

The importance of microRNA molecular analysis in the field of postharvest biology and technology

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ABSTRACT

Postharvest processing goes far beyond being a merely technical stage within the agricultural supply chain. It represents a critical bridge between production and consumption that can substantially improve farmers' livelihoods, enhance consumer satisfaction, and contribute meaningfully to sustainable development. Among the emerging scientific topics relevant to postharvest science, microRNA compounds are recognized as a class of important non-coding RNA molecules that play a central role in the regulation of gene expression. These small regulatory molecules influence a wide range of biological processes by controlling the translation or stability of target messenger RNAs. This study shows that during storage, transportation, and processing, microRNAs can affect ripening, senescence, stress tolerance, and quality attributes such as texture, color, flavor, and shelf life. By synthesizing existing research, this review paper highlights how a deeper understanding of microRNA-mediated regulatory mechanisms can contribute to the development of innovative postharvest technologies. Moreover, it introduces and investigates microRNAs that can be reliable markers of the quality of fruits and vegetables over storage. Such knowledge may ultimately support more efficient processing methods, reduced postharvest losses, improved product quality, and enhanced sustainability across agricultural value chains.

1. Introduction

Postharvest processing is one of the most critical stages in the agricultural production chain, playing a highly vital role in maintaining product quality, reducing losses, extending shelf life, and increasing the added value of agricultural commodities (Mujumdar and Law, 2010). This process not only helps farmers deliver higher-quality products to the market, but also has a direct and significant impact on consumer satisfaction, economic profitability, and national and global food security. For these reasons, postharvest processing is widely recognized as a strategic component of modern agricultural systems. In the following sections, the importance of postharvest processing is examined from multiple perspectives (Kitinoja et al., 2011).

One of the primary and most compelling reasons for emphasizing postharvest processing is the reduction of agricultural losses. A substantial proportion of agricultural products, particularly in developing countries, is lost before reaching the market due to inadequate processing facilities, poor storage conditions, and inefficient transportation systems (Chen and Pan, 2022). These losses represent not only wasted food, but also wasted resources such as water, labor, energy, and capital. Postharvest operations such as cleaning, sorting, grading, packaging, and drying are among the most important measures used to preserve product quality and prevent deterioration (Dayeh et al., 2024). When these processes are implemented correctly and in a timely manner, the likelihood of spoilage, mechanical damage, and microbial contamination is significantly

reduced, leading to a marked decrease in overall postharvest losses (Zheng et al., 2023).

MicroRNAs are increasingly recognized in postharvest science as a significant group of non-coding RNA molecules with a central role in regulating gene expression (Samadi et al., 2025b; Sharbati et al., 2025). These small regulatory elements modulate numerous biological processes by influencing the translation and stability of specific messenger RNAs (Mohammadi and Asefpour Vakilian, 2023). Throughout storage, transportation, and processing, microRNAs can impact ripening, senescence, stress responses, and key quality traits, including texture, color, flavor, and shelf life. This review examines the importance of studying microRNA compounds within the framework of postharvest processing of agricultural products.

2. The Importance of Postharvest Technology

Food security refers to the condition in which all individuals have continuous access to safe, nutritious, and sufficient food at all times (Ganjdoost et al., 2021). By minimizing spoilage and preserving food quality, postharvest processing helps ensure that a greater proportion of produced food reaches consumers in usable form (Kumar and Kalita, 2017). Moreover, during periods of crisis—such as natural disasters, armed conflicts, pandemics, or disruptions in supply chains—the availability of processed and storable food products can prevent severe food shortages and humanitarian emergencies. In such situations, processed foods serve as a strategic reserve that enhances the resilience of food

systems and supports continuity in food supply (Hodges et al., 2011).

Many agricultural products are highly vulnerable to environmental factors after harvest, including temperature fluctuations, humidity, light exposure, and the activity of microorganisms. Without appropriate intervention, these factors can rapidly accelerate physiological degradation and quality loss (Liu et al., 2025). Proper postharvest processing helps control and manage these environmental conditions, thereby extending the storage life of products. For example, different techniques such as drying, freezing, and canning enable products to remain suitable for consumption over extended periods without significant reductions in their nutritional value (Chen et al., 2021). These methods slow down enzymatic activity, inhibit microbial growth, and maintain the sensory attributes of food products, making them more reliable and accessible for consumers throughout the year (Hayat et al., 2023).

In addition to preservation, postharvest processing significantly enhances the visual and commercial appeal of agricultural products. Proper processing results in products with more attractive appearances, uniform size and shape, and suitable, standardized packaging (Anusha et al., 2024). These attributes are especially important in both domestic and international markets, where consumers and industrial buyers increasingly demand consistent quality and compliance with established standards. Well-processed products are better positioned to compete in global markets and can often be sold at higher prices due to their improved quality, safety, and presentation (Nordhagen et al., 2023).

Through appropriate postharvest processing, more efficient use of natural resources such as water, soil, and energy can also be achieved. Agricultural production requires significant inputs, and when large volumes of food are lost after harvest, these valuable resources are effectively wasted (Nath et al., 2024). By reducing losses and improving preservation, postharvest processing lowers the overall pressure on natural resources and contributes to more sustainable resource management. When postharvest operations are carried out using environmentally sound practices—such as energy-efficient technologies, reduced chemical use, and sustainable packaging materials—they can align closely with the goals of sustainable agricultural development. In this way, postharvest processing not only supports productivity and profitability but also helps prevent environmental degradation and the long-term depletion of natural ecosystems (Elik et al., 2019).

In today's highly competitive global markets, agricultural success depends not only on the volume of production but also on product quality, consistency, safety, and presentation (Sarlaki et al., 2023). Simply producing sufficient quantities of agricultural commodities is no longer enough; the manner in which these products are processed, packaged, and delivered to markets is equally critical. Countries with well-developed processing infrastructure are better positioned to export high-quality agricultural products that meet international standards and consumer expectations (Emana et al., 2017). This capability allows them to gain a larger share of global markets, increase foreign exchange earnings, and enhance overall economic growth. Ultimately, effective postharvest processing strengthens a country's position in international trade, improves its agricultural competitiveness, and supports long-term economic development (Ntsoane et al., 2019; Kheiralipour, 2022; Sajadipour and Kheiralipour, 2025).

3. MicroRNAs and Their Importance in Postharvest Processing

MicroRNAs are very small molecules found in cells that help control how genes work. They are short pieces of RNA, usually about 20 to 24 units long, and they do not make proteins

themselves. Instead, microRNAs regulate gene activity by binding to messenger RNA (mRNA) and reducing or stopping protein production. In this way, they act like switches or dimmers that fine-tune gene expression. MicroRNAs are important for many biological processes, including growth, development, stress responses, and disease (Asefpour Vakilian, 2019; 2020). In plants and animals, they help cells respond properly to internal signals and environmental changes.

In the postharvest period, the importance of microRNA compounds becomes particularly evident, as harvested fruits and vegetables continue to undergo active metabolic and physiological changes (Shi et al., 2019). MicroRNAs play an essential role in regulating ripening processes by controlling genes involved in hormone signaling pathways, such as those related to ethylene production and response (Hashemi Shabankareh et al., 2023). By influencing the timing and rate of ripening, microRNAs can affect texture, color development, flavor formation, and overall consumer acceptability of agricultural products. Proper regulation of these processes is critical for extending shelf life and maintaining market quality during storage and distribution (Samadi et al., 2025a).

In addition to their role in ripening, microRNAs are also involved in plant senescence and aging processes after harvest. They regulate genes associated with cell wall degradation, chlorophyll breakdown, and nutrient remobilization, all of which contribute to the gradual decline in product quality. Furthermore, microRNAs participate in defense responses against various postharvest stresses, including mechanical injury, temperature stress, oxidative stress, and pathogen attack (Sui et al., 2023). By modulating stress-responsive genes, microRNAs can enhance the resistance of harvested products to spoilage and decay, thereby reducing postharvest losses. Figure 1 depicts the most investigated microRNAs in the field of postharvest biology and technology. The data used to design this figure were based on microRNA data provided in Ma et al. (2020). The main fields include ripening and senescence, decay control, and stress resistance. Moreover, Table 1 provides the main target genes identified for many of these microRNAs, which are described in the following sections.

4. The Role of microRNAs in Regulating the Ripening Process

Ripening is one of the most fundamental physiological processes of fruits and vegetables occurring after harvest and is directly associated with eating quality, consumer acceptance, and marketability of agricultural products. The progression of ripening determines key quality attributes such as texture, color, aroma, flavor, and nutritional value, all of which strongly influence consumer preferences and commercial value. Numerous microRNA compounds play critical roles in regulating the expression of genes involved in the ripening process, acting as fine regulators of complex molecular networks that control postharvest fruit development (Chen et al., 2020).

For example, microRNAs such as miR156 and miR172 have been shown to be actively involved in regulating genes associated with major hormonal signaling pathways, particularly those related to ethylene and abscisic acid (ABA) (Jin et al., 2020; Ahmad et al., 2022). These two hormones are considered primary regulators of ripening in climacteric fruits, including tomato, banana, and apple, where ripening is characterized by a sharp increase in respiration rate and ethylene production. By influencing transcription factors and signaling components within these hormonal pathways, miR156 and miR172 can modulate the timing and intensity of ripening-related responses. As a result, these microRNAs indirectly affect critical ripening events such as starch-to-sugar conversion, pigment accumulation, and volatile compound synthesis (Pradhan et al., 2025).

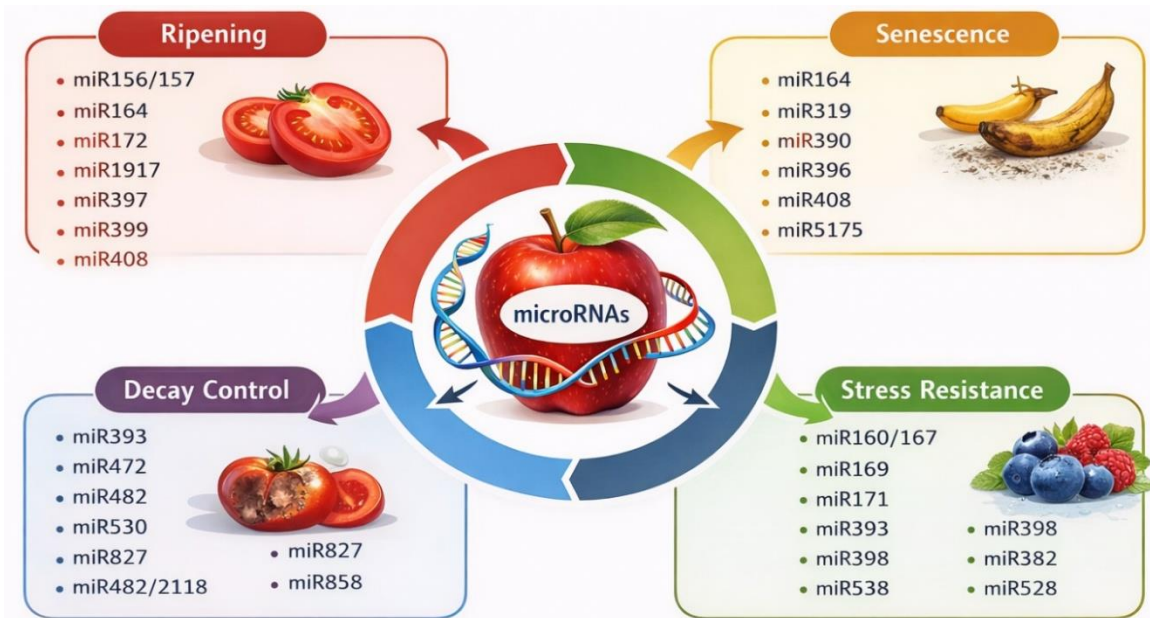


Figure 1. The most investigated microRNAs in the field of fruit postharvest biology and technology

Table 1. The main target genes identified for various microRNAs involved in fruit storage

Postharvest characteristic	Agricultural product	Involved microRNA	Target gene / Functional category	Reference
Ripening and senescence	Apple	miR172	<i>AP2/ERF</i> ; ethylene pathway	Xia et al. (2025)
Ripening regulation	Tomato	miR156/miR157	<i>AP2-like</i> and <i>SPL</i> transcription factors	Karlova et al. (2013)
Ripening timing	Tomato	miR396	Regulatory involvement in ripening	Zuo et al. (2012)
Senescence delay	Strawberry	PC-5p-176409_20	<i>ABA</i> signaling components	Xu et al. (2015)
Senescence regulation	Strawberry	miR164	<i>NAC</i> transcription factors	Xu et al. (2015)
Senescence regulation	Strawberry	miR167	<i>ARF</i> transcription factors	Xu et al. (2015)
Ripening / quality	Pineapple	miR164	Post-ripening differential expression	Yusuf and Kumar (2010)
Developmental regulation	Pineapple	miR390	<i>TAS3</i> / regulatory modules	Yusuf and Kumar (2010)
Ripening profile	Strawberry	PC-5p-67794_53	Hydrolase family genes	Xu et al. (2015)
Ripening profile	Strawberry	PC-5p-1004_3092	Glycosyl hydrolase	Xu et al. (2015)
Ripening network	Sweet cherry	novel/known miRNAs	<i>SPL</i> , <i>TCP</i> , <i>NAC</i> , and <i>MYB</i> families	Wang et al. (2019)
Ethylene & ripening	Tomato	miR390	Auxin response via <i>TAS3</i>	Karlova et al. (2013)
Ripening modulation	Grapevine	miR477b / miR399	Ripening timing regulators	Kong et al. (2021)
Anthocyanin & color	Sweet cherry	miR159 / miR828	<i>MYB</i> and <i>SPL</i> transcription factors	Wang et al. (2019)
Oxidative stress response	Various fruits	miR398	Antioxidant enzymes (Cu/Zn SOD)	Ma et al. (2020)
Stress & hormone cross-talk	Banana	miR156a	<i>SPL7/9</i> ; ethylene signaling	Kong et al. (2021)
Stress & salt network	Banana	miR395d	<i>EIN3</i> ethylene regulator	Kong et al. (2021)
Texture / softening	Pear	miR397	Laccases; cell wall metabolism	Huang et al. (2022)
Browning control	Sponge gourd	miR172a	Browning modulation genes	Kong et al. (2021)
Browning control	Litchi	miR159	<i>GAMYB</i> transcription factors	Yin et al. (2023)
Defense response	Litchi	miR160	<i>ARF18</i>	Yin et al. (2023)
Defense response	Litchi	miR167	<i>ARF8</i>	Yin et al. (2023)
General quality/physiology	Multiple fruits	miR159	<i>MYB</i> family regulators	Ma et al. (2020)
General quality/physiology	Multiple fruits	miR166	Homeobox / developmental TFs	Ma et al. (2020)
General quality/physiology	Multiple fruits	miR171	<i>GRAS</i> family TFs	Ma et al. (2020)
Flavor component	Tomato	miR399	Sugar–acid balance; predicted targets	Ma et al. (2020)
Phytohormone cross-talk	Banana	miR535a	<i>NHE6</i> sodium/hydrogen exchanger	Kong et al. (2021)
Stress & senescence	Banana	miRn60	Browning and stress genes	Kong et al. (2021)
Fruit quality network	Multiple fruits	miR858	<i>MYB</i> family	Kong et al. (2021)
Cell wall & texture	Multiple fruits	miR3627 / miR479	Cell wall metabolism enzymes	Kong et al. (2021)

In addition to hormonal regulation, certain microRNA compounds influence the expression of enzymes directly involved in structural changes of fruit tissues. For instance, microRNAs can regulate enzymes such as polygalacturonase, pectin methylesterase, and cellulase, which are responsible for cell wall degradation and tissue softening during ripening (Samadi et al., 2025a). By upregulating or downregulating the expression of these enzymes, microRNAs can indirectly control the rate of fruit softening, which is a key determinant of shelf life and resistance to mechanical damage during storage and transportation. Excessive or uncontrolled softening often leads to reduced marketability and increased postharvest losses,

highlighting the importance of precise regulatory mechanisms (Bisht and Singh, 2024).

The fine-tuned regulation of ripening pathways by microRNA compounds offers significant potential for improving postharvest management strategies. By understanding how specific microRNAs influence ripening-related genes and metabolic pathways, it may be possible to develop targeted approaches to delay ripening, synchronize maturity, or maintain optimal quality for longer periods (Kong et al., 2021). Such strategies could include genetic selection, biotechnological interventions, or postharvest treatments that modulate microRNA activity. Ultimately, precise regulation of fruit ripening

through microRNA-mediated pathways can contribute to improved shelf life, reduced losses, enhanced fruit quality, and greater flexibility in postharvest handling and marketing of agricultural products (Huang et al., 2022; Zaman et al., 2023).

5. The Role of microRNAs and Cellular Senescence in Postharvest Crops

Another major challenge during the postharvest period is senescence, a complex and genetically regulated process that leads to a gradual decline in the visual appearance, nutritional value, and overall marketability of agricultural products. Senescence is accompanied by physiological and biochemical changes such as chlorophyll degradation, loss of membrane integrity, increased respiration, nutrient depletion, and reduced resistance to environmental and biological stresses (Hossain et al., 2020). These changes collectively accelerate quality deterioration and significantly shorten the shelf life of fruits and vegetables, thereby increasing postharvest losses and reducing economic returns.

Research has demonstrated that specific microRNA compounds play an important role in regulating the genetic pathways associated with the onset and progression of senescence. For example, miR164 has been shown to regulate NAC transcription factor genes, which are recognized as key regulators initiating senescence-related processes (Kim et al., 2016). NAC proteins are involved in controlling programmed cell death, nutrient remobilization, and stress responses, all of which contribute to aging and tissue breakdown after harvest. By modulating the expression of NAC genes, miR164 can influence the timing and intensity of senescence, thereby affecting how rapidly quality declines in harvested products (Li et al., 2017; Wang et al., 2023). Similarly, miR319 has been identified as an effective regulator of TCP transcription factor genes, which are associated with the maintenance of tissue freshness and the delay of senescence (Koyama et al., 2017). TCP genes influence cell division, hormone signaling, and metabolic balance, and their proper regulation helps preserve structural integrity and physiological activity in postharvest tissues. Through its regulatory effect on TCP genes, miR319 contributes to sustaining freshness, delaying yellowing, and slowing down degenerative processes that negatively impact product quality (Kong et al., 2021).

6. Response to Postharvest Stresses through microRNAs

After harvest, agricultural products are exposed to a wide range of biotic and abiotic stresses, including water deficit (dehydration), low or high temperature stress, light stress, and attacks by microbial and fungal pathogens. These stresses can disrupt normal cellular functions, accelerate physiological deterioration, and ultimately lead to rapid quality loss and increased postharvest spoilage. In this context, microRNA compounds play a critical role in enhancing stress tolerance by regulating plant defense signaling pathways and maintaining cellular homeostasis during the postharvest period (Sharbati et al., 2025). MicroRNAs function as key molecular regulators that enable harvested plant tissues to respond adaptively to unfavorable conditions. By modulating the expression of stress-responsive genes, microRNAs can influence antioxidant systems, hormone signaling pathways, and defense-related metabolic processes. For example, miR398 is known to play an important role in controlling the plant response to oxidative stress by regulating genes encoding antioxidant enzymes such as superoxide dismutase (Javed et al., 2019). Oxidative stress is a common consequence of postharvest handling and storage, particularly under temperature extremes or mechanical injury (Toivonen, 2004). Through its regulatory activity, miR398 helps

limit the accumulation of reactive oxygen species, thereby reducing cellular damage and delaying quality degradation (Li et al., 2022).

Another important microRNA, miR393, is involved in defense-related pathways associated with plant hormones, particularly auxin signaling (Hussein et al., 2024). By modulating auxin receptors and related signaling components, miR393 contributes to the regulation of plant immune responses and stress adaptation (Yu et al., 2024). In the postharvest context, altered auxin signaling can influence tissue integrity, susceptibility to pathogens, and stress-induced senescence. The regulatory role of miR393 highlights its potential importance in maintaining postharvest quality under both biotic and abiotic stress conditions. In addition, members of the miR482/2118 family are recognized for their role in defense against pathogens through the regulation of resistance (R) genes (Zhang et al., 2022). These microRNAs are involved in fine-tuning immune responses by balancing defense activation and energy conservation. After harvest, when fruits and vegetables become more vulnerable to fungal and bacterial infections due to tissue damage and weakened defense systems, miR482/2118-mediated regulation can significantly influence disease resistance and spoilage progression (de Vries et al., 2015).

Artificial enhancement or inhibition of specific microRNA compounds offers a promising strategy for increasing the resistance of agricultural products to postharvest deterioration. Approaches such as targeted breeding, molecular treatments, or biotechnological interventions aimed at modulating microRNA expression could strengthen stress tolerance, reduce decay, and prolong shelf life. Overall, the strategic manipulation of microRNA-mediated defense mechanisms represents a novel and effective avenue for improving postharvest resilience, minimizing losses, and maintaining the quality and safety of agricultural commodities under diverse storage and handling conditions.

7. Using microRNAs as Biomarkers Over Storage

One of the emerging and innovative applications of microRNA compounds in the postharvest period is their use as biomarkers, or biological indicators, for monitoring the physiological status of agricultural products. Biomarkers are measurable biological signals that provide insight into internal biological processes, and microRNAs are particularly well-suited for this role due to their stability, specificity, and close association with gene regulation (Ajit, 2012). By analyzing the expression patterns of specific microRNA compounds in fruits and vegetables, it becomes possible to obtain precise information about the physiological condition of the product at different stages after harvest (Hashemi Shabankareh et al., 2023). For example, changes in the expression levels of certain microRNAs can indicate whether a fruit or vegetable is at an early, optimal, or advanced stage of ripening, or whether it has entered the senescence phase (Sharbati et al., 2025; Samadi et al., 2025a). Similarly, specific microRNA expression profiles may reveal increased susceptibility to diseases or stress conditions before visible symptoms appear (Kong et al., 2021). This early detection capability is especially valuable, as it allows producers, storage managers, and distributors to make timely and informed decisions regarding handling, storage duration, and marketing strategies. In contrast to traditional quality assessment methods, which often rely on external appearance or destructive testing, microRNA-based monitoring offers a more sensitive and molecular-level assessment of product quality (Dayeh et al., 2024).

Conventional biosensors for microRNA measurement rely primarily on optical and electrochemical detection strategies to achieve sensitive and specific analysis (Johnson and Mutharasan, 2014). Optical biosensors commonly use fluorescence, surface plasmon resonance, or colorimetric signals generated by the

hybridization between target microRNAs and complementary probes, enabling real-time and label-based or label-free detection (Asefpour Vakilian, 2025). Electrochemical biosensors, in contrast, measure changes in current, voltage, or impedance resulting from microRNA–probe interactions at electrode surfaces (Keshavarz et al., 2015). These platforms often incorporate nanomaterials, enzymes, or redox indicators to enhance signal amplification and detection specificity (Ren et al., 2013).

The use of microRNA compounds as postharvest biomarkers has significant implications for optimizing storage and distribution conditions. By continuously or periodically monitoring microRNA expression patterns, storage parameters such as temperature, humidity, atmospheric composition, and handling practices can be adjusted to better match the physiological needs of the product (Bai et al., 2023). This targeted management approach can slow down ripening and senescence, reduce the risk of disease development, and minimize postharvest losses. Furthermore, such precision-based postharvest management supports more efficient logistics, reduces unnecessary waste, and helps ensure that products reach consumers at their highest possible quality (Dayeh et al., 2024). Overall, the application of microRNA compounds as biological markers represents a promising advancement in postharvest science and technology (Ninama et al., 2024). Integrating microRNA-based diagnostics into postharvest management systems could lead to smarter, data-driven decision-making, improved quality control, and more sustainable supply chains. As research in this area continues to expand, microRNA biomarkers may become a key tool for enhancing shelf life, ensuring food safety, and maximizing the economic value of agricultural products throughout the postharvest period.

8. Future Perspectives

As advancements in biotechnology continue to accelerate and scientific understanding of the specific mechanisms, regulatory networks, and molecular targets of microRNA compounds deepens, it is increasingly expected that their application in agriculture and postharvest management will become more widespread and impactful in the near future. Ongoing research is steadily uncovering how microRNAs influence gene expression, stress responses, growth regulation, and senescence processes in plants, thereby providing a strong foundation for their practical use across diverse agricultural systems. As knowledge in this area expands, microRNA-based approaches are likely to transition from experimental concepts to routinely applied tools in crop production and postharvest handling (Yan et al., 2025).

At the same time, significant progress in analytical tools, high-throughput sequencing technologies, molecular biology techniques, and biotechnological interventions is making it possible to identify, manipulate, and apply microRNAs in a more precise, targeted, and efficient manner. These technological

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improvements enable researchers to better characterize microRNA expression patterns, predict their functional roles, and design strategies that modulate their activity with greater accuracy. As a result, the integration of microRNA research into applied agricultural practices is becoming increasingly feasible and cost-effective (Xu et al., 2026).

Together, these developments open new opportunities for designing innovative and sustainable strategies to maintain product quality, delay physiological deterioration, and enhance the resilience of agricultural commodities throughout the entire supply chain, from field production to storage, transportation, and retail. By regulating key biological pathways, microRNA-based interventions have the potential to improve stress tolerance, extend shelf life, and reduce losses caused by environmental factors or postharvest disorders. Investing in research focused on microRNA compounds and expanding their applications in genetic engineering, molecular breeding, and postharvest quality control, therefore, represents an effective and forward-looking approach to addressing critical challenges in modern agriculture. Such investments can directly contribute to increased productivity, improved food security, enhanced crop sustainability, and substantial reductions in postharvest losses and food waste on a global scale.

9. Conclusion

MicroRNA compounds play a pivotal role in regulating the physiological processes that occur during the postharvest period of agricultural products. This review shows that from controlling fruit ripening and senescence to mediating responses to environmental stresses and pathogenic attacks, these small RNA molecules possess substantial potential to improve product quality, extend shelf life, and significantly reduce postharvest losses. Through precise regulation of gene expression, microRNAs influence key metabolic and signaling pathways that determine how harvested products respond to storage conditions, handling practices, and biotic or abiotic challenges. Integrating microRNA-based technologies into postharvest systems has the potential to support more sustainable agricultural practices, strengthen food supply chains, and ensure the delivery of high-quality products to consumers while minimizing economic and environmental losses.

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Competing interests

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Data availability statement

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