Molecular Plant Breeding 2025, Vol.16, No.3, 191-201
http://genbreedpublisher.com/index.php/mpb

Research Insight Open Access

Enhancing Postharvest Characteristics in Durian via Genome Editing: Regulation of Pericarp Softening and Shelf-Life Extension

Dandan Huang[1], Haimei Wang[1,2]
1 Hainan Institute of Biotechnology, Haikou, 570206, Hainan, China
2 Hainan Institute of Tropical Agricultural Resources, Sanya, 572025, Hainan, China
Corresponding email: Haimei.wang@hibio.org
Molecular Plant Breeding, 2025, Vol.16, No.3 doi: 10.5376/mpb.2025.16.0019
Received: 11 May, 2025
Accepted: 13 Jun., 2025
Published: 21 Jun., 2025

Preferred citation for this article:
Huang D.D., and Wang H.M., 2025, Enhancing postharvest characteristics in durian via genome editing: regulation of pericarp softening and shelf-life extension, Molecular Plant Breeding, 16(3): 191-201 (doi: 10.5376/mpb.2025.16.0019)

Abstract This study explored the use of CRISPR-mediated gene editing to reduce the softening rate of durian peel and delay senescence, focusing on key targets such as ethylene synthesis pathways (such as ACS2 and ACO1), cell wall degradation enzymes (such as PG, PME, EXP), peel cuticle formation (CER1) and antioxidant pathways (such as SOD, CAT, AOX). Strategies for applying genome editing to durian improvement were proposed, including phenotypic screening of edited lines and mechanistic analysis of how editing regulates the softening process at the molecular level. The potential advantages of breeding harder and more storable durian varieties were also discussed, including reducing postharvest losses, expanding market channels and improving economic benefits. At the same time, the challenges and risks that may be faced in this process were analyzed, such as off-target effects, regulatory barriers and the need to maintain the flavor quality of the fruit. Combined with the molecular biology research results of durian and the successful experience of gene editing in other fruit trees, genome editing technology is expected to become an important tool for improving the postharvest characteristics of durian, which can change the supply chain of durian, extend shelf life and maintain quality, thus benefiting growers, distributors and consumers.
Keywords Durian; Postharvest; Fruit Softening; Shelf Life; Genome editing

1 Introduction

Durian (*Durio zibethinus* L.), as one of the important tropical fruits in the Southeast Asian economy, is deeply loved by consumers due to its unique flavor characteristics. However, under the influence of unique regional climate conditions, durian fruit will ripen rapidly, causing the skin to soften quickly and greatly shortening its shelf life, reducing the commercial value of durian and seriously restricting its industrial development potential (Suntichaikamolkul et al., 2021; Khaksar et al., 2024). The physiological process of softening durian skin not only directly affects the market sales of the fruit, but also has adverse effects on the economic value and consumer acceptance of the product. Therefore, it is necessary to adopt effective post harvest quality management strategies for its fruit (Yang et al., 2017; Suntichaikamolkul et al., 2021).

Traditional durian post-harvest management mainly relies on low-temperature refrigeration and chemical inhibitors to slow down ripening. Proper refrigeration can delay respiration, but too low a temperature can easily cause chilling damage, resulting in browning of the peel and loss of flavor. 1-methylcyclopropene (1-MCP) is a commonly used inhibitor of ethylene action, which can delay the ripening and softening of many fruits, and has also shown certain effects in higher plants such as durian.

However, studies have shown that 1-MCP treatment of durian can only temporarily inhibit ethylene release, and excessive or long-term use may lead to abnormal ripening of the flesh, such as the “green skin ripe fruit” disorder of bananas and rubbery flesh of papayas. In addition, these exogenous treatments increase logistics and processing costs and may affect flavor and texture (Lobato-Gómez et al., 2021). Therefore, relying on traditional methods to extend the shelf life of durian has limited effect, and it is urgent to start from the crop itself and develop new ways to fundamentally slow down the softening of fruits after harvest.

Recently, modern gene editing technologies represented by the CRISPR/Cas9 system have demonstrated unique advantages, providing a new pathway for genetic improvement of fruit quality. By precisely regulating ripening related genes, fruit hardness can be enhanced, ripening can be delayed, and shelf life can be extended (López Casado et al., 2023). CRISPR/Cas9 can enhance fruit firmness, improve post harvest disease resistance, and achieve the dual goals of extending shelf life and improving overall fruit quality by silencing or modifying key genes such as polygalacturonase and pectin lyase (Yang et al., 2017; López Casado et al., 2023).

This study will explore the use of genome editing to regulate the softening process of durian peel, with a focus on analyzing relevant molecular pathways and genetic regulatory networks, and identifying potential genetic modification targets. Utilizing technological innovation to extend the commercial shelf life of durian and reduce post harvest losses can not only provide theoretical basis for the application of gene editing technology in improving the quality of tropical fruits, but also help cultivate new varieties with higher market adaptability and promote the sustainable development of the durian industry.

2 Phenotypic and Molecular Characteristics of Durian Fruit

2.1 Phenotypic identification of gene-edited durian fruit

Durian is a typical climacteric fruit, and its ripening process is accompanied by a sharp increase in ethylene and a peak in respiration. Shortly after harvesting, the durian peel begins to soften and its hardness decreases rapidly. The study compared the softening rates of different durian varieties: Monthong and Kanyao are slow-ripening varieties, and the peel softens about 5 days after harvesting; while fast-ripening varieties such as Chanee and Phuangmanee reach edible maturity 3 days after harvesting (Khaksar et al., 2019; Khaksar and Sirikantaramas, 2020). Instrumental measurement of the texture of the peel showed that the peel of durian was still hard one day after harvesting, and the hardness value in the texture profile analysis decreased sharply as it matured.

In the report of Khaksar and Sirikantaramas (2020), the hardness of durian pulp dropped from about 3.4 N in the unripe stage to 1.55 N in the fully ripe stage, confirming the occurrence of significant softening of the peel and pulp. Peel softening directly determines the shelf life and storage characteristics of durian: the softer the peel, the harder it is for the fruit to withstand handling vibrations, and it is very easy to crack or rot, limiting long-distance transportation and long-term storage. Therefore, phenotypic measurement of durian postharvest softening characteristics by the rate of peel hardness reduction and shelf life is very important for screening storage-resistant varieties and evaluating improvement effects.

2.2 Molecular characterization analysis of gene-edited durian

The softening process of durian is precisely regulated by a series of genes related to cell wall degradation and hormone signals. To perform genome editing on these genes, their sequences and functions must first be clarified. Durian whole genome sequencing and transcriptome analysis provide a basis for this: the draft durian genome published in 2017 identified a large number of candidate genes related to fruit ripening. For example, polygalacturonase (Pg, encoding pectinase PG) and cellulase (Cel) genes are highly expressed during durian ripening and are believed to be responsible for decomposing cell wall polysaccharides in the peel and pulp, resulting in softening texture (Pan et al., 2022). The β-galactosidase (BGal) gene increases the porosity of the cell wall by removing the galactosyl group of the pectin side chain of the cell wall, accelerating the action of other enzymes on the cell wall. In addition, there are also multiple ethylene biosynthesis-related genes in the durian genome, such as 1-aminocyclopropane-1-carboxylic acid synthase ACS2 and oxidase ACO1; these genes directly determine the ethylene production rate and are key switches for regulating the ripening process. For example, the MaACO1 homologous gene found in banana is also highly conserved in durian, and its knockout or functional loss is expected to significantly reduce ethylene release and delay ripening (Hu et al., 2021).

3 Molecular Mechanisms of Durian Pericarp Softening

3.1 Physiological and biochemical processes of pericarp softening

Durian peel softening is a complex physiological and biochemical process driven by a multi-level regulatory network, including cell wall degradation, hormone signals, and metabolic changes. From a physiological point of view, fruit softening mainly stems from the disintegration of cell wall structure and the increase of cell membrane

permeability, which makes the flesh tissue loose and juicy. The cell wall is composed of macromolecules such as pectin, cellulose, and hemicellulose, and its stability ensures the hardness of unripe fruits. During ripening, various cell wall hydrolases are triggered by signals such as ethylene, synthesized in large quantities and secreted into the cell wall, synergistically catalyzing the degradation of cell wall components.

Polygalacturonase (PG) is one of the key enzymes for pectin degradation, which can hydrolyze the α-1,4-galacturonic acid bonds of the pectin backbone, leading to the disintegration of the intercellular mesoglea. In models such as tomatoes, PG has been shown to be expressed in large quantities from color change to maturity, and its activity is closely related to the softening rate of the fruit (Lobato-Gómez et al., 2021). Cellulase (also known as endo-β-1,4-glucanase) can degrade cellulose and hemicellulose networks, weaken the skeleton structure of the cell wall, and also play an important role in the softening of durian. The latest research shows that in tomatoes, the combined action of expansin and endoglucanase Cel can synergistically promote cell wall relaxation and fruit softening; it is speculated that a similar mechanism also exists in durian.

β-galactosidase (β-Gal) accelerates cell wall decomposition by removing sugar residues from the side chains of pectin and hemicellulose, increasing the accessibility of other enzymes to the main chain of the cell wall (Pan et al., 2022). It is worth mentioning that there is also a synergistic or cascade effect between enzymes during cell wall degradation. For example, expansin first loosens the cell wall structure, exposing the substrate to further action by PG, Cel, etc.; β-galactosidase removes the side chains and promotes the hydrolysis of the pectin main chain by PG.

3.2 Key genes and regulatory pathways in pericarp softening

Ethylene is one of the main hormones that control the softening of the durian peel. During ripening, the genes that help make ethylene, such as ACS (aminocyclopropane-1-carboxylic acid synthase), become more active. This leads to higher ethylene levels, which speeds up the softening process (Teh et al., 2017). Ethylene also increases the expression of genes for enzymes that break down the cell wall. In addition, it works together with other plant hormones, showing that the softening process is controlled by a complex network of signals (Osorio et al., 2013; Suntichaikamolkul et al., 2021).

Several genes directly control the making of cell wall-degrading enzymes. These include PG, pectin lyase (PL), expansins (EXP), and pectin methylesterase (PME). Among these, PG and PME are especially important because their activity rises a lot as the fruit ripens, breaking down pectin and causing the peel to soften (Imsabai et al., 2002). Swelling protein genes, such as DzEXP1 and DzEXP2, are also involved in this process. The expression of these genes is regulated by ethylene (Palapol et al., 2015). They work synergistically with other cell wall degrading enzyme genes (such as PME, PL, EXP, and XTH) to degrade pectin and hemicellulose, rearrange microfibers, and cause softening of durian peel (Figure 1) (Palapol et al., 2015; Peng et al., 2022).

4 Postharvest Impacts on Durian

4.1 Impact of rapid pericarp softening

When the skin of durian softens too quickly, the shelf life of the fruit will be greatly shortened, which not only reduces its market value but also increases the difficulty of export transportation. Many fruits face similar problems, as traditional post harvest treatments such as low temperature, controlled atmosphere, and radiation can delay aging and reduce losses, but often result in a decline in quality. Although early harvesting extends the shelf life, insufficient maturity affects flavor and nutrition, while mature harvesting faces the problem of short shelf life. According to a survey, about 33% of fruits and vegetables worldwide are wasted due to rapid decay (Figure 2) (Shipman et al., 2021), which brings huge economic losses to farmers and sellers.

Fast softening also affects the texture and taste of durian, which are very important for consumer choice. As the cell wall breaks down, with cellulose and pectin being the main parts affected, the fruit becomes too soft and loses its good texture (Gao et al., 2024). When the texture changes too much, people may not like the fruit as much, which can lower demand.

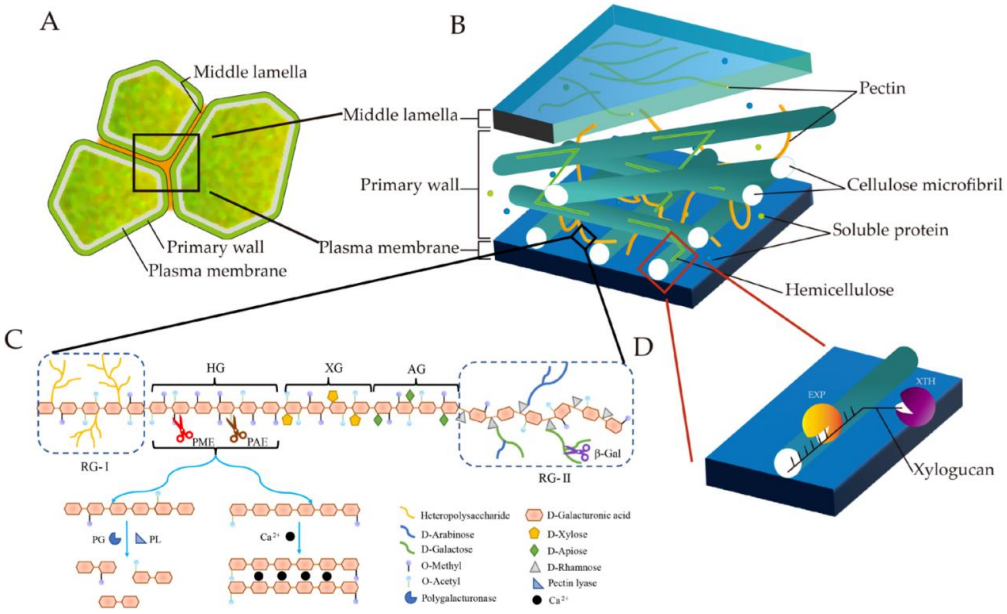

Figure 1 Cell wall structure (Adopted from Peng et al., 2022)

Image caption: (A) Schematic representation of the cell wall structure of three cells; (B) schematic representation of the structural components of the cell wall; (C) schematic representation of the pectin structure. Pectin is composed of five different types of polysaccharides, and various pectin-degrading enzymes are involved in pectin degradation (see text); (D) The cross-linking structure of hemicellulose and cellulose microfibril, EXP and XTH are involved in the depolymerization of the structure (Adopted from Peng et al., 2022)

4.2 Limits of current postharvest methods

Current post-harvest management methods also have limitations in dealing with durian softening. Low temperature storage is one of the commonly used methods, but durian is sensitive to low temperatures. If the temperature is lower than 13°C, chilling damage may occur, which manifests as brown spots on the skin and tissue vitrification, which reduces the commodity value. At the same time, the effect of low temperature in slowing down softening is limited. After returning to normal temperature, the fruit often completes the ripening process quickly (Adhikary and Das, 2022). Although chemical regulation may have a certain effect, it may bring health risks and usually cannot keep the fruit fresh for a long time (Chairat et al., 2022).

Controlled atmosphere storage (regulating the concentration of O_2 and CO_2 in the storage environment) can delay respiration in some fruits, but because durian itself breathes vigorously and releases odorous gases, the implementation cost of controlled atmosphere technology is high and the risks (such as anaerobic fermentation) are difficult to control, so it is rarely used commercially (Ikwan and Fikkri, 2020). Postharvest treatments such as hot water baths and coating preservation have also been tried: hot water treatment can induce the expression of some resistance genes, delay disease infection and lenticel aging; edible coatings (such as chitin coatings) can form barriers on the peel, reducing water loss and gas exchange.

Due to the many limitations of these methods, there is an urgent need to find more effective postharvest preservation strategies. In recent years, new gene editing tools such as CRISPR-Cas9 have provided a possible solution to this problem. By intervening in the softening mechanism of durian itself, the softening rate can be slowed down from the source, and the shelf life can be extended without relying on external measures (Shipman et al., 2021). By targeting and regulating genes related to cell wall degradation, it is expected that durian varieties with slower softening and better storage performance can be cultivated (Adhikary and Das, 2022; Gao et al., 2024). The storage resistance brought about by genetic improvement is inherently stable, which can reduce dependence on cold chain and chemical preservation, reduce energy consumption and the use of additives, and achieve a more sustainable supply chain.

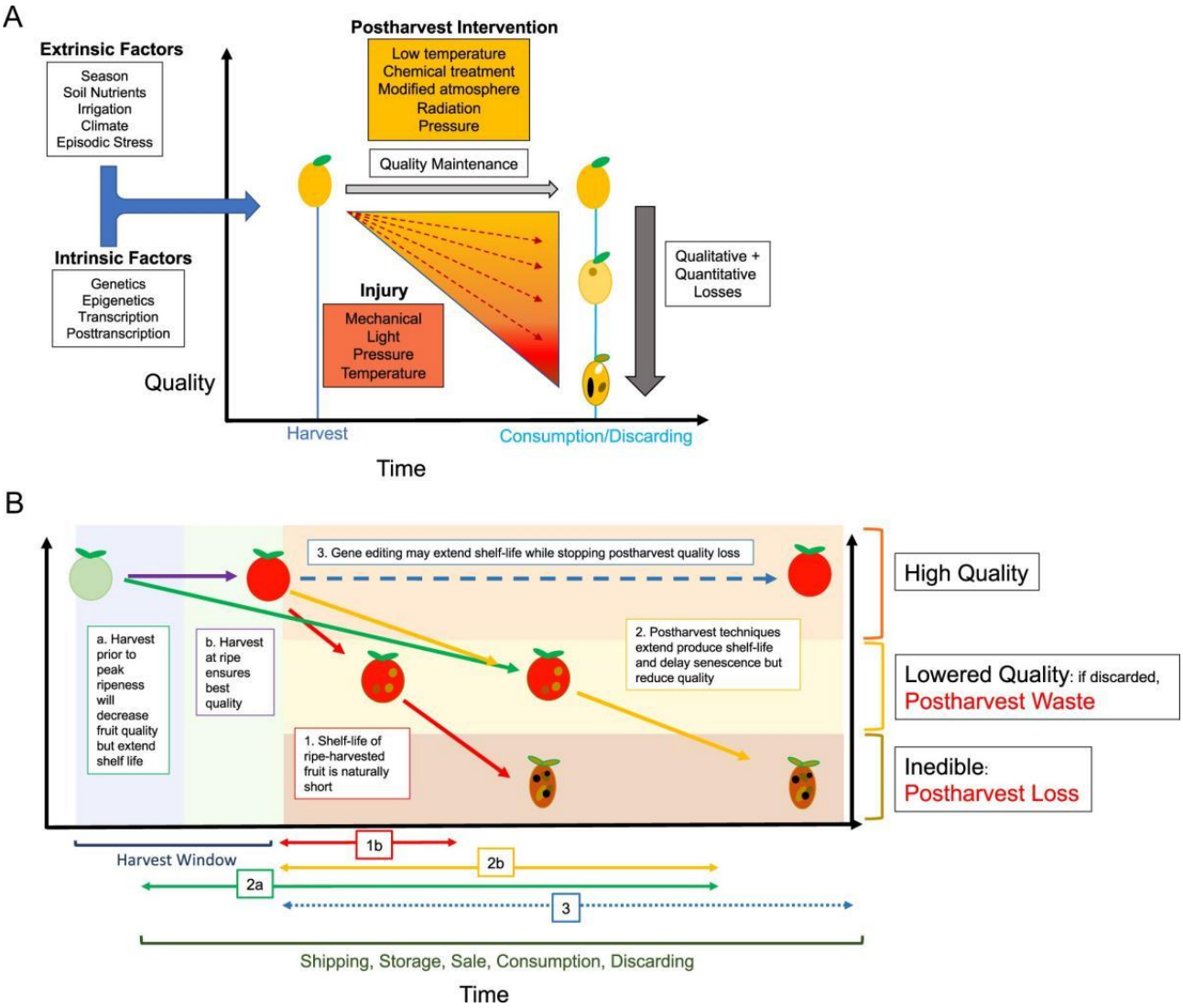

Figure 2 Determinants of produce quality (Adopted from Shipman et al., 2021)

Image caption: a Extrinsic environmental factors such as season, irrigation, soil nutrition and minerals, climate, stress, pathogens and pests, and agronomic practices as well as physiological genetic factors together determine fruit quality at harvest. Postharvest intervention, including refrigeration, chemical treatment, radiation, and modified atmospheres and pressure aims to maintain that quality through shipping and storage. Minor injury, ranging from mechanical or pathogenic damage to temperature, light, or pressure-induced damage, lowers the quality of fruit. More extensive injury renders produce inedible and contributes to the quantitative loss. b Potential postharvest outcomes for produce. Harvesting fruit prior to full ripeness will increase its shelf-life [a], but compromises quality during and after ripening [2a]. Fruit harvested at ripe [b] has a limited shelf-life before it declines in quality or rots [1b]. Postharvest intervention delays senescence and typically also results in some compromise of quality [2b]. The goal of gene editing is to extend shelf-life without loss of quality [3] and therefore reduce postharvest loss and waste (Adopted from Shipman et al., 2021)

5 Application Strategies of Gene Editing in Regulating Durian Pericarp Softening

5.1 Using CRISPR-Cas9 to control fruit softening

CRISPR-Cas9 can help control fruit softening by editing genes that make enzymes which break down the cell wall. These enzymes include polygalacturonase (PG), cellulase (Cel), and beta-galactosidase (BGal). When these genes are knocked out, the enzyme levels drop, which helps keep the fruit firm and extends shelf life.

This method has already been tested in other fruits. It shows that CRISPR-Cas9 can change how fruits ripen and soften by controlling these biological processes (Shipman et al., 2021; Gao et al., 2024). Reducing the activity of these enzymes helps keep the cell wall strong, which slows down softening (Gao et al., 2024).

5.2 Targeting genes for ethylene production

Ethylene is the dominant signal that triggers the ripening and softening of durian, and reducing ethylene production is considered to be one of the most effective ways to delay softening. By knocking out key enzyme genes in the ethylene synthesis pathway (such as ACO1 or ACS2) through CRISPR, the accumulation of ethylene during ripening can be greatly reduced, thereby slowing down the entire ripening process (Hu et al., 2021).

It should be noted that completely blocking ethylene may cause durian to fail to ripen normally (becoming a "never ripe" state), so the strategy should pursue "slowing down" rather than "completely blocking". For example, the key amino acids of the ACS2 enzyme are replaced with a partially inactivated form using base editing technology, so that the ethylene production rate is reduced but not zero. This fine regulation is expected to delay softening while still allowing the fruit to eventually mature and show the desired flavor. This is similar to the situation in which weak mutant alleles in tomatoes delay ripening but do not affect flavor (Hewitt and Dhingra, 2020).

5.3 Regulating transcription factors

Fruit ripening is a complex gene network, in which core transcription factors such as MADS-box and NAC play the role of "master switch" (Hewitt and Dhingra, 2020). Durian ripening is likely to have master effect transcription factors similar to tomato RIN and NOR. Once knocked out, they will greatly delay or even stop the ripening process. For example, if durian has NAC transcription factors that function similar to tomato NOR genes, in theory, CRISPR knockout of this gene will greatly delay the softening of the fruit, accompanied by the postponement of apparent ripening characteristics. In early breeding, the natural tomato mutants rin and nor had extremely long shelf life due to slow ripening, but also had problems of incomplete ripening and poor flavor (Lobato-Gómez et al., 2021). Therefore, for such key transcription factors, it is not advisable to knock out all of them, but it is possible to consider creating partial loss of function or low-function alleles.

The advantage of gene editing is that point mutations can be introduced precisely. In durian, attempts can be made to edit the promoters or enhancers of similar transcription factor genes to reduce their expression levels. For example, the CRISPR-Cas12a system was used to remove the key cis-elements on the promoter of the durian MADS-box gene, so that it was only weakly expressed after harvest, and the activation of downstream softening genes would be delayed or weakened (Lobato-Gómez et al., 2021). For another example, the putative durian NAC master regulator can be genetically edited to make its protein lack a transcriptional activation domain, changing from an activated type to a partially inactivated type, which can delay maturity without causing complete unripening. This refined editing scheme can be technically achieved through site-directed base editing or sequence-specific deletion.

5.4 Other emerging gene editing strategies

In addition to traditional gene knockout, upgraded versions of gene editing technology (such as CRISPR/Cas base editing, in situ editing, and genome reprogramming) can also be applied to durian softening regulation (Prado et al., 2024). For example, base editors can directly mutate one base to another without cutting the DNA double strand, thereby accurately generating point mutations. This is very useful for creating the above-mentioned "weak function" alleles, such as changing the key codon of the ethylene receptor gene ETR to a mutant type (similar to the mutation with ethylene resistance phenotype in Arabidopsis), so that durian is less sensitive to ethylene but not completely unresponsive.

Another example is genome reprogramming tools, which can direct the epigenetic state or transcription level of genes. Multi-gene stacking editing is also one of the strategies. As mentioned above, multiple softening enzyme genes and regulatory factors can be targeted at the same time to cultivate "slow-ripening" comprehensive trait lines (Lobato-Gómez et al., 2021). Some cutting-edge methods such as hormone combination culture medium and co-expression of morphogenesis regulatory genes can be used to improve the regeneration rate of durian and provide the necessary conditions for gene editing.

6 Extending the Shelf Life of Durian Through Genetic Engineering

6.1 Reducing the respiration rate

Excessive respiration will accelerate nutrient consumption and tissue decay. Therefore, in addition to the strategy of weakening ethylene synthesis, it is also possible to consider regulating metabolic pathways related to respiration. For example, enhancing the alternative oxidase (AOX) pathway to reduce the accumulation of excessive reactive oxygen species, thereby protecting cell function and delaying aging (Hewitt and Dhingra, 2020). Gene editing can be used to upregulate the function of such beneficial genes, such as enhancing the expression of durian *AOX* genes through promoter engineering, so that the fruit can better handle respiratory chain electrons during the transition period and reduce free radical damage. Another idea is to reduce the consumption of respiratory substrates, such as regulating the metabolic balance of starch and organic acids. When durian matures, starch rapidly degrades to provide respiratory substrates. Studies have shown that by editing a transcription factor that affects starch degradation in tomatoes, softening was delayed and texture was improved (Miao et al., 2025).

6.2 Regulating the composition of the cuticle layer of the peel to reduce water loss

The structural integrity of the peel is essential for fruit preservation. The cuticle and the wax layer covering it are natural barriers to prevent water evaporation and microbial infection. If the peel loses water too quickly, it will intensify softening and quality deterioration. Therefore, genetic modification can make the durian peel cuticle denser and higher in wax content, which can slow down water loss and maintain the hardness and freshness of the peel. Studies have shown that certain genes such as KCS (β-ketoacyl-CoA synthase) and CER1 (cuticular wax alkane synthase) are directly involved in the synthesis of very long-chain fatty acids and paraffins, and are key factors in determining the composition of peel wax (Wang et al., 2020; Yang et al., 2023).

In addition, the integrity of the cuticle is also related to pathogen defense. The increase in wax can reduce the adhesion and germination of fungal spores and improve disease resistance. In tomatoes, silencing the pectin lyase gene has been shown to increase fruit hardness and reduce sensitivity to pathogens, which indirectly helps to reduce water loss and extend the shelf life of fruits (Uluisik et al., 2016; Yang et al., 2017). In addition, the study also found that overexpression of certain genes in tomatoes can increase fruit firmness and reduce cell wall degradation, which further supports the role of genetic modification in maintaining fruit quality (Gao et al., 2024). For durian, gene editing can also be considered to increase wax accumulation, thereby giving the peel a “self-contained plastic wrap” function.

6.3 Delaying aging by improving antioxidant capacity

Post-harvest softening and decay of fruits are closely related to oxidative stress. During the maturation and aging process, cells produce a large amount of reactive oxygen species (ROS), such as superoxide anions and hydrogen peroxide. These ROS can attack membrane lipids and cell wall polymers, accelerating tissue softening and browning. Therefore, enhancing the antioxidant defense capacity of the fruit itself is expected to slow down the process of softening and aging. Antioxidant enzymes such as SOD and CAT can remove ROS and keep them at a low level (Meitha et al., 2020).

Genetic engineering can promote the role of the antioxidant system in durian fruit: first, overexpression of key antioxidant enzyme genes, such as SOD, CAT or APX (ascorbate peroxidase), so that the fruit can quickly remove excess ROS when ripening, protecting the cell membrane and wall structure from excessive oxidation and decomposition. Such attempts have been reported in other crops, such as overexpression of SOD/CAT to improve the storage antioxidant capacity of cassava tubers (Meitha et al., 2020). The second is to enhance the synthesis of antioxidant metabolites: for example, genes that regulate the synthesis of tomato lycopene or polyphenols can be edited to allow durian pulp to accumulate more antioxidants, thereby reducing oxidative stress during ripening. However, durian itself is rich in antioxidants such as vitamin C, so it can be decided according to the specific situation.

6.4 Case analysis of gene editing of other fruits

When studying the prospects of extending the shelf life of durian genetic engineering, it is worth referring to the successful experiences or lessons of other fruits. The genetically modified tomato Flavr Savr is the earliest

commercial product that delays softening. It extends the shelf life by inhibiting PG expression through antisense RNA. It verifies the feasibility of cell wall enzyme regulation, but also reminds us that we need to balance flavor-Flavr Savr was withdrawn from the market due to limited texture improvement and high cost (Lobato-Gómez et al., 2021). Gene editing technology has also been applied to fruit trees such as grapes and citrus to improve quality and disease resistance, such as editing grape powdery mildew resistance genes to obtain disease-resistant plants. Of particular note is the practice of gene editing in bananas and tomatoes: the achievement of extending the shelf life of bananas through CRISPR has proved that the technology can be used for tropical fruits (Prado et al., 2024). Tomatoes have become a pioneer in gene editing breeding. After high GABA healthy tomatoes entered the Japanese market, there have been many recent studies on gene editing tomatoes to improve flavor and delay softening (Tariq et al., 2024).

7 Challenges and Future Research Directions

7.1 Technical challenges

The genetic transformation and regeneration system of durian is not yet mature. Compared with model plants, durian needs to establish an efficient tissue culture method before gene editing. In addition, durian is a perennial woody plant, usually cross-pollinated, and the edited strains need to undergo multiple generations of self-pollination to purify mutations or be applied through grafting, which is more complicated and time-consuming than annual crops. In the case of multi-gene editing, the phenotypes of different mutation combinations require a large number of planting tests and comparisons, which also requires a long period of time. Potential off-target effects also need to be paid attention to. Although plant genomes are large and have many redundant sequences, a small number of off-target mutations are unlikely to cause serious effects, but applications in food should strive to avoid any unexpected changes. To this end, higher-fidelity editing enzymes, specific sgRNA design, and whole-genome sequencing screening of edited offspring can be used to ensure safety (Akanmu et al., 2024).

7.2 Economic and ecological benefits

Despite the challenges, successful gene editing of durian will bring huge economic benefits. Extending the shelf life means that exporters can use cheaper transportation methods (such as sea transportation instead of air transportation) to reduce logistics costs; fruit farmers can also keep durian on the tree for longer to achieve optimal maturity before harvesting, without worrying about not being able to sell it in the short term. A longer sales window is conducive to the market regulating supply and demand, avoiding depreciation caused by concentrated listing, and reducing waste caused by throwing away due to unsalable goods. Consumers can store and eat durian more calmly, improving consumer experience and demand stability. In terms of ecology, reducing post-harvest losses means that planting the same number of durian trees can meet the needs of more people and improve the efficiency of agricultural resource utilization. Storage-resistant durian can also reduce the cold chain energy consumption and chemical preservative input required for preservation, reducing carbon footprint and environmental pollution. At the same time, if durian can be kept fresh for a long time, it will reduce a large amount of organic waste and methane emissions caused by fruit rot, which is beneficial to the environment. Of course, these benefits can only be fully realized after a large-scale supply chain is built.

7.3 Food safety and public acceptance

Any new technology related to food must put safety and public awareness first. Genome editing essentially makes minor changes to the durian's own DNA without introducing exogenous genes, and theoretically does not produce new toxic and harmful substances. Current scientific evidence also shows that there is no difference in food safety between gene-edited fruits and traditionally bred fruits. For example, an analysis of the ingredients of genetically modified papayas that delay ripening found that their main nutrients, such as beta-carotene and vitamin C, were not significantly different from those of ordinary papayas (Cabanos et al., 2014). Nevertheless, before launching gene-edited durian, a comprehensive safety assessment is still required, including genetic stability, component equivalence testing, and allergen inspection to ensure that the improvement only occurs in the expected traits and no other negative changes are introduced.

In terms of supervision, different countries have different management policies for gene-edited crops. At present, the United States, Japan, etc. distinguish gene-edited products that do not contain exogenous DNA from genetically modified ones and implement relatively loose reviews. Countries such as China are still formulating corresponding regulations, but they have also released positive signals. If gene-edited durian varieties can emphasize their convenience (such as being able to store longer without spoiling after purchase) and quality improvement (such as delayed softening but still sweet), and pass safety certification by authoritative departments, they will be more easily accepted.

7.4 Future development prospects

Gene editing can be combined with traditional hybrid breeding and mutagenesis breeding to produce synergistic effects. For example, high-yield and disease-resistant varieties can be obtained through conventional means, and then gene editing can be used to give them post-harvest storage resistance. Such new combination varieties will have all-round advantages. With the deepening of understanding of the durian genome and ripening mechanism, a clear list of breeding indicator genes can be formulated and implemented through a package of multi-gene editing. Recently, a study has edited multiple sites in wild tomatoes at one time to achieve simultaneous improvement of multiple traits such as fruit size, quantity, and nutrition (Zsögön et al., 2018). A similar model is expected to be staged in durian. New editing tools such as Cas12a, Cas13, and improvements in gene-targeted vectors can improve editing efficiency and accuracy. The application of plant somatic mutation screening and haploid breeding technology may also accelerate the acquisition of homozygous edited lines. With the development of synthetic biology, in the future it may even be possible to achieve the purpose of "one-time editing" by temporarily expressing editing tools in the fruit without changing the plant's reproductive system, thereby avoiding the transmission of genetic modifications - this may be a revolutionary idea for tree species that have long generations like durian.

Acknowledgments

Thanks to Mai Rudi and Liang Qixue for their support and assistance in literature search and library analysis.

Funding

This study was supported by Hainan Institute of Tropical Agricultural Resources Funding (No. H2025-03).

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Akanmu A.O., Asemoloye M.D., Marchisio M.A., and Babalola O.O., 2024, Adoption of CRISPR-Cas for crop production: present status and future prospects, PeerJ, 12: e17402.
https://doi.org/10.7717/peerj.17402

Adhikary T., and Das P., 2022, Conventional and biotechnological approaches for enhancing shelf-life of horticultural crops, Bhartiya Krishi Anusandhan Patrika, 37(2): 114-120.
https://doi.org/10.18805/bkap398

Cabanos C., Sajise A., Garcia R., Siar S., and Mendoza E., 2014, Compositional analysis of transgenic papaya with delayed ripening trait, Philippine Agricultural Scientist, 96(4): 331-339.

Chairat R., Lertsiri S., and Tananuwong K., 2022, Volatile compound production and quality characteristics of durian fruit Cv. Monthong as affected by 1-methylcyclopropene and modified atmosphere storage, International Journal of Fruit Science, 22: 481-494.
https://doi.org/10.1080/15538362.2022.2060418

Gao J., Tang X., Yu X., Wu Z., Liu Y., and Miao M., 2024, Overexpression of *Solanum lycopersicum* DDB1 interacting protein 4 (SlDDI4) extends tomato shelf life by methylation-mediated suppression of softening-related genes expression, Postharvest Biology and Technology, 216: 113040.
https://doi.org/10.1016/j.postharvbio.2024.113040

Hewitt S., and Dhingra A., 2020, Beyond ethylene: new insights regarding the role of alternative oxidase in the respiratory climacteric, Front. Plant Sci., 11: 543958.
https://doi.org/10.3389/fpls.2020.543958

Hu C., Sheng O., Deng G., He W., Dong T., Yang Q., Dou T., Li C., Gao H., and Liu S., 2021, CRISPR/Cas9-mediated genome editing of MaACO1 (aminocyclopropane-1-carboxylate oxidase 1) promotes the shelf life of banana fruit, Plant Biotechnology Journal, 19(4): 654-656.

Ikwan W., and Fikkri M., 2020, Quality of ripe tree-dropped "Musang King" durian as affected by low oxygen storage, International Journal of Agriculture, Forestry and Plantation, 10: 274-281.

Imsabai W., Ketsa S., and Doorn W., 2002, Effect of temperature on softening and the activities of polygalacturonase and pectinesterase in durian fruit, Postharvest Biology and Technology, 26: 347-351.
https://doi.org/10.1016/S0925-5214(02)00067-4

Khaksar G., Kasemcholathan S., and Sirikantaramas S., 2024, Durian (*Durio zibethinus* L.): nutritional composition, pharmacological implications, value-added products, and omics-based investigations, Horticulturae, 10(4): 342.
https://doi.org/10.3390/horticulturae10040342

Khaksar G., Sangchay W., Pinsorn P., Sangpong L., and Sirikantaramas S., 2019, Genome-wide analysis of the *Dof* gene family in durian reveals fruit ripening-associated and cultivar-dependent Dof transcription factors, Scientific Reports, 9: 12109.
https://doi.org/10.1038/s41598-019-48601-7

Khaksar G., and Sirikantaramas S., 2020, Auxin response factor 2A is part of the regulatory network mediating fruit ripening through auxin-ethylene crosstalk in durian, Frontiers in Plant Science, 11: 543747.
https://doi.org/10.3389/fpls.2020.543747

López-Casado G., Sánchez-Raya C., Ric-Varas P., Paniagua C., Blanco-Portales R., Muñoz-Blanco J., Posé S., Matas A., and Mercado J., 2023, CRISPR/Cas9 editing of the polygalacturonase *FaPG1* gene improves strawberry fruit firmness, Horticulture Research, 10(3): uhad011.
https://doi.org/10.1093/hr/uhad011

Lobato-Gómez M., Hewitt S., Capell T., Christou P., Dhingra A., and Girón-Calva P.S., 2021, Transgenic and genome-edited fruits: background, constraints, benefits, and commercial opportunities, Horticulture Research, 8: 166.
https://doi.org/10.1038/s41438-021-00601-3

Meitha K., Pramesti Y., and Suhandono S., 2020, Reactive oxygen species and antioxidants in postharvest vegetables and fruits, Int. J. Food Sci., 2020: 8817778.
https://doi.org/10.1155/2020/8817778

Miao H., Zhang J., Zheng Y., Jia C., Hu Y., Wang J., Zhang J., Sun P., Jin Z., Zhou Y., Zheng S., Wang W., Rouard M., Xie J., and Liu J., 2025, Shaping the future of bananas: advancing genetic trait regulation and breeding in the post-genomics era. Horticulture Research, 12(5): uhaf044.
https://doi.org/10.1093/hr/uhaf044

Osorio S., Scossa F., and Fernie A., 2013, Molecular regulation of fruit ripening, Frontiers in Plant Science, 4: 198.
https://doi.org/10.3389/fpls.2013.00198

Palapol Y., Kunyamee S., Thongkhum M., Ketsa S., Ferguson I., and van Doorn W., 2015, Expression of expansin genes in the pulp and the dehiscence zone of ripening durian (*Durio zibethinus*) fruit, Journal of Plant Physiology, 182: 33-39.
https://doi.org/10.1016/j.jplph.2015.04.005

Pan H., Sun Y., Qiao M., Zhou X., and Li H., 2022, Beta-galactosidase gene family genome-wide identification and expression analysis of members related to fruit softening in melon (*Cucumis melo* L.), BMC Genomics, 23: 795.
https://doi.org/10.1186/s12864-022-09006-5

Peng Z., Liu G., Li H., Wang Y., Gao H., Jemrić T., and Fu D., 2022, Molecular and genetic events determining the softening of fleshy fruits: a comprehensive review, International Journal of Molecular Sciences, 23(20): 12482.
https://doi.org/10.3390/ijms232012482

Prado G.S., Rocha D.C., Santos L.N.D., Contiliani D.F., Nobile P.M., Martinati-Schenk J.C., Padilha L., Maluf M.P., Lubini G., Pereira T.C., Monteiro-Vitorello C.B., Creste S., Boscariol-Camargo R.L., Takita M.A., Cristofani-Yaly M., and Souza A.A.D., 2024, CRISPR technology towards genome editing of the perennial and semi-perennial crops citrus, coffee and sugarcane, Frontiers in Plant Science, 14: 1331258.
https://doi.org/10.3389/fpls.2023.1331258

Shipman E., Yu J., Zhou J., Albornoz K., and Beckles D., 2021, Can gene editing reduce postharvest waste and loss of fruit, vegetables, and ornamentals, Horticulture Research, 8: 1.
https://doi.org/10.1038/s41438-020-00428-4

Suntichaikamolkul N., Sangpong L., Schaller H., and Sirikantaramas S., 2021, Genome-wide identification and expression profiling of durian CYPome related to fruit ripening, PLoS One, 16(11): e0260665.
https://doi.org/10.1371/journal.pone.0260665

Tariq S., Gul A., Negri S., and Mujtaba T., 2024, Genetic engineering in tomato, In: Gul A. (eds.), Targeted genome engineering via CRISPR/Cas9 in plants, Academic Press, New York, USA, pp.101-133.
https://doi.org/10.1016/B978-0-443-26614-0.00015-1

Teh B., Lim K., Yong C., Ng C., Rao S., Rajasegaran V., Lim W., Ong C., Chan K., Cheng V., Soh P., Swarup S., Rozen S., Nagarajan N., and Tan P., 2017, The draft genome of tropical fruit durian (*Durio zibethinus*), Nature Genetics, 49: 1633-1641.
https://doi.org/10.1038/ng.3972

Uluisik S., Chapman N., Smith R., Poole M., Adams G., Gillis R., Besong T., Sheldon J., Stiegelmeyer S., Perez L., Samsulrizal N., Wang D., Fisk I., Yang N., Baxter C., Rickett D., Fray R., Blanco-Ulate B., Powell A., Harding S., Craigon J., Rose J., Fich E., Sun L., Domozych D., Fraser P., Tucker G., Grierson D., and Seymour G., 2016, Genetic improvement of tomato by targeted control of fruit softening, Nature Biotechnology, 34: 950-952.
https://doi.org/10.1038/nbt.3602

Wang Y., Jin S., Xu Y., Li S., Zhang S., Yuan Z., Li J., and Ni Y., 2020, Overexpression of *BnKCS1-1*, *BnKCS1-2*, and *BnCER1-2* promotes cuticular wax production and increases drought tolerance in *Brassica napus*, Crop Journal, 8: 26-37.
https://doi.org/10.1016/J.CJ.2019.04.006

Yang H., Zhang M., Li X., Zhu Z., Xu R., Zhu F., Xu J., Deng X., and Cheng Y., 2023, CsERF003, CsMYB7 and CsMYB102 promote cuticular wax accumulation by upregulating *CsKCS2* at fruit ripening in *Citrus sinensis*, Scientia Horticulturae, 310: 111744.
https://doi.org/10.1016/j.scienta.2022.111744

Yang L., Huang W., Xiong F., Xian Z., Su D., Ren M., and Li Z., 2017, Silencing of *SlPL*, which encodes a pectate lyase in tomato, confers enhanced fruit firmness, prolonged shelf-life and reduced susceptibility to grey mould, Plant Biotechnology Journal, 15(12): 1544-1555.
https://doi.org/10.1111/pbi.12737

Zsögön A., Čermák T., Naves E., Notini M., Edel K., Weinl S., Freschi L., Voytas D., Kudla J., and Peres L., 2018, *De novo* domestication of wild tomato using genome editing, Nature Biotechnology, 36: 1211-1216.
https://doi.org/10.1038/nbt.4272