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Review Article

Postharvest Elicitation Strategies for Enhancing Phytochemicals and Nutraceutical Quality in Horticultural Crops: A Review

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Abstract

Postharvest elicitation has emerged as an innovative and sustainable approach to enhance the phytochemical composition and nutraceutical quality of horticultural crops. This strategy involves the application of physical, chemical, and volatile elicitors to harvested fruits and vegetables, triggering defense-related metabolic pathways that lead to increased accumulation of bioactive compounds such as phenolics, flavonoids, carotenoids, and glucosinolates. Among physical elicitors, technologies such as high hydrostatic pressure (HHP) and ultrasound (US) are widely studied due to their ability to induce mild abiotic stress and stimulate secondary metabolism while maintaining postharvest quality. Chemical elicitors including salicylic acid, methyl jasmonate, and chitosan, as well as volatile compounds such as hexanal and ethylene derivatives, further regulate signalling pathways associated with antioxidant and defense responses. The activation of key biochemical mechanisms, including phenylpropanoid metabolism, reactive oxygen species (ROS) signalling, and enzyme induction (e.g., phenylalanine ammonia-lyase), plays a central role in enhancing nutraceutical attributes of horticultural produce. However, the effectiveness of elicitation depends on crop type, developmental stage, treatment intensity, and storage conditions. Despite promising results, challenges such as standardization, scalability, and variability in response remain. Overall, postharvest elicitation represents a promising approach for developing value-added functional foods with improved health-promoting properties and extended postharvest life.

Keywords: Postharvest elicitation; Horticultural crops; Phytochemicals; High hydrostatic pressure; Ultrasound

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Introduction

Fruits and vegetables are important dietary sources of essential nutrients and phytochemicals, including proteins, lipids, carbohydrates, vitamins, minerals, and a wide range of bioactive compounds such as phenolics and glucosinolates (Cisneros-Zevallos, 2021; Santini and Novellino, 2018). These compounds contribute not only to human nutrition but also to plant defense mechanisms against biotic and abiotic stresses. Plant secondary metabolites (PSMs) are organic compounds that are not directly associated with the primary processes of plant growth, development, or reproduction, but are essential for plant defense, adaptation to stress, and interactions with the surrounding environment (Yeshi *et al*., 2022). Among these compounds, phenolics are particularly important due to their contribution to flavor, color, and sensory quality of plant-based foods (Cisneros-Zevallos, 2021). Similarly, glucosinolates influence bitterness and aroma in cruciferous vegetables and are associated with important bioactive properties (Dinkova-Kostova and Kostov, 2012).

From a health perspective, phenolics and glucosinolates are associated with reduced risks of chronic diseases, including cardiovascular disorders and various cancer diseases (Cisneros-Zevallos, 2021; Santini and Novellino, 2018). Therefore, improving phytochemical composition in fruits and vegetables is considered a cost-effective strategy for enhancing human health. The phytochemical composition of plant foods is generally influenced by genetic, physiological, and environmental factors, including cultivar, maturity stage, photoperiod, and agronomic practices. These factors can be strategically manipulated to enhance metabolite accumulation in horticultural crops (Cisneros-Zevallos and Jacobo-Velázquez, 2020). In this context, controlled postharvest abiotic stresses have emerged as an effective strategy to stimulate secondary metabolism and enhance bioactive compound accumulation (Cisneros-Zevallos and Jacobo-Velázquez, 2020). Although wounding is considered an effective elicitor, its industrial application is limited due to quality deterioration. To overcome these limitations, non-thermal technologies such as high hydrostatic pressure (HHP), ultrasound (US), and pulsed electric fields (PEF) have been proposed as alternative elicitors that can induce a wound-like response in plant tissues (Jacobo-Velázquez *et al*., 2017). These technologies have been shown to enhance the biosynthesis of bioactive compounds in fruits and vegetables, making them promising tools for improving nutritional quality (Jacobo-Velázquez *et al*., 2017; Cisneros-Zevallos and Jacobo-Velázquez, 2020). In addition to non-thermal technologies, several physical, chemical, and volatile elicitors including ultraviolet radiation, light-emitting diodes (LEDs), salicylic acid, methyl jasmonate, and chitosan have also demonstrated significant potential in modulating secondary metabolism and improving nutraceutical quality in horticultural produce. These elicitors activate defense-related pathways and promote the accumulation of phenolics, flavonoids, anthocyanins, carotenoids, and other bioactive compounds during postharvest storage (Jacobo-Velázquez *et al*., 2017).

This review focuses on the role of postharvest elicitation strategies in enhancing phytochemical accumulation and nutraceutical quality in fruits and vegetables, with particular emphasis on the mechanisms, major elicitors, and their effects on bioactive compounds and postharvest quality attributes.

Elicitation

Elicitation is considered one of the most effective techniques for enhancing the production of plant secondary metabolites (PSMs). Elicitors are compounds capable of stimulating plant defense responses, thereby activating secondary metabolism and promoting the accumulation of bioactive compounds (Baenas *et al*., 2014). Based on their origin, elicitors are generally classified into biotic and abiotic elicitors. Abiotic elicitors include non-biological factors such as salts, metal ions, ultraviolet radiation, temperature stress, and other physical treatments (Gorelick and Bernstein, 2014). Biotic elicitors are mainly recognized by specific receptors present on the plasma membrane of plant cells. After perception, the elicitor signal is transmitted through a signal transduction system, resulting in several biochemical and molecular changes that ultimately induce the synthesis of phytoalexins and other defense-related metabolites (Baenas *et al*., 2014). The response of plants to elicitation is largely influenced by their genetic characteristics and physiological state.

Mechanism of Postharvest Elicitation

The response of plants to elicitor-induced stress is generally initiated at the plasma membrane, where elicitor molecules are recognized by specific membrane-associated receptors. Although receptors are also present in the cytosol and nucleus, plasma membrane receptors are among the most extensively studied in plant cell systems. Various elicitor-binding sites have been identified for elicitors with different chemical structures, suggesting the existence of common perception mechanisms among plant species. The recognition process is strongly influenced by resistance (R) genes and avirulence (avr) gene products, which play important roles in elicitor perception and defense activation.

Following elicitor recognition, signal transduction pathways are activated through the involvement of secondary messengers that amplify and transmit the stress signal within the cell. Elicitor recognition activates signaling pathways involving Ca^{2+} influx, MAPKs, and ROS generation, leading to secondary metabolite accumulation (Zhao *et al*., 2005). These signaling events further induce jasmonate biosynthesis, activation of defense-related genes, and accumulation of secondary metabolites, as shown in **Figure 1**.

Despite considerable progress in understanding elicitor-mediated signaling, the mechanisms underlying elicitation remain highly complex and incompletely understood. Different elicitors may activate distinct receptors, signaling pathways, and target genes, resulting in variable metabolic responses depending on plant species and metabolite type. Furthermore, multiple signaling pathways often interact through cross-talk mechanisms, enabling plants to coordinate spatial and temporal defense responses against diverse environmental stresses.

Classification of Postharvest Elicitors

Postharvest elicitors are physical, chemical, or biological factors capable of inducing stress responses in harvested fruits and vegetables, thereby stimulating secondary metabolism and enhancing the accumulation of bioactive compounds. Based on their mode of action, postharvest elicitors can be broadly classified into physical, chemical, and volatile elicitors.

Physical Elicitors

Physical elicitors induce abiotic stress through physical stimuli such as radiation, temperature, pressure, or mechanical injury. These elicitors activate defense-related pathways and promote the synthesis of secondary metabolites in plant tissues. Common physical elicitors include ultraviolet (UV) radiation, light-emitting diodes (LEDs), low temperature, ultrasound, high hydrostatic pressure (HHP), pulsed electric fields (PEF), and wounding stress.

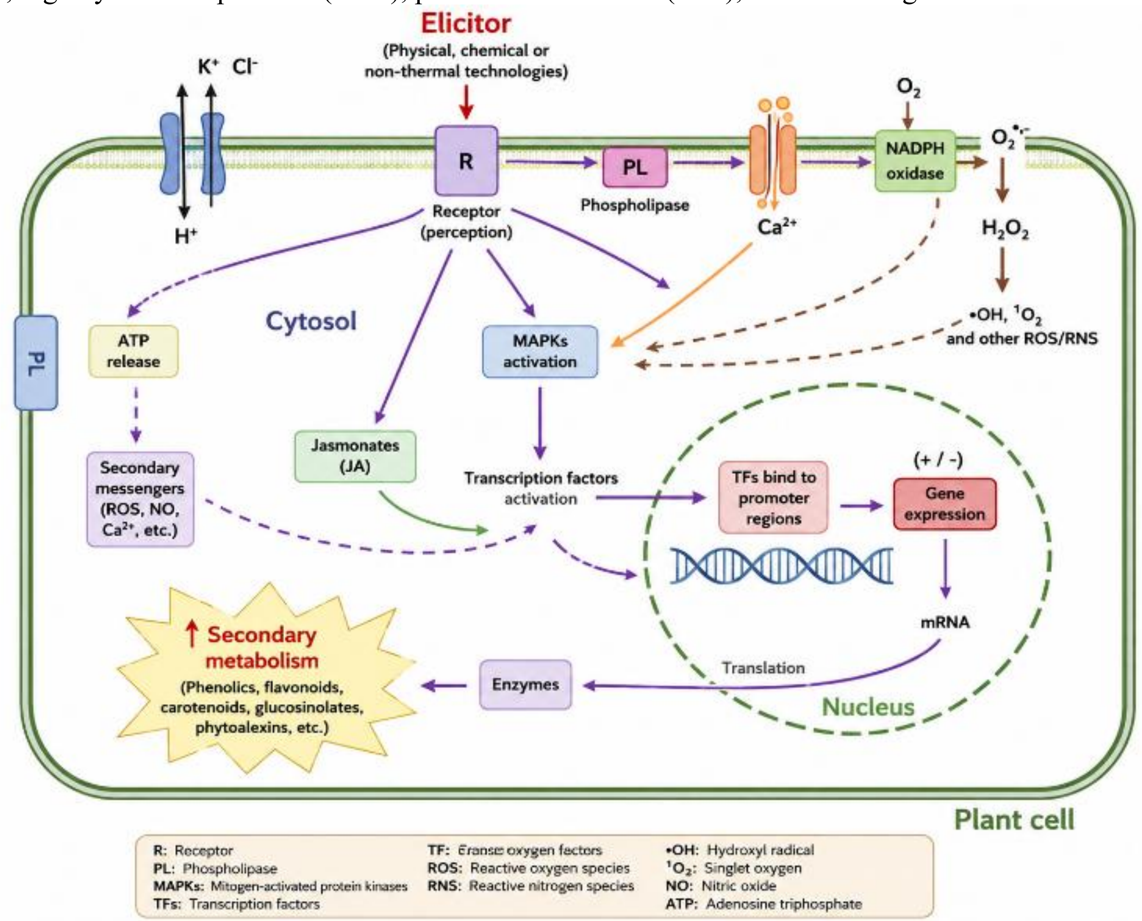

Figure 1 Schematic representation of elicitor-induced signaling pathways and secondary metabolite accumulation in plant cells. R: receptor; PL: phospholipase; MAPKs: mitogen-activated protein kinases; ROS: reactive oxygen species; RNS: reactive nitrogen species; TF: transcription factors.

High Hydrostatic Pressure (HHP)

High Hydrostatic Pressure (HHP) is a non-thermal food processing technique in which food materials are subjected to extremely high pressure (generally 100–600 MPa) transmitted uniformly through water. This pressure disrupts cellular structures, inactivates spoilage and pathogenic microorganisms, and modifies enzyme activity while largely preserving nutritional and sensory quality. In postharvest systems, HHP is also reported to induce mild stress responses that can enhance the accumulation of bioactive compounds such as phenolics and antioxidants without the use of heat, thereby improving overall product quality and shelf life (Jacobo-Velázquez and Benavides, 2021; Martínez-Chávez *et al*., 2024).

Ultrasound (US)

Ultrasound is a non-thermal processing technology that uses high-frequency sound waves (typically 20–100 kHz for power ultrasound) to generate cavitation in biological tissues. The formation and collapse of microbubbles produce localized mechanical, thermal, and oxidative effects that enhance mass transfer and increase cell permeability. In postharvest applications, ultrasound has been widely used to improve extraction efficiency, reduce microbial load, and stimulate stress-related metabolic pathways, ultimately enhancing the biosynthesis of bioactive compounds and improving the nutritional and functional quality of horticultural produce (Cisneros-Zevallos, 2021).

Chemical Elicitors

Chemical elicitors are compounds that trigger physiological and biochemical responses associated with plant defense mechanisms. These elicitors regulate signaling pathways involved in secondary metabolite biosynthesis and antioxidant activity. Salicylic acid (SA), methyl jasmonate (MeJA), chitosan, and potassium nitrate (KNO_3) are commonly used chemical elicitors in postharvest systems.

Salicylic Acid (SA)

Salicylic acid (SA) is an important chemical elicitor that enhances postharvest quality by activating systemic acquired resistance (SAR) and stimulating the phenylpropanoid pathway. It promotes the accumulation of phenolic compounds, flavonoids, and antioxidant enzymes, thereby reducing oxidative stress and delaying senescence (Jeyasri *et al*., 2023). Postharvest SA treatment has been shown to improve phytochemical content and antioxidant activity in horticultural crops such as tomato, strawberry, broccoli, and cucumber. However, its effectiveness depends on crop species, treatment concentration, and storage conditions, emphasizing the need for optimized application protocols.

Methyl Jasmonate (MeJA)

Methyl jasmonate (MeJA) is a potent chemical elicitor that regulates plant defense responses and stimulates the biosynthesis of secondary metabolites. It activates jasmonate signaling pathways, enhancing the accumulation of phenolics, flavonoids, glucosinolates, anthocyanins, and antioxidant compounds while delaying postharvest senescence (Jeyasri *et al*., 2023). Recent studies have shown that pre- and postharvest MeJA treatments significantly improve red colour development, anthocyanin accumulation, flavonoid content, and antioxidant activity in blood oranges during cold storage (Vithana *et al*., 2024). Similarly, MeJA has been reported to enhance phytochemical content and postharvest quality in broccoli, tomato, mango, and strawberry, although its effectiveness depends on crop type, maturity stage, and treatment conditions.

Chitosan

Chitosan is a natural biopolymer that acts as both a chemical elicitor and an edible coating, enhancing postharvest quality by activating plant defense responses and antioxidant metabolism. It promotes the accumulation of phenolic compounds and antioxidant enzymes, thereby reducing oxidative stress and delaying senescence. Postharvest chitosan treatment has been shown to maintain quality and suppress bacterial growth in spinach by enhancing antioxidant enzyme activity and eliciting defense responses (Meitha *et al*., 2022). Similar improvements in phytochemical content and shelf life have also been reported in strawberry, tomato, citrus, and mango, demonstrating its potential as an effective postharvest elicitor.

Potassium Nitrate (KNO_3)

Potassium nitrate (KNO_3) is a chemical elicitor that enhances postharvest quality by modulating nitrogen metabolism and antioxidant defense mechanisms. It has been reported to stimulate the accumulation of phenolic compounds, improve antioxidant activity, and delay senescence in certain horticultural crops. However, compared with salicylic acid, methyl jasmonate, and chitosan, studies on the postharvest elicitation effects of KNO_3 are limited, indicating the need for further research to optimize its application and evaluate its effectiveness across different crops.

Volatile Elicitors

Volatile elicitors are gaseous or aroma-producing compounds that act as signaling molecules and influence plant metabolic responses during storage. These compounds can stimulate stress-related pathways and improve phytochemical accumulation in horticultural produce. Hexanal, ethylene, and nitric oxide (NO) are among the important volatile elicitors used in postharvest elicitation studies.

Hexanal

Hexanal is a naturally occurring volatile aldehyde that functions as an effective postharvest elicitor by inhibiting phospholipase D (PLD), thereby delaying membrane degradation and fruit senescence. It enhances antioxidant defense mechanisms, maintains fruit firmness, and promotes the accumulation of bioactive compounds while extending shelf life. Hexanal treatment has been reported to improve postharvest quality and phytochemical retention in horticultural crops such as tomato, raspberry, bell pepper, and banana through the activation of defense-related pathways and suppression of oxidative damage (Öz *et al*., 2023).

Ethylene

Ethylene is a naturally occurring gaseous phytohormone that regulates fruit ripening, senescence, and stress responses during postharvest storage. As a volatile elicitor, controlled ethylene exposure can stimulate the biosynthesis of secondary metabolites, including phenolics, anthocyanins, and aroma compounds, thereby improving nutritional and sensory quality. In strawberry, ethylene elicitation has been reported to alter the metabolic profile and enhance the accumulation of health-promoting compounds during fruit ripening (Reis *et al*., 2020). However, excessive ethylene exposure may accelerate ripening and quality deterioration, emphasizing the importance of optimizing its application.

Nitric Oxide (NO)

Nitric oxide (NO) is an important gaseous signaling molecule that enhances postharvest quality by regulating antioxidant defense systems and reducing oxidative stress. It delays senescence, maintains membrane integrity, and promotes the accumulation of phenolic compounds and other bioactive metabolites. Postharvest NO treatment has been shown to improve fruit quality, antioxidant activity, and phytochemical retention in horticultural crops by modulating reactive oxygen species (ROS) metabolism and defense-related pathways (Wei *et al*., 2024). However, its effectiveness depends on crop species, treatment concentration, and storage conditions.

Table 1 Comparative Overview of High Hydrostatic Pressure (HHP) and Ultrasound (US) as Postharvest Non-Thermal Technologies

Horticultural Crop	HHP (High Hydrostatic Pressure) – Bioactive + Quality Effects	US (Ultrasound) – Bioactive + Quality Effects	References
Mango	↑ Carotenoids (up to +43.7%), ↑ phenolics, ↑ ascorbic acid retention. ↓ respiration rate (20–41%), delayed ethylene, improved ripening color.	—	(Hu *et al*., 2021)
Carrot	↑ Phenolics (chlorogenic acid, quercetin etc.), ↑ PAL activity (up to +380%), ↑ xanthophylls. ↑ respiration rate; tissue-dependent physiological response.	↑ Carotenoids (+21% immediate), later stabilization during storage. ↑ phenolics after storage (+129%). ↑ respiration + VOCs; PAL activation.	(Viacava *et al.* 2020)
Lettuce	—	↑ Phenolics (+22.5% after storage). ↑ PAL activity. ↑ firmness, no major color change.	(Yu *et al*., 2016)
Strawberry	—	↑ Ascorbic acid retention (up to ~36%). ↑ phenolics (optimum 10–40 min). Improved firmness & color retention.	(Gani *et al*., 2016)
Broccoli	—	↑ Glucosinolates (very high increase e.g. glucoraphanin +795%). ↑ phenolics. ↓ ascorbic acid (but preserved with MJ/ET combination).	(Aguilar-Camacho *et al*., 2019)
Common bean sprouts	—	↑ Phenolics, flavonoids, anthocyanins (up to >1000%). ↑ sprouting rate, vigor. ↑ ROS, PAL, defense enzymes.	(Ampofo and Ngadi, 2020)
Soybean sprouts	—	↑ GABA (+43.5%), ↑ isoflavone aglycones. ↓ antinutrients (trypsin inhibitor, allergens). improved germination & flavor.	(Yang *et al*., 2015)
Peanut sprouts	—	↑ Resveratrol (~980%). ↓ allergenic proteins. improved germination.	(Yu *et al*., 2016)

Effectiveness of Different Postharvest Elicitors

Different postharvest elicitors vary considerably in their ability to enhance phytochemical accumulation, depending on their mode of action, treatment intensity, crop species, and storage conditions. Physical elicitors such as high hydrostatic pressure (HHP), ultrasound (US), ultraviolet (UV) radiation, and pulsed electric fields (PEF) induce controlled abiotic stress, leading to the activation of antioxidant defense systems and secondary metabolic pathways (Khan *et al*., 2025). Among these, ultrasound is particularly effective in increasing phenolic compounds and antioxidant activity due to cavitation-induced mechanical stress, whereas HHP effectively enhances carotenoid retention and phenolic accumulation while maintaining fruit quality (Bao *et al*., 2026).

Chemical elicitors such as salicylic acid (SA), methyl jasmonate (MeJA), and chitosan activate defense signaling pathways associated with systemic acquired resistance and jasmonate-mediated responses (Jeyasri *et al*., 2023). MeJA is especially effective in stimulating glucosinolate biosynthesis in *Brassica* vegetables, whereas SA generally promotes phenolic and flavonoid accumulation in fruits such as tomato and strawberry (Jeyasri *et al*., 2023). Chitosan acts both as an elicitor and as an edible coating, improving antioxidant metabolism while reducing postharvest deterioration.

Volatile elicitors, including hexanal, ethylene, and nitric oxide, regulate ripening and stress signaling pathways (Choudhary *et al*., 2008). Hexanal delays senescence by suppressing phospholipase D activity and slowing membrane degradation, whereas nitric oxide enhances antioxidant enzyme activity and delays oxidative damage during storage. Ethylene-mediated elicitation can stimulate secondary metabolite biosynthesis in climacteric fruits; however, excessive ethylene exposure may accelerate ripening and shorten storage life.

Overall, no single elicitor is universally superior. Their effectiveness depends on crop species, developmental stage, treatment dose, exposure duration, and the targeted phytochemical. Therefore, selecting an appropriate elicitor should be based on the physiological characteristics of the crop and the desired postharvest quality attributes. A comparative overview of the major postharvest elicitors, including their mechanisms of action, phytochemicals enhanced, advantages, limitations, and representative horticultural crops, is presented in **Table 2**.

Table 2 Comparative Overview of Postharvest Elicitors and Their Effectiveness

Sr No.	Elicitor	Main mechanism	Major phytochemicals enhanced	Advantages	Limitations	Suitable crops
1.	HHP	Mild abiotic stress	Phenolics, carotenoids	Maintains quality	Expensive	Mango, carrot
2.	Ultrasound	Cavitation-induced stress	Phenolics, flavonoids	Chemical-free	Overexposure damages tissue	Strawberry, lettuce
3.	UV-B/UV-C	ROS signalling	Phenolics, anthocyanins	Fast treatment	Excess dose causes injury	Tomato, grape
4.	Salicylic acid	SAR signalling	Phenolics, antioxidants	Cheap	Crop-specific response	Tomato, broccoli
5.	Methyl jasmonate	Jasmonate pathway	Glucosinolates, flavonoids	Very effective	Costly	Broccoli, mango
6.	Chitosan	Defense elicitor + coating	Phenolics, antioxidant enzymes	Edible coating	Variable response	Strawberry, citrus
7.	Hexanal	Ethylene inhibition	Phenolics	Shelf-life extension	Limited studies	Mango
8.	Ethylene	Ripening & signaling regulation	Phenolics, anthocyanins, aroma compounds	Enhances ripening-related metabolites	Excess accelerates senescence	Strawberry, tomato
9.	Nitric oxide	Signalling molecule	Antioxidants	Delays senescence	Dose sensitive	Peach, tomato

Crop-Specific Responses to Postharvest Elicitors

The effectiveness of postharvest elicitors varies among horticultural crops due to differences in their genetic background, physiological characteristics, endogenous hormone balance, and metabolic capacity (Jeyasri *et al*., 2023). Crop-specific responses are largely determined by the ability of plant tissues to perceive elicitor signals and activate defense-related pathways involved in secondary metabolite biosynthesis. For example, methyl jasmonate (MeJA) is particularly effective in *Brassica* vegetables because glucosinolate biosynthesis is closely regulated by jasmonate signaling, whereas salicylic acid (SA) is more effective in fruits such as tomato, strawberry, and blood orange by stimulating the phenylpropanoid pathway and enhancing phenolic and flavonoid accumulation (Jeyasri *et al*., 2023; Vithana *et al*., 2024). Similarly, physical elicitors such as high hydrostatic pressure (HHP) and ultrasound exhibit crop-dependent responses owing to differences in tissue structure, water content, and stress tolerance, influencing the accumulation of carotenoids, phenolics, and antioxidant compounds (Bao *et al*., 2026). Furthermore, elicitor effectiveness is influenced by the maturity stage, treatment concentration, exposure duration, and storage conditions. Therefore, crop-specific optimization of elicitor type and treatment protocols is essential to maximize phytochemical enhancement while maintaining postharvest quality (Wei *et al*., 2024).

Conclusion & Future Prospects

Postharvest elicitation is a promising and sustainable approach for enhancing the phytochemical composition and nutraceutical quality of horticultural crops. Physical, chemical, and volatile elicitors stimulate plant defense responses, resulting in increased accumulation of phenolics, flavonoids, carotenoids, glucosinolates, and other bioactive compounds. Among physical elicitors, high hydrostatic pressure and ultrasound have shown significant potential to improve antioxidant capacity, secondary metabolite biosynthesis, and postharvest quality attributes. However, elicitor responses vary depending on crop type, treatment conditions, and storage environment. Overall, postharvest elicitation offers an effective strategy to improve the nutritional and functional quality of fresh produce without the use of synthetic additives.

Despite significant advances in postharvest elicitation strategies, several knowledge gaps and unresolved challenges remain. Most studies have been conducted under controlled laboratory conditions, with limited validation under commercial storage and supply chain environments. In addition, the lack of standardized treatment protocols and crop-specific variability in elicitor responses limits their broader application. Postharvest elicitation is a promising strategy for improving phytochemical content and nutraceutical quality of horticultural crops; however, further optimization is required for commercial application. Future research should focus on standardizing treatment conditions such as dose, exposure time, and intensity for different crops and cultivars. Greater understanding of genotype- and tissue-specific responses, along with long-term storage and consumer acceptability studies, is also necessary. In addition, combined elicitor treatments and advanced omics approaches may help better understand and enhance elicitor-induced metabolic changes. Challenges related to large-scale application, cost, and process standardization must also be addressed to successfully integrate postharvest elicitation into sustainable food systems.

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