU P., 2024 - *Micronutrients and their effects on Horticultural crop quality, productivity and sustainability*. - *Sci. Hortic.*, 323: 112512.
- ALEMU T.T., OANH V.T.K., 2024 - *Effect of maturity stages on the quality of cold storage iceberg lettuce (Lactuca Sativa var. capitata) for export*. - *Vietnam J. Agric. Sci.*, 7(1): 2052-2063.
- BAR-YOSEF B., MATTSON N.S., LIETH H.J., 2009 - *Effects of  $NH_4^+$ :  $NO_3^-$  urea ratio on cut roses yield, leaf nutrients content and proton efflux by roots in closed hydroponic system*. - *Sci. Hortic.*, 122(4): 610-619.
- BJØRKLUND G., CHIRUMBOLO S., 2017 - *Role of oxidative stress and antioxidants in daily nutrition and human health*. - *Nutrition*, 33: 311-321.

- BOLIN H.R., STAFFORD A.E., KING A.D., HUXSOLL C.C., 1977 - *Factors affecting the storage stability of shredded lettuce*. - J. Food Sci., 42(5): 1319-1321.
- CHADWICK M., GAWTHROP F., MICHELMORE R.W., WAGSTAFF C., METHVEN L., 2016 - *Perception of bitterness, sweetness and liking of different genotypes of lettuce*. - Food Chem., 197: 66-74.
- CHASE K., BELISLE C.E., AHLAWAT Y.K., YU F., SARGENT S.A., SANDOYA G.V., BEGKY K., LIU T., 2024 - *Examining preharvest genetic and morphological factors contributing to lettuce (Lactuca sativa L.) shelf-life*. - Sci. Rep., 14(1): 4235.
- CLIFFORD M.N., 2000 - *Chlorogenic acids and other cinnamates. Nature, occurrence, dietary burden, absorption and metabolism*. - J. Sci. Food Agric., 80(7): 1033-1043.
- CLYDESDALE F.M., 1993 - *Color as a factor in food choice*. - Crit. Rev. Food Sci. Nutr., 33(1): 83-101.
- CORY H., PASSARELLI S., SZETO J., TAMEZ M., MATTEI J., 2018 - *The role of polyphenols in human health and food systems: A mini-review*. - Front. Nutr., 5: 87.
- DAMERUM A., CHAPMAN M.A., TAYLOR G., 2020 - *Innovative breeding technologies in lettuce for improved post-harvest quality*. - Postharvest Biol. Technol., 168: 111266.
- DAMERUM A., SELMES S.L., BIGGI G.F., CLARKSON G.J.J., ROTHWELL S.D., TRUCO M.J., MICHELMORE R.W., HANCOCK R.D., SHELLCOCK C., CHAPMAN M.A., 2015 - *Elucidating the genetic basis of antioxidant status in lettuce (Lactuca sativa)*. - Hortic. Res., 2: 15034.
- DANKWA A., MACHADO R.M., PERRY J.J., 2019 - *Sources of food contamination in a closed hydroponic system*. - Lett. Appl. Microbiol., 70(1): 55-62.
- DEBANGSHI U., 2021 - *Hydroponics. An overview*. - Chronicle Bioresource Manage., 5(3): 110-114.
- GUO J., YAN Y., DONG L., JIAO Y., XIONG H., SHI L., TIAN Y., YANG Y., SHI A., 2019 - *Quality control techniques and related factors for hydroponic leafy vegetables*. - HortScience, 54(8): 1330-1337.
- HOLMES S.C., WELLS D.E., PICKENS J.M., KEMBLE J.M., 2019 - *Selection of heat tolerant lettuce (Lactuca sativa L.) cultivars grown in deep water culture and their marketability*. - Horticulturae, 5(3): 50.
- HOQUE M.M., AJWA H., OTHMAN M., SMITH R., CAHN M., 2010 - *Yield and postharvest quality of lettuce in response to nitrogen, phosphorus, and potassium fertilizers*. - HortScience, 45(10): 1539-1544.
- IHL M., ARAVENA L., SCHEUERMANN E., UQUICHE E., BIFANI V., 2003 - *Effect of immersion solutions on shelf-life of minimally processed lettuce*. - LWT Food Sci. Technol., 36(6): 591-599.
- JAN S., RASHID Z., AHNGAR T.A., IQBAL S., NAIKOO M.A., MAJEED S., BHAT T.A., GUL R., NAZIR I., 2020 - *Hydroponics. A review*. - Int. J. Curr. Microbiol. Appl. Sci., 9(8): 1779-1787.
- KADER A.A., 1983 - *Postharvest quality maintenance of fruits and vegetables in developing countries*, pp. 455-470. - In: LIEBERMAN M. (ed.) *Post-harvest physiology and crop preservation*. Plenum Press, New York, USA, pp. 572.
- KADER A.A., 2002 a - *Postharvest technology of horticultural crops*. - University of California Agriculture and Natural Resources, Oakland, USA, pp. 535.
- KADER A.A., 2002 b - *Quality parameters of fresh-cut fruit and vegetable products*, pp. 11-20. - In: LAMIKANRA O. (ed.) *Fresh-cut fruits and vegetables: science, technology and market*. CRC Press, Boca Raton, USA, pp. 456.
- KADER A.A., LIPTON W.J., MORRIS L.L., 1973 - *Systems for scoring quality of harvested lettuce*. - HortScience, 8: 408-409.
- KADER A.A., SALTVEIT M.E., 2002 - *Respiration and gas exchange*, pp. 31-56. - In: JERRY A.B. (ed.) *Postharvest physiology and pathology of vegetables*. Marcel Dekker, New York, USA, pp. 928.
- KASIM M.U., KASIM R., 2017 - *Continuous white LED lighting increases chlorophyll content (SPAD) while green LED light reduces infection rate of lettuce during storage*. - J. Food Process. Preserv., 41(6): e13266.
- KIM G., LEE S.H., KIM Y.M., 2013 - *Quercetin regulates sestrin 2-AMPK-mTOR signaling pathway and induces apoptosis via increased intracellular ROS in HCT116 colon cancer cells*. - J. Cancer Prev., 18(3): 264-270.
- KIM M.J., MOON Y., TOU J.C., MOU B., WATERLAND N.L., 2016 - *Nutritional value, bioactive compounds and health benefits of lettuce (Lactuca sativa L.)*. - J. Food Compos. Anal., 49: 19-34.
- KRAMER P.J., BOYER J.S., 1995 - *Water relations of plants and soils*. - Academic Press, San Diego, USA, pp. 495.
- LEE J.S., CHANDRA D., 2018 - *Effects of different packaging materials and methods on the physical, biochemical and sensory qualities of lettuce*. - J. Food Sci. Technol., 55(5): 1685-1694.
- LIU R., SU Z., ZHOU H., HUANG Q., FAN S., LIU C., HAN Y., 2020 - *LsHSP70 is induced by high temperature to interact with calmodulin, leading to higher bolting resistance in lettuce*. - Sci. Rep., 10: 15155.
- LLORACH R., MARTINEZ-SANCHEZ A., TOMAS-BARBERAN F.A., GIL M.I., FERRERES F., 2008 - *Characterisation of polyphenols and antioxidant properties of five lettuce varieties and escarole*. - Food Chem., 108(3): 1028-1038.
- LUGTENBERG B., ROZEN D.E., KAMILOVA F., 2017 - *Wars between microbes on roots and fruits*. - F1000Research, 6: 343.
- LUO Y., HE Q., MCEVOY J.L., 2010 - *Effect of storage temperature and duration on the behavior of Escherichia coli O157:H7 on packaged fresh-cut salad*. - J. Food Sci., 75(7): M390-M397.
- MANSFIELD T.A., 2012 - *The physiology of stomata: New*

- insights into old problems, pp. 155-224. - In: STEWARD F.C. (ed.) *Plant physiology: A treatise (Volume IX)*. Academic Press, San Diego, USA, pp. 458.
- MANZOCCO L., FOSCHIA M., TOMASI N., MAIFRENI M., DALLA COSTA L., MARINO M., CORTELLA G., CESCO S., 2011 - *Influence of hydroponic and soil cultivation on quality and shelf life of ready-to-eat lamb's lettuce (Valerianella locusta L. Laterr)*. - J. Sci. Food Agric., 91(8): 1373-1380.
- MARTIN C., 2013 - *The interface between plant metabolic engineering and human health*. - Curr. Opin. Biotechnol., 24(2): 344-353.
- MATTIUZ B.H., FILHO A.B.C., MUNIZ A.C.C., MORGADO C.M.A., MARQUES K.M., GALATI V.C., 2015 - *Silicon in the turgidity maintenance of American lettuce*. - Afr. J. Agric. Res., 10(51): 4699-4705.
- MCLAUGHLIN S.B., WIMMER R., 1999 - *Tansley review No. 104: Calcium physiology and terrestrial ecosystem processes*. - New Phytol., 142(3): 373-417.
- MICELI A., VETRANO F., MONCADA A., 2021 - *Influence of Ecklonia maxima extracts on growth, yield and postharvest quality of hydroponic leaf lettuce*. - Horticulturae, 7(11): 440.
- MICELI A., VETRANO F., SABATINO L., D'ANNA F., MONCADA A., 2019 - *Influence of preharvest gibberellic acid treatments on postharvest quality of minimally processed leaf lettuce and rocket*. - Horticulturae, 5(3): 63.
- MIN Q., MARCELIS L.F.M., NICOLE C.C.S., WOLTERING E.J., 2021 - *High light intensity applied shortly before harvest improves lettuce nutritional quality and extends the shelf life*. - Front. Plant Sci., 12: 615355.
- MYSZKA K., SCHMIDT M.T., MAJCHER M., JUZWA W., CZACZYK K., 2017 -  *$\beta$ -Caryophyllene-rich pepper essential oils suppress spoilage activity of Pseudomonas fluorescens KM06 in fresh-cut lettuce*. - LWT Food Sci. Technol., 83: 118-126.
- NEVES M.G., JÚNIOR M.L.S., NETO C.F.O., OKUMURA R.S., ALBUQUERQUE G.D.P., SANTIAGO T.S., 2020 - *Growth, yield and post-harvest evaluation of lettuce plants subjected to different leaf silicon concentrations*. - Rev. Agric. Neotrop., 7(4): 40-48.
- NICOLLE C., CARNAT A., FRAISSE D., LAMAISON J.L., ROCK E., MICHEL H., AMOUREUX P., REMESY C., 2004 - *Characterisation and variation of antioxidant micronutrients in lettuce (Lactuca sativa folium)*. - J. Sci. Food Agric., 84(15): 2061-2069.
- PACE B., CAPOTORTO I., GONNELLA M., BARUZZI F., CEFOLA M., 2018 - *Influence of soil and soilless agricultural growing system on postharvest quality of three ready-to-use multi-leaf lettuce cultivars*. - Adv. Hort. Sci., 32(3): 353-362.
- PERERA W.P.T.D., NAVARATNE S., WICKRAMASINGHE I., 2022 - *Impact of spectral composition of light from light-emitting diodes (LEDs) on postharvest quality of vegetables. A review*. - Postharvest Biol. Technol., 191: 111955.
- PERUCKA I., OLSZÓWKA K., CHILCZUK B., 2014 - *Changes in the chlorophyll content in stored lettuce (Lactuca sativa L.) after pre-harvest foliar application of CaCl<sub>2</sub>*. - Acta Agrobot., 66(4): 137-142.
- RESH H.M., 2016 - *Hydroponic food production: A definitive guidebook for the advanced home gardener and the commercial hydroponic grower*. - CRC Press, Boca Raton, FL, USA, pp. 560.
- RICO D., MARTIN-DIANA A.B., BARAT J.M., BARRY-RYAN C., 2007 - *Extending and measuring the quality of fresh-cut fruit and vegetables. A review*. - Trends Food Sci. Technol., 18(7): 373-386.
- RUANGRAK E., SALAEMAE N., SORNNOK S., HTWE N.M.P.S., 2023 - *Effect of pre-harvest periods by replacing nutrient solution with tap water on nitrate and quality in hydroponic lettuce*. - ASEAN J. Sci. Technol. Rep., 26(1): 76-83.
- SAHIN O., SEYREK G.C., DEMIR K., GUNES A., 2025 - *Regulation of lettuce growth and calcium-magnesium nutrition by sheep wool-derived hydrolyzed keratin under natural and LED light spectra*. - J. Soil Sci. Plant Nutr., 25(3): 5626-5637.
- SALTVEIT M., 2016 - *Lettuce*, 386-390. - In: GROSS K.C., C.Y. WANG, and M. SALTVEIT (eds.) *The commercial storage of fruits, vegetables, and florist and nursery stocks*. U.S. Department of Agriculture, Agricultural Research Service, Washington DC, USA, pp. 792.
- SALTVEIT M.E., 2015 - *The three responses of plant tissue to wounding*, pp. 13-20. - In: CANTWELL M.I. (ed.) *Proceedings of the VIII International Postharvest Symposium*. International Society for Horticultural Science (ISHS), Leuven, Belgium, pp. 412.
- SENA S., KUMARI S., KUMAR V., HUSEN A., 2024 - *Light emitting diode (LED) lights for the improvement of plant performance and production. A comprehensive review*. - Curr. Res. Biotechnol., 7: 100184.
- SHEZI S., NGCOBO M.E.K., KHANYILE N., NCAMA K., 2024 - *Physio-metabolic mechanisms behind postharvest quality deterioration in broccoli (Brassica oleracea var. italica) and Swiss chard (Beta vulgaris L. var. cicla). A review*. - Plants, 13(22): 3174.
- SIMKO I., HAYES R.J., 2018 - *Accuracy, reliability, and timing of visual evaluations of decay in fresh-cut lettuce*. - PLoS ONE, 13(4): e0194635.
- SUO R., WANG W., MA Y., FU L., CUI Y., 2021 - *Effect of different root lengths for retaining freshness of hydroponic lettuce*. - J. Agric. Food Res., 4: 100151.
- TOIVONEN P.M.A., BRUMMELL D.A., 2008 - *Biochemical bases of appearance and texture changes in fresh-cut fruit and vegetables*. - Postharvest Biol. Technol., 48(1): 1-4.

- TOUZANI K., SCLAFANI A., 2017 - *Learned flavor aversions and preferences*, pp. 1-12. - In: STEIN J. (ed.) *Reference module in neuroscience and biobehavioral psychology*. Elsevier, Oxford, UK, pp. 500.
- USDA-ARS, 2019 - *FoodData Central: lettuce*. - Agricultural Research Service, U.S. Department of Agriculture, Washington DC, USA.
- USDA-ARS, 2022 - *FoodData Central: lettuce*. - Agricultural Research Service, U.S. Department of Agriculture, Washington DC, USA.
- WUR, 2025 - *Lettuce quality*. - WUR, Wageningen University and Research, Wageningen, The Netherlands.
- WATADA A.E., QI L., 1999 - *Quality of fresh-cut produce*. - Postharvest Biol. Technol., 15(3): 201-205.
- YANG H., JIE Y., 2005 - *Uptake and transport of calcium in plants*. - J. Plant Physiol. Mol. Biol., 31(3): 227-234.
- YANG J., SONG J., LIU J., DONG X., ZHANG H., JEONG B.R., 2024 - *Prolonged post-harvest preservation in lettuce (Lactuca sativa L.) by reducing water loss rate and chlorophyll degradation regulated through lighting direction-induced morphophysiological improvements*. - Plants, 13(18): 2564.
- ZHANG L., ZHANG M., LAW C.L., MA Y., 2023 - *Effect of vibration and broken cold chain on the evolution of cell wall polysaccharides during fruit cucumber (Cucumis sativus L.) shriveling under simulated transportation*. - Food Packag. Shelf Life, 38: 101126.