# Post-Harvest Biotechnology or genetic engineering Solutions: Extending Shelf Life and Reducing Food Waste


## Abstract

Post-harvest losses and food waste have become critical challenges in the global food supply chain, contributing to economic losses, environmental degradation, and food insecurity. This article explores the innovative applications of post-harvest biotechnology and genetic engineering as promising solutions to address these issues by extending the shelf life of perishable products and minimizing food waste. Advancements in genetic engineering techniques have paved the way for the development of crops with enhanced resistance to pests, diseases, and environmental stresses. Additionally, the manipulation of genes associated with ripening and senescence has allowed scientists to engineer fruits and vegetables with extended shelf life. These genetically modified organisms (GMOs) exhibit improved post-harvest characteristics, providing a longer window for transportation, storage, and consumption. Biotechnological interventions also include the use of biocontrol agents and beneficial microorganisms to suppress post-harvest pathogens, thereby reducing spoilage and decay. The development of bio-preservatives, such as antimicrobial peptides and natural compounds, offers an eco-friendly alternative to traditional chemical preservatives, contributing to both food safety and sustainability. Furthermore, the integration of smart packaging technologies with genetic modifications enhances the monitoring and control of environmental conditions during storage and transportation. Intelligent packaging materials equipped with sensors can detect changes in temperature, humidity, and gas composition, enabling real-time adjustments to prolong the freshness of perishable goods.



Keywords: environmental, eco-friendly, storage, bio-preservatives


Comment [RW1]: Post-Harvest



## Introduction

An essential part of the physiological processes that occur in fruits, vegetables, and decorative crops is played by ethylene, which is a gaseous plant growth regulator that contains two carbon atoms. At micromolar quantities, it has the ability to hasten the ripening process of ethylene-sensitive fruits, leafy greens, and vegetables, which ultimately results in the deterioration of the fruit and its waste during the postharvest stage[1]. With the ultimate goal of extending the shelf life of produce and enhancing its quality after harvest, a number of different approaches have been undertaken in order to gain a better understanding of the pathways that regulate ethylene as well as the biochemical and physiological processes that are dependent on ethylene [2].

ET receptors, protein kinases, transcription factors, and other transcription factors are all components of the conventional ET signaling pathway. An alternative mechanism that involves AHP and ARR regulatory proteins has also been suggested as a possible explanation. According to the findings of recent studies, the production of food ought to be increased by a factor of two in the next fifty years in order to prevent malnutrition, starvation, and other related repercussions. In order to minimize food waste and guarantee quality throughout the whole food production and distribution chain, it is essential to preserve the quality of the food once it has been harvested [3].

The extensive network of biological processes that involve this phytohormone is highlighted

in this review, which covers the function that ET plays in postharvest quality as well as the advancement of breeding technology. There are a number of roles that ET plays in the postharvest management of fruits, vegetables, and ornamental crops [4]. Some of these roles include influencing the marketability of immature and non-climacteric fruits, acting as a signaling molecule in the development of certain postharvest physiological disorders, and influencing the storability and quality of a number of vegetables, including leafy greens, which are frequently sold as fresh cuts [5].

Editing plant genes has been regarded as the most significant advancement in plant breeding since the Green Revolution. This technological advancement has the potential to produce new crops that possess desirable features. The majority of authorities, on the other hand, believe that in order to keep up with the rise of the population, food production will need to double during the next fifty years [6]. Despite the fact that horticultural crops are frequently rich in nutrients and contain bioactive phytochemicals, they are frequently disregarded or undervalued in the context of global food security. A further 25–40% of all fruits and vegetables that are produced around the world are never consumed once they have been harvested, with an average of 33 percent of them being never consumed [7].

According to the authors, technology-assisted breeding for new and enhanced fruit, vegetables, and ornamentals that are compatible with supply chain constraints but supplied to the consumer at peak quality could be an important part of the solution both in the short term and in the long term. This paper investigates the possibility that gene editing could have a significant and quantitative impact on postharvest waste and loss [8]. This is accomplished by establishing a connection between the bio physiology of postharvest produce, the requirements of the produce sector, and the vast amount of molecular research that is already available.

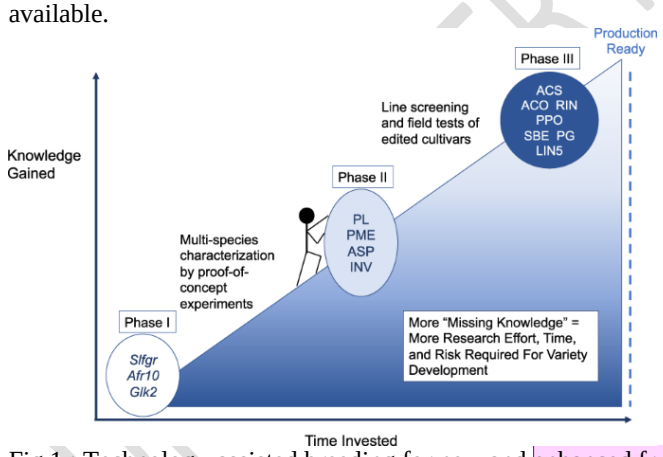


Fig 1 : Technology-assisted breeding for new and enhanced fruit

Comment [RW2]: reference

**Climacteric and non-climacteric principles**

In recent years, ET's effect on climacteric fruit ripening has been extensively studied, using tomato as a model fruit. New approaches have been developed to control losses and avoid product degradation during storage and transit [9].

Molecular investigations have shown that ET affects climacteric fruit storability and marketability. ET-receptor therapy can help explain this. Using 1-methylcyclopropene (1-MCP), a recent research examined tomato ET receptor transcriptomes throughout ripening and off vine [10]. The study sought to investigate ET activity's role in ripening time management. Recent investigations demonstrate that methyl jasmonate (MJ) and ethylene tetrahydrocannabinol (ET) metabolism increases climacteric fruit ripening [11].

Also, ET metabolism influences fruit ripening by interacting with other plant hormones.

Exogenous salicylic acid (SA) injection slows ripening in several species. However, ethylene tetrahydrocannabinol (ET) and a complicated interplay of auxin, jasmonates, GA, and ABA govern avocado ripening [12]. Melatonin increases ethylene production and ACC gene expression [13].

Tomato research has examined ET and membrane catabolic enzymes such phospholipases and lipoxygenase. To prove that lipoxygenase regulates ET production via ACO, TomloxB, the gene's major isoform, was silenced. A conclusion was reached. This finding may improve tomato shelf life and postharvest management [14].
Technological methods can reduce ET exposure in climacteric fruit postharvest treatment. Heat treatments may extend tomato storage by inducing DNA methylation by ET signaling mechanisms. Packaging, controlled environments, and one microgram per cubic centimeter are further choices [15].
ET absorbers and scavengers, ventilation systems, ozone, active oxygen, and 1-MPC extend product shelf life. Vacuum UV photolysis is a novel method for decreasing the negative effects of ethylene tetrahydrofuran. This method uses highly reactive radicals to kill harmful bacteria and oxidize ethylene tetrahydrofuran (ET) to carbon dioxide and water [16].
In another investigation, ethanol prevented tomato fruit ripening and increased ET production. This urges more investigation on this topic [17].
Non-climacteric vegetables like zucchini have a lower shelf life than fully ripe fruits sold commercially. Postharvest handling of these fruits might cause chilling damage (CI) in cold storage [17]. ET and ET-related genes are implicated in CI development, as zucchinis stored at 20 degrees Celsius produced more ET. ET synthesis may be linked to oxidative stress, which causes CI in immature fruits [18].
ET-mediated CI may be mitigated by using the ET-inhibitor 1-MCP. 1-MCP downregulated ET synthesis and perception genes in zucchini cultivars susceptible to CI, reducing CI symptoms. Shrink-wrapping packaging may also reduce the negative effects of ET-mediated CI [19].
A recent study evaluated ET receptors and associated proteins in climacteric and non-climacteric fruits. The researchers found that both fruits share several ET sensing and signaling mechanisms. Non-climacteric fruits like grapes and citrus have far less ethylene-responsive components. ET receptors like FaEtr1 and FaErs1 let strawberry mature into non-climacteric fruits [20].
Inhibiting ET with 1-MCP can help us comprehend non-climacteric fruit physiological and metabolic processes. This can lengthen the commercial life of produce, especially non-climacteric fruits. During the postharvest phase, it can delay the onset of senescence and related problems and limit the development of physiological ailments such chilling damage. 1-MCP may affect respiration and decay in non-climacteric fruit differently depending on the crop [21].

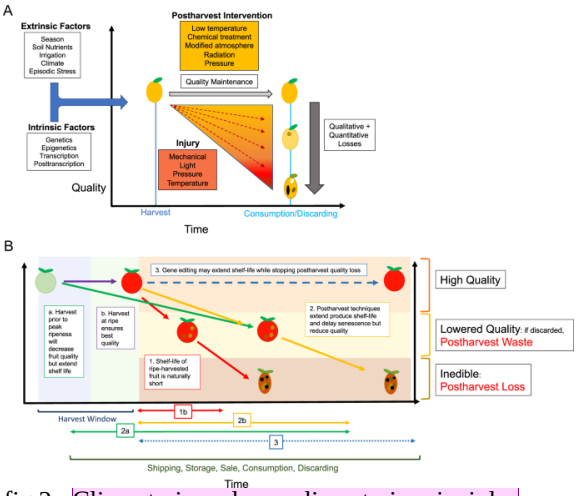


fig 2 : Climacteric and non-climacteric principles

**Comment [RW3]:** reference

**Causes of losses in post-harvest**

Variety of factors affect output quality and cause postharvest losses of agricultural commodities. Poor harvesting is the main cause, although bird and rodent attacks, pathogens, and natural catastrophes can also cause major losses [22]. Delayed threshing and washing are essential for separating grains from panicles. Poor drying can cause microbial development in grains, which is bad for storage and grinding [23].

Respiration converts organic molecules into simple chemicals to release energy for metabolic functions. Respiration is proportional to horticultural product degradation, which is quantified in carbon dioxide or oxygen consumption [24]. Transpiration is the physiological mechanism by which plants lose water as vapour. The substantial amount of water lost from harvested food compromises its quality, nutritional content, palatability, and customer desire. Reduce transpiration loss by lowering storage conditions [25]. Limiting air flow, decreasing the temperature, raising relative humidity, waxing, modified atmospheric packing, and polyethylene sheets can achieve this [26].

Microbes in stored agricultural products induce postharvest infections. These bacteria include Penicillum, Botrytis, Fusarium, and Phytophthora infestans. Harvesting and other agricultural operations can cause mechanical damage and bruising that let harmful germs in [27]. These microorganisms can reduce product quality, quantity, and marketability. Postharvest processing of agricultural goods involves ethylene, a gaseous hormone. Although it controls fruit and vegetable ripening, it can cause early ripening and skin damage [28].

Temperature, relative humidity, atmospheric condition, and light exposure can cause situations. Temperature affects postharvest shelf life. High temperatures enhance transpiration and water loss, whereas cold temperatures promote microbial growth. Relative humidity, which is defined by the difference in vapour pressure between nearby airs, is crucial to evaluating the quality of harvested product [29]. To reduce respiration and extend shelf life, product gaseous composition must be regulated. Light exposure can also cause physiological changes in produce, including as the creation of solanin and chlorophyll, which are harmful to humans [30].

**Technologies intervention**

Modern technology allows scientists to modify gene organization in plant genomes. These gene editing or targeted alterations are quite useful. Genome targeting allows targeted mutagenesis by permanently altering a specific region [31]. Double-Stranded Breaks (DSBs) trigger cellular DNA repair machinery. The HDR or NHEJ mechanisms can repair double-stranded breaks [32].

The NHEJ repair process is more common in plants than the homology-directed repair (HDR) mechanism because it depends on donor DNA structure and target cell repair machinery. This is because NHEJ happens more often. The establishment of DSB-dependent genome editing in plant cells requires selective and rare-cutting restriction enzymes [33]. At specific chromosomal sites, these enzymes must cause double-stranded breaks. Nucleases target long nucleotide sequences and generate double-stranded breaks. Gene editing approaches use meganucleases, zinc finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), and the recently developed CRISPR-Cas endonuclease [34].

Zinc Finger Protein (ZFP) and Fok1 restriction enzyme create chemically generated endonuclease systems, ZFNs. ZFNs have been used as site-specific mutagens in model and crop plant species to facilitate the integration of the targeted transgene into donor genome sequences, stimulate the repair of defective transgenes, replace donor DNA sequences with foreign DNA molecules, and make integration easier [35].

The Transcription Activator-like Effector and Fok1 endonuclease catalytic domain formed TALENs. The proteobacterium Xanthomonas spontaneously produces TALE proteins that induce plant infection [36]. They carry TALE proteins to the plant cell nucleus, where they bind to the target gene promoter and start transcription. The structure of TALENs has three domains. Type III secretion system (T3SS) and non-canonical repeats (NCR) are in the N terminal, whereas a transcription factor binding site, Nuclear Localization Signal (NLS), and activation domain are in the C terminal. Archaea and eubacteria harbour the naturally occurring RNA-guided DNA endonuclease system CRISPR/Cas [37].

CRISPR has been widely accepted for genome editing and gene therapy in several species. Genetic engineering is the most precise, accurate, simple, and site-specific method for plant systems [38]. It can create plants without undesirable traits. The CRISPR/Cas system involves adaptation, expression, and interference. Bacteria adapt by integrating invaders' short, unique protospacer sequences into their genomes at nearby CRISPR sites. This lets bacteria adapt to their surroundings. New CRISPR spacer sequences increase the array. This extension builds a cell-invading creature memory [39].

The CRISPR locus is translated into pre-crRNA in the expression stage. The pre-crRNA is then processed into mature crRNAs. The crRNA and Cas protein form a complex once the invading organism's protospacer is inserted into the CRISPR locus. The crRNA-Cas complex then pairs with the second invader's protospacer. The crRNA directs the last stage, when the Cas endonuclease protein cleaves DNA [40].

For gene targeting, the system needs a guide RNA and a Cas9 endonuclease. After exposure to a virus or plasmid, tiny pieces of foreign DNA are integrated into the host's CRISPR repeat-spacer array, forming spacer DNA. They indicate invasive species. This spacer DNA is cleaved and transcribed to produce crRNA, short CRISPR RNA [41].

Plasmid DNA, messenger RNA, or ribonucleoproteins can convey the CRISPR/Cas9 complex to the target cell. Effective complex delivery to the target cell is crucial. Ribonucleoprotein (RNP), a Cas9 protein and gRNA, is another genome-editing approach being developed [42]. The fact that RNP-based genome editing does not require DNA or transgenes is crucial. This technique has modest off-target effects and is DNA-free, reducing toxicity [43].

The use of CRISPR/Cas9 to change plant genomes offers promising genomic and epigenetic control. Cas9 and sgRNA, both parts of the CRISPR/Cas9 system, can operate as a scaffold

to drive effectors or markers to particular DNA sites [57]. Double-stranded breaks allow off-target gene editing, hence several strategies have been developed to avoid these. One technique is using dead Cas9 (dCas9). This variant inactivates the two catalytic domains by point mutation [44].

Base editing, which does not need double-strand breaks, has been used to change plant genomes. This method requires base editors (CBEs). The editors delaminate cytosine into uracil, which is then transformed into thymidine by DNA replication or repair [45]. CBEs are used for targeted base editing in Arabidopsis, rice, and tomato plantations. Adenine Deaminase (ABEs) combined with dCas9 cause the base mutation when adenine becomes inosine. Inosine can be base-paired with cytosine to alter DNA [46].

Epigenetic changes including DNA acetylation, methylation, and Histone modification can influence gene expression. These adjustments do not alter the parents' DNA [47]. Changes can be made using epigenetic modifiers fused with the dCAS9 protein. Kang and his team used CRISPR/Cas9 to methylate CpG sites to target Oct4. Gallego-Bartolome and his team developed the CRISPR/dCas9 SunTag system to target DNA demethylation in plants, causing late flowering [48].

Prime editing is a new toolbox for CRISPR-mediated genome editing. No donor templates or double-strand breaks are needed for this toolbox. This process requires the Cas9 nickase, pegRNA, and PBS [49]. PegRNA differs from other short guide RNAs in several ways. These features include a 5' end sequence complementary to the template DNA target site, a 3' end Primer Binding Site (PBS), and a sequence with the required changes after the PBS [50].

Genome editing has improved ornamental plant, fruit, and vegetable post-harvest goods. Prioritization of intrinsic fruit and vegetable nutritional, physiological, and physiochemical qualities has replaced extrinsic visual-quality aspects [51]. Post-harvest loss is a major barrier, thus innovative editing technologies must be used alongside traditional ones. Meganucleases, ZFNs, TALENs, and CRISPR/Cas are site-directed nucleases (SDNs) used in plant editing to change genomes [52].

Conventional breeding operations struggle with sterility, self-incompatibility, high heterozygosity, poor allele recovery, and long life cycles. CRISPR can overcome these obstacles, making these surgeries difficult or impossible [53]. The simplicity of removing unwanted traits has increased study on the non-interference of constitutive genome editing on other cellular operating capacities. CRISPR-TSKO or TSGE can generate somatic mutations in plant cells, tissues, and organs. It produces more precise plant KO (knock-out) variants [54].

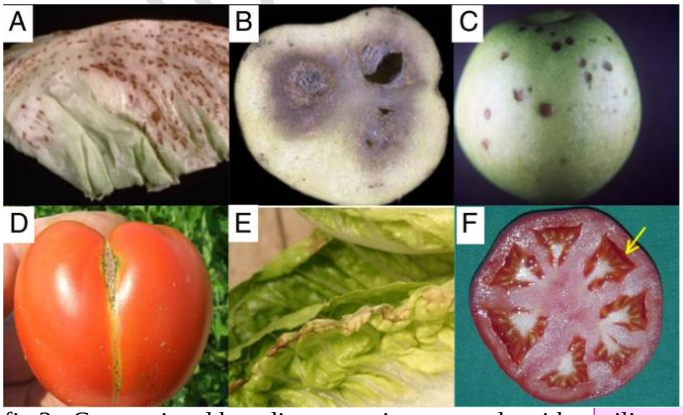


fig 3 : Conventional breeding operations struggle with sterility, self-incompatibility, high heterozygosity, poor allele recovery, and long life cycles

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Genome editing has transformed the food industry by targeting fruit genes including cassava promoters, chimeric transcription factors (XVE), and estradiol-induced XVE. These methods have been used on carrots, Arabidopsis, apples, tobacco, and soybeans. Genome editing uses SDN1 for repair [55]. This enzyme produces non-homologous end products when CRISPR/Cas9 breaks host DNA. SDN2 modifies sequences using the Homology-Directed Repair (HDR) pathway to control gene activity in plants. SDN3 uses a DNA insertion or substitution at a specific site [56].
Oligo-directed Mutagenesis (ODM) modifies genomic loci with targeted mutations. ODM works well for maize, rice, and oilseed rape. PEG-fusion, electroporation, and biolistics comprise SDN delivery. No expression system is needed for this procedure. However, Agrobacterium-mediated plant transport is the most reliable gene editing transformation [57].
The genome editing tools established for tomato have been applied to other fleshy fruits, revealing several potential gene targets. Due to strawberry browning after harvest, the food industry has lost money. Genome editing has enabled study on natural bioactive chemicals like anti-browning extracts. This discovery might replace artificial additives. An industrial solution has been created using Polyphenol Oxidase (PPO) enzyme activity control [58].
Innovations targeting plant genome alteration have advanced rapidly. These developments have been extensively studied. The revolution in ONM and ENs has been driven by ZFNs, TALENs, EMNs, mi-RNA, and CRISPR. MiRNA and CRISPR knock-out mutations reduced eggplant berry browning by 52%. These were achieved by manipulating PPO and POD genes [59].
Post-harvest storage keeps freshly harvested fruits fresh and extends their shelf life. Chemical-free storage can be done with optimum storage conditions such controlled atmosphere, DCA, or ULO. Chemical pesticide treatments have been used to control germs, but their use has reduced due to hazardous byproducts and residues. Physical-natural alternatives to chemical therapies have been developed via extensive research. Essential oil, led light, and edible coating are options. To improve and employ natural extracts, research on enzyme inhibitors and nano and microencapsulation of bioactive compounds is needed [60].
Fruit genome editing demolished a signaling and biological pathway network. This network should help find genes that generate advantageous post-harvest characteristics [61].

**Gene editing in post-harvest management**

Gene editing has improved crop quality and postharvest aspects in horticulture crops. CRISPR–Cas9 is the preferred gene-editing approach because it allows precise genome alteration and has been used to create favorable traits in many crop species. CRISPR can overcome sterility, self-incompatibility, high heterozygosity, low frequency of recovering desirable alleles and features, and extended life cycles, which can prolong or stop conventional breeding [62].
CRISPR, a prokaryotic mechanism that shields organisms against viral infection, has been used by scientists to delete or insert nucleotides to promote desirable traits in animals. CRISPR protects organisms from viruses. A synthetic guide RNA (gRNA) is customized to a protospacer adjacent motif (PAM) in the sequence of interest during CRISPR editing. This gRNA and Cas protein sequence are then transferred into a cell, where the gene expression system processes them. Plant-produced Cas protein creates a DSB. This break happens at gRNA-designated bases. Because DNA double-strand break (DSB) repair is seldom exact, non-synonymous mutations may be introduced into the genome [63].
For basic and practical plant research, it is often desirable to precisely produce the Cas protein spatially-temporally and in conjunction with other enzymes. Precision site-directed editing may replace a gene or genes with one base. This has been done in grains and horticultural crops like tomato and potato. CRISPR-TSKO tissue-specific knockouts can

cause somatic mutations in cells, tissues, and organs by using particular promoters. An inducible chimeric transcription factor (XVE) can regulate planta Cas protein synthesis in another gene-editing method [64].
Using CRISPR to target gene regulatory areas can fine-tune expression and enhance post-transcriptional gene expression, which can affect phenotype. De novo domestication, a unique crop improvement method, has been shown in several wild Solanum plants using CRISPR targeting [65].
Finally, numerous CRISPR methods may be used to change gene expression in nuanced ways. CRISPR also helps examine the cellular mechanisms that control ripening, senescence, and quality [66].

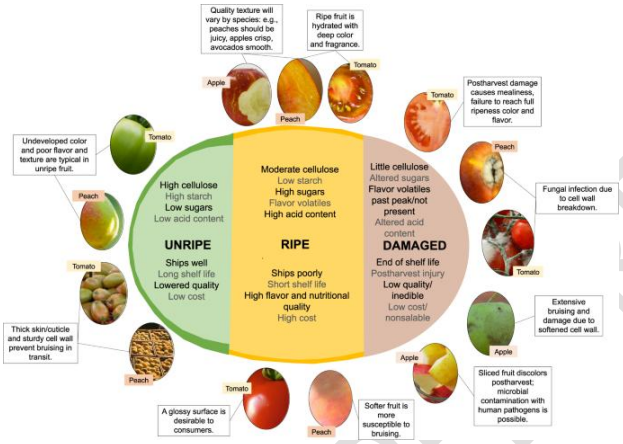


**Fig 4 : Gene editing in post-harvest management**

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## Method adopted

Non-thermal physical technologies have grown in favor as postharvest methods to extend fruit and vegetable shelf life have grown. These technologies attempt to replace water-intensive thermal processing methods that might degrade fresh food quality. Recent technologies reduce bacteria in fruits and vegetables to preserve quality and freshness. These technologies include microwave heating, pulsed electric fields, high hydrostatic pressure, and cold plasma [67].
Traditional heating methods can reduce the amount of flavor-related compounds and critical nutrients in plant tissue due to heat application and delayed dispersion. Microwave heating offers an option. Microwaves are used to prevent microbial growth during minimal processing, reducing quality loss and environmental effect [68]. However, there is little published literature on this cutting-edge physical approach for reducing postharvest quality loss. Pulsed electric field (PEF) technology produces safe meals with low heat, attracting attention. Pulses from microseconds to milliseconds with strong electric field intensity achieve this. PEF-treated goods have a longer shelf life, increased microbiological safety, and superior fresh flavor, texture, and function [69].
Most high hydrostatic pressure (HHP) applications include microbe reduction or inactivation and enzyme denaturation. However, due to its wide range of product types, HHP can also specifically affect protein functions including enzymes and tissue formation. HHP treatment has been shown to affect minimally processed horticultural commodities, whole vegetables,

and juice. Food safety and quality have improved greatly with these uses [70].
Cold plasma, a novel microorganism-management technology, is widely utilized in the processed and minimally processed fruit and vegetable industries. Several research have shown that non-thermal plasma may be used on horticultural products. In particular, plasma treatment of fruit-based fresh-cut goods has improved quality metrics and microbiological suppression. Plasma-activated water (PAW) has been studied for fresh-cut processing of several commodities. This has helped manufacturers avoid cold plasma-induced cell damage. PAW can replace washing [71].
Conclusion: Emerging non-thermal physical technologies have shown promise in extending fruit and vegetable shelf life. However, further research is needed to achieve quality using cost-effective methods [72].
Physical variables like mechanical injuries and the loss of exterior protective coatings affect the quality of fresh-cut fruit and vegetables during refrigeration, as do physiological changes like enzymatic browning caused by tissue damage and high respiration rates. Innovative food processing methods include sanitizing, lowering enzymatic browning, increasing texture, and fortifying with nutrients. Such processes include dipping and vacuum impregnation [73].
Immersing the product with or without mechanical agitation and draining any excess solution are dipping treatments. Whole, peeled, shredded, and sliced foods and spoilage-prone goods are often processed this way. It facilitates solution dispersion, which covers the product's maximum surface area without injury or stress. One of the biggest benefits of these dipping treatments is the removal of cellular exudates, which lower commodity quality after harvest [74].
Adjustments to the dipping process include soaking duration, frequency, solute composition, temperature, and solution concentration. These characteristics vary per food product. Several investigations have examined whether calcium (Ca) salt dipping can extend shelf life. Ca enrichment reduces microbial growth by decreasing water activity, improves texture, acceptability, and storability, and prevents browning and off-flavours in fresh-cut foods [75].
Using natural extracts as anti-browning agents (polyphenols, carotenoids, organic acids, and bioactive peptides) to improve fresh-cut fruit and vegetable quality and shelf life is a novel strategy. To prevent browning in fresh-cut fruits, tomato skin, pineapple juice, pomegranate peel, mango peel, aloe vera gel, pumpkin, artichoke, grape, and broccoli extracts work [76].
Food vacuum impregnation (VI) allows producers to directly introduce, dissolve, or suspend substances in the void fraction (pores) of a food matrix in a controlled way. VI has two main steps: (1) the system pressure is reduced (under vacuum), native gases and liquids are removed, and the product pores are expanded by pressure gradients until mechanical equilibrium is reached; (2) during the relaxation period, the atmospheric pressure is restored and the external solution fills the pores while the tissues relax until a new equilibrium is reached [77].
Before applying VI, porosity, tissue structure, food size and geometry, impregnation solution (concentration and type of solute), and process parameters must be considered. Fruit and vegetables have a lot of gas-filled intercellular space, making VI an ideal instrument for adding substances that help food manufacturers extend shelf life without changing cellular structure [78].
Edible active packaging made from natural ingredients is successful. This packaging delays ripening, retains nutritional qualities, and prevents quality loss by limiting gaseous exchange, respiration, and transpiration. Recent study has shown that antioxidant and antibacterial active natural components improve edible coatings. These active packaging materials interact with food by releasing biological components, enhancing oxidative stability and minimizing food-borne illnesses [79].
Alginate and chitosan coatings with olive leaf extract are edible active packaging. These



**Comment [RW6]:** The effect of using cellulose in improving coating:

Different kinds of industrial safe-to-eat coatings are broadly used to prevent moisture loss and to add shine to fruits and vegetables. Refer it:
Sabbaghi, H. Perspective Chapter: Cellulose in Food Production—Principles and Innovations. In *Cellulose—Fundamentals and Conversion into Biofuel and Useful Chemicals*; Jeyakumar, R.B., Ed.; IntechOpen: London, UK, 2023.

coatings prolong cherry shelf life, preserve phenolic and antioxidant content, and postpone ripening. Chitosan and ascorbic acid prevent browning, keep meat solid, limit microbial development, and preserve phenolic components. Alginate coatings with citric and acetic acid preserve antioxidant activity, phenolic content, and color in fresh-cut mangoes. Chitosan and ascorbic acid inhibit browning [94].

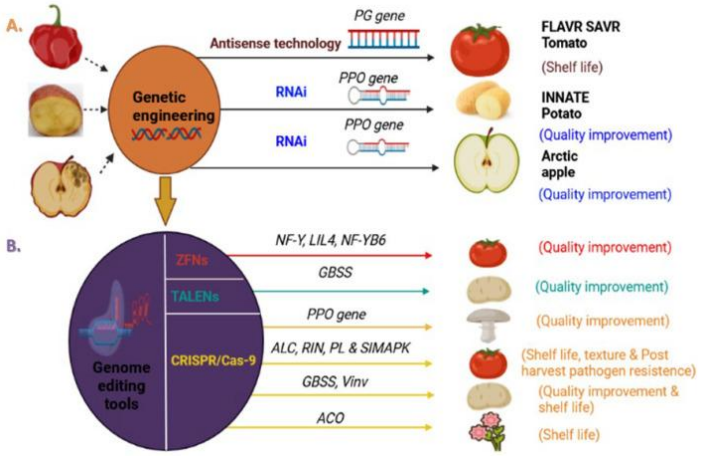


fig 5 : Antisense technology

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It has been shown that gallic acid-grafted chitosan film preserves mushrooms. Compared to commercial polyethylene film, this film has a lower respiration rate, browning degree, malondialdehyde content, electrolyte leakage rate, superoxide anion production rate, and hydrogen peroxide content. If refrigerated at four degrees Celsius, pectin-based coatings with lemon by-product extract preserve fresh-cut carrots for 14 days [80].

Lemon essential oil with chitosan edible coatings reduces strawberry respiration and increases Botrytis cinerea antifungal activity. Chitosan edible coatings with natural functional chemicals from oil cake and orange peel (OPE and OCE, respectively) on fresh Barhi date fruit have also been studied [81].

Raspberry fruits are preserved using chitosan active film pads. Green tea and rosemary ethanolic extracts function as antifungals in these pads. These pads inhibit fungal development, maintain quality, and extend raspberry fruit shelf life by 14 days [82].

Microbiota, especially fruit and vegetable microbiota, is becoming a hot issue in agri-food research. These complex microbial ecosystems are formed by naturally occurring bacteria, yeasts, and filamentous fungi. The diversity of microorganisms at harvest might affect the quality and safety of items. These unwanted microorganisms may be associated to infections, toxin producers, antibiotic-resistant bacteria, and spoiling activities. Barrier technology applications sometimes use many methods to control these unwanted bacteria. Postharvest procedures, operators, and environments can produce these bacteria [83].

In biological therapeutics, biocontrol is one of the most essential methods since it uses bacteria to inhibit the proliferation of unwanted germs. The fruit or vegetable microbiome provides a unique perspective on biocontrol variables, including the growing interest in pre- and post-harvest biological control products [84].

All market solutions employ yeast and bacteria as control agents. Because yeast physically colonize surfaces, they compete for resources to overcome commonly used pesticides, release lytic enzymes, and induce host resistance, making them useful in postharvest biocontrol. These are yeast traits. These eukaryotic microbes can also create several deadly poisons. These deadly poisons target particular biological targets in susceptible tiny creatures' cells

[85].
Even prokaryotic microbes use lytic enzymes, biofilms, and resistance induction to fight postharvest pathogens. This arsenal includes dietary steric competition and antagonism. Bacillus and Pseudomonas are some of the best postharvest antagonists. Bacillus is a popular biological fungicide and bactericide in agriculture. However, Pseudomonas's wide field distribution shows its agricultural resilience [86].
For postharvest applications, the varied group of lactic acid bacteria (LAB) provides potential bio-based solutions for sustainable agriculture. This is especially true for prokaryotes. LAB have been employed in food fermentations for a long time without harm, and certain species have simplified food safety testing. The biological methods used to control unwanted bacteria on fruits and vegetables after harvesting are numerous and have been widely studied in other food applications [87].
Within barrier technology, future biocontrol projections for fresh plant products postharvest show the need for a clear and unified worldwide regulatory environment. This speeds up new activities and biocontrol assessment with other physical and chemical treatments [88].

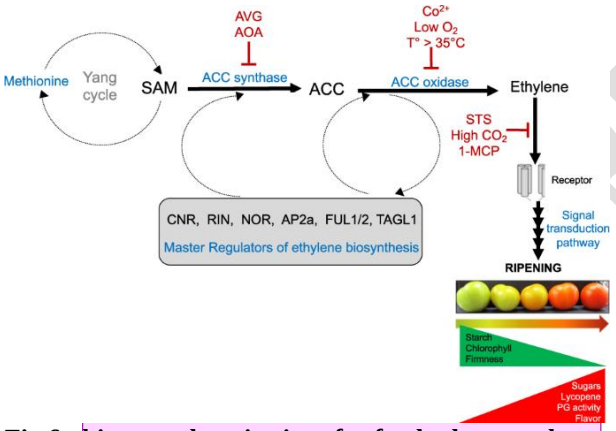



**Fig 6 : biocontrol projections for fresh plant products**

**Comment [RW8]:** Reference and description

## Computer based technologies

In-line fruit and vegetable grading uses computer vision systems (CVSs). The technique is non-destructive and contactless. These systems may extract visual information from photos to categorize, grade, assess quality, find defects, and estimate internal properties. CVS food management is objective, uniform, and supply chain-wide [89]. This reduces waste and improves consumer happiness. They usually use a digital camera, lighting system, and PC to extract categorization features and build models using statistical or machine learning methods. CVSs assess fresh product quality and marketability [90]. Colour is crucial to commercial acceptance. CVS technology provides more objective and consistent evaluations than conventional colorimeters. Because it estimates pixel-level color properties. Recently, an innovative CVS was developed to assess rocket leaf quality and discriminate various growth methods using color information from digital pictures. The CVS described used a random forest model to automatically pick significant variables for classification, achieving 95% accuracy in quality-level rating and 65-70% in cultivation method distinction [91].

The CVS is an effective tool for checking fresh-cut fruit quality across the supply chain, avoiding food loss and ensuring market freshness. It has been used on artichokes, nectarines, iceberg lettuce, radicchio, apples, and potatoes [92]. To evaluate packaging material quality,

the identification of regions affected by light-induced shadows or highlights on a plastic bag is a major challenge. This is about packaging. A sophisticated segmentation method that selects places where colors may be quantified effectively is needed to get results equivalent to unpackaged samples [93].

Additionally, CVS may analyze agricultural product internal quality. Ripening or senescence can alter a product's nutritional composition during storage. These alterations can also affect food color and texture. Yellowing of green leafy vegetables is solely caused by chlorophyll loss, although polyphenol oxidase and peroxidase on phenolic compounds brown freshly cut things. Fruit acidity decreases as total soluble solids rise and color improves. Because different ripening phases affect total soluble solids and pH statistically [94].
CVS regression models can measure carrot antioxidant activity (AA) and total phenols (TP). Image processing was used to predict the enzyme activity of polyphenol oxidase (PPO) and peroxidase (POD) on banana samples to measure peel browning after nine days of storage at 25 degrees Celsius. The anticipated and actual PPO and POD values were not significantly different, according to the correlation coefficients [95].
Recently, a CVS was used to collect strawberries at three different times to determine their ripening phase. This level involves half-red and red. Image data was statistically related with titratable acidity, making it beneficial for non-destructive strawberry ripening assessment. Chemical indicators of ripening include titratable acidity [96].
Image analysis and the random forest model were used to predict chlorophyll and ammonia concentrations, objective indicators of senescence, for unpackaged and packed rocket leaves. SVM-R models that used HSV colour space characteristics outperformed MLR models in predicting total soluble solids and pH [97].
Li et al. created a cutting-edge and intelligent method that can properly assess the shelf-life and quality of kiwifruit stored in a cold environment using RGB values from smartphone photos. R to B ratios correlated negatively with titratable acidity, vitamin C, and hardness. However, R to B ratio values correlated positively with soluble solids, total soluble sugar, and total plate counts. The smartphone image analysis system developed by these authors is simpler and faster than earlier prediction approaches. This speeds up kiwifruit postharvest quality evaluation [98].

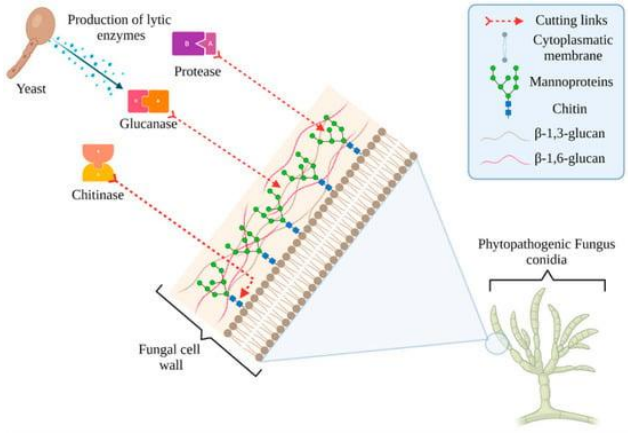
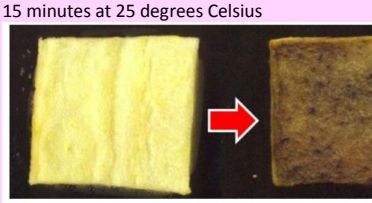



fig 7 : Computer based technologies

E-nose, or electronic nose, is a prospective sensing technology that can replace headspace solid-phase microextraction (HS-SPME) and gas chromatography–mass spectrometry (GC-MS). E-nose uses partially selective and broad-spectrum electronic chemical sensors to

**Comment [RW9]:** Catechol was used as a substrate for measuring PPO activity
To evaluate the enzymatic activity of polyphenol oxidase (PPO) by use of catechol solutionand kinetic modelling of Vitamin C loss: use following paper
Also You can use the photo inside the articleabout ppo activity and reference it Sabbaghi, H., Ziaiifar, A. M., &Kashani-Nejad, M. (2018). Degradation kinetic of vitamin C (L-ascorbic acid) during simultaneous infrared dry-blanching and dehydration of apple slices with intermittent heating method. *Iranian Food Science and Technology Research Journal*, *14*(5), 789-802.

5 mm apple slice sample heated at 70 degrees Celsius for 30 minutes (A), intensification of enzyme activity and sample color change due to catechol solution spray and final color after 15 minutes at 25 degrees Celsius



**Comment [RW10]:** Using a flatbed scanner to take pictures:
Sabbaghi H, Ziaiifar AM (2013) Color quality variation of french fries during frying using image processing, in the first electronic conference on innovation in food processing, Corpus ID: 61031961m, https://civilica.com/doc/389219

Or
Using the Laviband device:

Sabbaghi, H., Ziaiifar, A. M., Sadeghi, A. R., Kashaninejad, M., & Mirzaei, H. (2016). Kinetic modeling of color change

**Comment [RW11]:** Reference and description

**Comment [RW12]:** Refer to the following articles regarding computer related technologies and image processing and color analysis. Post-harvest technologies should be mentioned in relation to maintaining the quality of agricultural products during processing

Sabbaghi, H., Ziaiifar, A.M., andKashani-Nejad, M. 2021. Simulation of temperature fuzzy controller during infrared dry blanching and dehydration of apple slices by intermittent heating method. Iranian Food Science and Technology Research Journal, 16(6), 133-150.

classify food matrices with varied smell signatures. These devices include sample handling equipment, detectors, and data gathering systems [99].
Olfactometric methods are used to assess horticulture food items' volatile organic compound (VOC) compositions. This approach is low-cost, easy to use, quick, non-destructive, eliminates sample preparation, is environmentally friendly, and handles data automatically. Metal oxide semiconductor (MOS) sensors are used mainly in E-nose applications due to their fast response time, high sensitivity, and low cost [100].
E-noses have been used to analyze plant-based diets in several papers. New study reveals that E-nose may be used to determine fruit ripeness. Palumbo et al. used E-nose, ATR-FTIR, and IA to distinguish two ripening periods in the strawberry variety "Sabrosa." The correlation research between E-nose data and HS-SPME/GC-MS VOC profiles showed that the E-nose responses matched the analysis
Aghilinategh et al. studied using a MOS gas sensor E-nose and pattern recognition to detect white and blackberry maturity. These methods included ANN, PCA, and LDA. The ANN had the best classification accuracy, scoring over 88%. Assessed naturally and artificially ripe crab apple fruit quality using an E-nose. Titratable acidity, soluble sugar, sugar–acid ratio, soluble solids, soluble protein, and taste profile were these parameters. According to the data, the RF algorithm, which has an average identification accuracy of 98%, is the best at distinguishing naturally ripe crab apples from artificially ripe ones [101].
Using the E-nose and chemometric methods, several studies have shown that fruits and vegetables may be classified by their geographical origin. Li et al. investigated the provenance of 303 maca samples from over 100 places in China's primary growing region. They identified maca samples' volatile and olfactory signatures using GC-MS and a MOS-based E-nose. Correlation and multi-regression tests showed that all sensors were statistically linked to maca variables [102].
Cozzolino et al. explored if the E-nose could quickly detect "Ferrovia." sweet cherry samples. These samples were packed in a high-CO2 environment (16% O2 + 20% CO2 + 64% N2) or air (20% O2 + 0.03% CO2 + 80% N2) for up to 21 days. The projection to latent structures (PLS) techniques performed on E-nose data indicated categorizing fresh fruit, packed fruit, and unpackaged fruit based on storage conditions and time. One or more E-nose sensors were used to correlate samples with certain taste profiles by correlating their responses with the overall volatile organic compounds (VOCs) found in a prior study using HS-SPME/GC-MS on the same cherry samples [103].
Ghasemi-Varnamkhasti et al. used an electronic nose with eight MOS sensors to assess strawberry freshness in three polymer packagings. PPP, EVOH, and PVC were used in these packing. The researchers used pattern recognition methods like PCA, LDA, and SVM to accurately categorize unpackaged and packed samples and study how polymer packaging affects strawberry freshness [104]. RSM was considered for choosing the best sensor array. Each sensor's contribution to sample classification was considered. On days 1, 8, and 16, sample headspace profiles were examined. While principle component analysis (PCA) explained 84% of the data variance, linear discriminant analysis (LDA) classified all sensor responses with 86.4% accuracy. Using a polynomial basis function, the support vector machine (SVM) approach differentiated samples by 86.4% and 50.6% in training and validation, respectively. With a radial basis function (Nu-SVM), the SVM approach has 85.2% training accuracy and 55.6% validation accuracy [105].

An assessment of postharvest spinach freshness after one to twelve days of cold storage.Chemometrics, machine vision, and an E-nose were used in this study. The process was swift and safe. Ten expert judges rated spinach freshness into four levels during cold storage. BPNN, SVM, and KNN were used to determine spinach freshness. The BPNN

model connected to machine vision predicted spinach freshness with 85.4% accuracy, similar to the KNN method. However, the BPNN model, which used E-nose data, outperformed the SVM approach with classification accuracies of 81.2% and 75.0%. The BPNN model, which used machine vision and E-nose data to fuse multisensory data, had a classification accuracy of 93.7%, improving postharvest spinach freshness evaluation [106].
NIR spectroscopy can differentiate functional groups in a molecule and the chemical makeup of a product. The vibrational properties of materials are linked to certain internal qualities in this method. NIR spectroscopy is a popular infrared (IR) technology in many sectors. These industries include food, agriculture, chemicals, pharmaceuticals, textiles, polymers, cosmetics, and medicine. NIR spectroscopy has three setup options depending on the application [107].

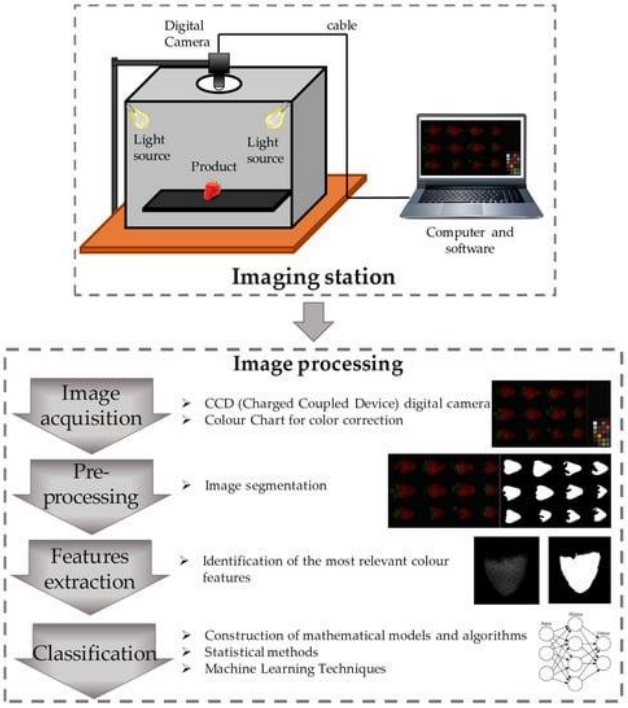



**Fig 8 : solid-phase microextraction**

**Post-harvest management through gene editing in vegetables**

**Comment [RW13]:** Reference and description

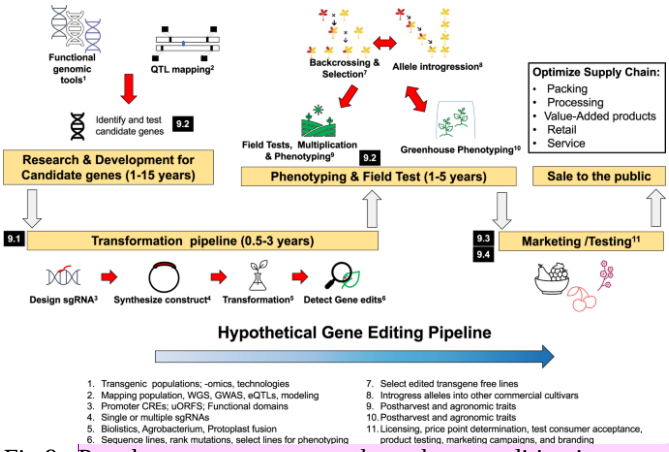



Fig 9 : Post-harvest management through gene editing in vegetables

**Comment [RW14]:** Reference and description

Various vegetable-based foods are sensitive to ethylene (ET) during postharvest and management throughout transportation, storage, and sale. ET is extremely sensitive to the Brassicaceae family of crops, which includes edible plants, and can cause yellowing and rapid food degradation after harvest and storage. Since broccoli florets are highly susceptible to ET activity, novel methods are needed to mitigate its effects. Using ET absorbers and packaging to extend the shelf life of this perishable vegetable product is effective .

Gene expression studies show that ET signaling genes are upregulated when broccoli and kale are kept at room temperature and downregulated when stored at cooler temperatures. Low temperatures selectively lower the expression of senescence association genes (SAGs) and ET receptors, suggesting that temperature regulates ET throughout storage and shelf life. Abscisic acid treatments on cabbage drastically reduce ET biosynthesis and accumulation in the storage package by 50% without affecting water or chlorophyll [108].

ET and cytokinin affect Brassica broccoli head postharvest quality. Their modification of lipoxygenase activity causes degreening. Using the ET antagonist (1-MCP) reduced chlorophyll breakdown and catabolism gene expression. Activities on many chlorophyllases achieved this. Ethylene affects fresh and fresh cut commodities quality postharvest. The environmental and physiological aspects outlined previously affect a crop's economic performance postharvest. Marketability and storage length are important, but quality must be maintained at the greatest level from field to consumer [109].

Melatonin has been studied as a way to postpone senescence and improve product shelf life by affecting ET metabolism and impact. Melatonin treatments delayed senescence, reduced ET, and improved broccoli floret quality. Broccoli treated with melatonin showed more chlorophyll and better color retention during storage. A recent study found that hydrogen sulphide, selenium, and 1-MCP can delay tomato fruit ripening and senescence while stored. This helps the fruits retain more chlorophyll, starch, soluble proteins, and ascorbic acid than untreated fruits. These treatments may reduce ET postharvest as signal molecules. Selenium treatments in tomatoes inhibited ET biosynthesis genes and increased enzymatic antioxidant systems, increasing shelf life [110].

In broccoli, amino acids reduced ET, delayed browning, and found the maximal antioxidant capacity. Modified environment storage was used to retain the quality of whole and fresh cut romaine lettuce. This approach changed the package's interior gas composition, affecting ET, sensory quality, and marketability. Postharvest commercial management of crops from farm to fork involves several issues throughout transit, and ripe fruits are especially at risk of losing quality. Mechanical injury to tomatoes is likely to decrease quality. A recent study

found that even modest tomato fruit compression can affect quality and marketability [111]. The switch from traditional breeding to transgenesis for ET has advanced postharvest product breeding. ET regulates several biochemical, physiological, and molecular processes that affect postharvest processing. ET biosynthesis and perception changes may lengthen product shelf life, but more may be done to improve crop postharvest quality [112].

Both ET-dependent and ET-independent systems drive tomato ripening, which is often used as a model for fleshy fruits. Most molecular assisted selection (MAS) research in conventional breeding uses crosses between cultivated tomato or elite lines and related species, or mutants. Microtom genotypes, short-lived genotypes, can optimize breeding efforts. Functional genomics studies use these genotypes as model transformation systems [113].

ET-dependent ripening's qualitative traits are determined by complex regulatory networks that are polygenic and quantitatively inherited. Transgenic tomato transformation illuminates ET and its biochemical and metabolomics mechanisms. An example of a transgenic transformation used to study ET. This research was followed by metabolomics. Commercial tomato varieties generated using recombinant DNA technology were another method. In 1994, the FDA approved FlavrSavr, which had a long shelf life. This was achieved by adding the ET-dependent antisense polygalacturonase (PG) gene, which softens fruit [1].

For 50 years, researchers have studied the relationship between ET biosynthesis and the production of the climacteric peak of respiration during tomato fruit ripening. However, this phenomenon's molecular and metabolomics processes are still being studied. Gene transfer via genome editing can integrate the transgene and cisgene for more predictable expression. Along with transgenic transformation technique. CRISPR/Cas9 is the most used site-specific genome editing method. This Streptococcus pyogenes-discovered method was first employed in five plant species in 2013 [115].

Synthesis, regulation, and perception of ethylene (ET) cause the transcription of ripening-regulated genes, which determine climacteric fruit quality. ET signaling has numerous components. ET receptors on the endoplasmic reticulum membrane, constitutive triple response 1 (CTR1), ET-insensitive 2 (EIN2), TFs EIN3 and EIN3like, and ET response factors are included. ET and phytohormones like auxins and ABA interact reciprocally, according to many studies [116].

Texture, color, and fragrance change throughout ripening. ET, transcription factors (TFs), and downstream genes control these changes. TFs have been extensively studied, and the ET signal route is a complex transduction network that activates downstream transcriptional regulators (ERFs). APETALA2/ethylene response factor (AP2/ERF) regulates ET-responsive genes and is important throughout ripening. Other families of transcription factors are involved in ET response and fruit ripening besides RIN-MADS, CLEAR NON-RIPENING, TAGL1, and LeHB-1. Positive ripening regulators are encoded [117].

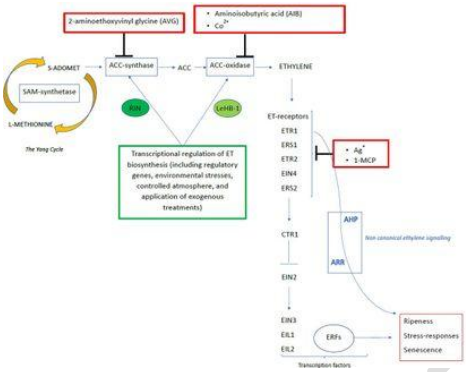
Studying the ripening phenotype and pinpointing the mutation-causing genes has allowed spontaneous tomato mutants to be used to research ET-dependent genes. The most important monogenic tomato mutants include ripening-inhibitor (rin), nonripening (nor), colorlessnonripening (Cnr), green-ripe (Gr), green flesh (gf), high pigment1 (hp1), high pigment2 (hp2), and never ripe. These mutations have been used to develop commercial varieties with a longer shelf life and lower produce degradation or losses and parental lines that delay fruit ripening and textural deterioration [118].

Broccoli, cauliflowers, Brussels sprouts, cabbage, kale, mustard (greens), and collards are Brassicaceae family members. ET research has illuminated the most important biochemical and physiological processes in these crops, but compared to tomatoes, breeding and molecular analysis research has been limited. Arabidopsis thaliana has recently been shown to have many senescence-associated gene (SAG) families and two transcription factor

families, NAC (NAM, ATAF, CUC) and WRKY. Senescence gene families have been studied in Brassicaceae plants including cabbage, kale, and broccoli [119].
ET and its functional equivalent, propylene, yellowed broccoli florets. Directed mutagenesis created a broccoli ET-response sensor (ers) gene mutant. Two transgenic lines were produced from two plasmids. Transgenic broccoli showed ET insensitivity, including a delay in leaf senescence and a one- to two-day delay in head yellowing, as measured by chlorophyll and color angle [120]. ACO-expressing broccoli was created using antisense transformation. They showed that this blocked ET production, increasing transformation rate. This was because inhibiting ET biosynthesis increased polyamine production, which boosts shoot regeneration [120].
The zucchini, also known as Cucurbita pepo, is one of the most important crops in the Cucurbitaceous family since it is planted worldwide and has a great economic value. ET has been extensively studied in zucchini for parthenocarpy breeding aims, but fruit quality after harvest has received less attention. A mutant collection of 3800 M2 families was produced using MUC-16 as the WT and EMS as the mutant agent. According to consistent mutant phenotyping, mutations that affected ET sensitivity impacted seedling germination, sex determination, sex expression parthenocarpy, and fruit set [121].
ET affects zucchini sensitivity to chilling damage (CI), with more resistant varieties producing less ET when exposed to low temperatures. Recently, an ET-insensitive mutant etr2b and its wild-type counterpart were compared for ET production, respiration, and oxidative stress. ET-insensitive zucchini cultivar etr2b was used to show how ET causes cold-induced postharvest oxidative damage [122].
Spanish genotypes were stored at four, twelve, and twenty degrees Celsius for seven days to study ACS and ACO gene expressions. CpACS and CpACO expression is lower in CI-resistant genotypes. However, the most susceptible genotypes exhibit a chilling-induced ET peak around 4 degrees Celsius after CI symptoms appear. A hybrid zucchini (C. pepo ssp. pepo)-scallops (C. pepo ssp. ovifera) population was sequenced for genotyping. Over 7,000 SNP markers and a high-density linkage map covering 2,817.6 cM of the genome were generated by this cross. Based on three environmental studies, 48 QTLs were found for vine, flowering, and fruit quality. DFeF_9 is also home to ET metabolism-related TF and other flowering genes [123].
New breeding methods (NBT) using CRISPR/Cas9 have reassessed tomato plant ethylene signal (ET) and TFs. Increasing knowledge and understanding of ethylene-dependent processes, which are crucial during postharvest, may lead to creative methods for improving crop quality and shelf life. In tomato, CRISPR technology has targeted deletion or substitution of regulatory proteins CNR and NOR and transcription factors AP2a, FUL1, and FUL2. Using gene-editing methods, TF functions were revealed by deleting their genes. Edited lines produced more ethylene than normal and mutant lines. Further evidence that AP2a harms ET production is that these lines ripened faster. CRISPR/Cas9 deletion and RNAi silencing of rin in wild-type tomatoes only partly restore the non-ripening phenotype in recent years. This is because it did not reduce ripening and the mutant fruits were somewhat crimson. Ripening was largely restored by inactivating the rin mutant allele. However, deletion or RNAi silencing of the chimeric RIN-MC mutant protein in a rin background partially restored ripening [124].
To inhibit AP2a, NOR, FUL1, and FUL2 gene expression, CRISPR/Cas9 mutagenesis was used. This NBT may be useful in tomato breeding for postharvest storage since ET biosynthesis knockout alleles can extend fruit shelf life without affecting organoleptic or nutritional quality. This NBT has also been used to create mutants with ET-related postharvest quality improvements. In addition to CRISPR/Cas9, ET's role in null mutants' ripening has been studied. In 2016, Uluisk and colleagues produced tomato mutants for ET-

dependent pectate lyase, which softens fruit. These mutants improved fruit texture and postharvest quality without changing color or soluble solids. Additional CRISPR/Cas9-based mutants for texture-related genes have been generated for pectin-degrading enzymes, including β-galactanase, polygalacturonase, and pectate lyase [125].
To our knowledge, no work has used CRISPR/Cas9-induced mutations for ET in breeding objectives related to postharvest quality in Brassica and zucchini. These findings supported the idea that CRISPR/Cas9-induced mutations in the tomato ripening transcription factor did not entirely stop ripening. The ripening transcriptional regulatory network featured several critical control sites, suggesting partial "back-up" features.

Fig 10:




**Benefits of biotechnologies inventions in post-harvest**

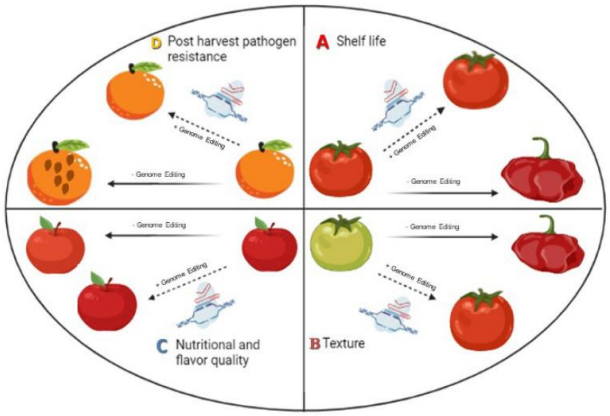



fig 11: Benefits of biotechnologies inventions in post-harvest

**Comment [RW15]:** Reference and description

Increasing desire for extrinsic quality in fruits and vegetables has led to the commercialization of GMOs. These include virus-resistant papayas, squash, apples that don't brown, plump pineapples, insect-resistant eggplants, Brassica oleracea, tomatoes, potatoes, and Lactuca sativa. Altering the genome has been used to create high-quality cultivars. Mutations improve nutritional benefits in these methods. Adaptations include increased flower and fruit size, fruit ripening, inflorescence branching, ascorbic acid synthesis, beta-

carotene fortification, perennial to annual transition (kiwi fruit), decreased tuber-browning, and improved strawberry berry quality [126].

Research shows that fruit flavor directly influences organic acids that determine organoleptic features and fruit individuality. Fruit quality, especially for processing, depends on harvest acidity. Early-ripening apples have high acidity and low sugar, reducing market demand for fresh apples and their organic acid to carb ratio. Thus, fresh apple demand falls. UV C has been shown to reduce post-harvest damage to room-temperature-grown early-ripened fruits. These include delayed ripening, senescence, preservation of fruit firmness, biosynthesis of flavonoids and phenolic content, increased antioxidant and defense-responsive molecules, and more [127].

Because worldwide horticulture crop output is insufficient to meet human nutritional needs, post-harvest loss and waste are becoming unsustainable. Unintentional postharvest loss includes physical injury, internal bleeding, early rotting, and insect damage. Ornamental products' worth averaged $16 billion in 2015, demonstrating their popularity has grown. The cold-chain process might reduce ornamental crop value by 50% because to their high moisture content. Ornaments lose 15% of their worth every day they are in transportation, and their vase life is usually 10–12 days after purchase. Moving things quickly through a cold chain ensures product quality and shelf life. To ensure crop shelf life and quality, temperature, moisture, ethylene hormone, and oxygen-to-carbon dioxide storage ratio must be regulated. Fruit components may caramelize when infectious organisms infiltrate harvested products. This will infect or cover fruits with spores and create metabolic byproducts [128].

However, overripe or underripe fruits are more prone to develop physiological anomalies, which can lead to wastage and food waste. Cold snaps, weather, water stress, heavy rainfalls, infections, physiological disorders, plant health, protection, water management, fertilizing, and cutting can damage fruits and vegetables before harvest without proper cultural practices. Many things can cause this harm. The loss of harvesting time can be caused by an inaccurate calculation, harvesting at the wrong time, improper harvesting procedures, and forgetting to pre-cool fruits. The International Refrigeration Institute (IIR) estimates that 23 percent of food waste in underdeveloped nations is caused by the lack of cooling equipment. Constant cold storage ensures that items reach consumers in perfect condition, but in impoverished countries, the lack of suitable storage facilities degrades both qualitative and quantitative aspects of food production, from harvest to consumption. Preventative measures include keeping a cool temperature, relative humidity, and proper shipping and packing can preserve fresh food [129].

Ethylene sensitivity and bloom length vary across ornamental plants including roses, liliums, lisianthus, chrysanthemums, and carnations. Breeding and ethylene screening have shown some success. Molecular methods, such as gene editing, can lengthen ornamental plant lifespans. Using CRISPR/Cas9, the 1-aminocyclopropane-1-carboxylate oxidase1 (PhACO1) gene may be altered with the ethylene-generating enzyme. Abiotic stressors include dehydration, soil salinity, and severe temperatures threaten crop development, yield, and quality. Tropical regions are more prone to face abiotic stress, which limits crop growth and yield due to high temperatures and dryness. CRISPR/Cas9 technology is being used to make transgenic crops that yield more and can withstand severe conditions [130].

Precision genome editing is a new genetic engineering technology for crop development. Plant genes have been targeted using TALENs, ZFNs, RGENs, and CRISPR/Cas9.

CRISPR/Cas9 may modify almost any sequence to expose its significance in an organism's DNA. This method has created tomatoes with dehydration, high-temperature, auxin, and drought tolerance. To better understand NCED4 and SIMAPK3 silencing in tomatoes under heat stress, CRISPR/Cas9 has been used to produce mutations in lettuce plants. ARGOS8 gene promoter was transformed into GOS2 to increase gene expression, which was used to create drought-resistant maize crops. This technique is used. Overexpressing the melatonin gene, which produces melatonin, helps plants tolerate abiotic stress [131].
CRISPR/Cas9 genome editing is being utilized to expand genome-wide screening for desired traits. Through precise base mutation at gene locations, the CRISPR/Cas9 system may create gain-of-function or loss-of-function mutants. Without a doubt, CRISPR/Cas9 might replace existing crop breeding methods. Using gRNA sequencing, unique allelic variations that match a desirable trait may be found and inserted into plant populations using genetic editing technologies.
Biogenic stresses including insects, viruses, fungi, and bacteria can affect plants. To make disease-resistant plants, CRISPR/Cas9 tools were developed. Despite this, CRISPR/Cas9 genome editing for biotic stress tolerance in ornamental crops, fruits, and vegetables has not made much progress. Plants' response to biotic stress involves overexpression and downregulation of several key genes, making it more complicated than other environmental stresses [132].

## Conclusion

The application of genetic engineering techniques can enhance the natural resilience of crops, making them less susceptible to spoilage and decay. This not only extends the shelf life of the produce but also reduces the amount of food waste generated. For instance, genetically modified fruits like the FlavrSavr tomato have been engineered to ripen without softening, a key factor contributing to its longer shelf life. Moreover, biotechnological interventions in post-harvest processes can help maintain the nutritional quality of the food products. This is particularly important in developing countries where post-harvest losses are high and nutritional security is a major concern. By ensuring that a greater proportion of harvested crops reach the consumer in a fresh and nutritious state, these technologies can play a significant role in enhancing food security. However, it's important to note that while these technologies offer promising solutions, they are not without their challenges. Ethical considerations around genetic modifications, potential ecological impacts, and the need for regulatory frameworks are some of the issues that need to be addressed. It's crucial that these technologies are developed and used in a responsible and sustainable manner. Furthermore, while these technologies can significantly reduce food waste, they are only part of the solution. Addressing food waste requires a multi-pronged approach that includes improving infrastructure, enhancing supply chain management, and changing consumer behaviour. In the future, as we continue to innovate and refine these technologies, we can look forward to a more sustainable and efficient food system. The potential of post-harvest biotechnology and genetic engineering solutions is immense and harnessing this potential could be key to solving some of the most pressing challenges of our time. In the final analysis, post-harvest biotechnology and genetic engineering solutions represent a powerful tool in our arsenal to extend shelf life and reduce food waste. As we move forward, it's imperative that we continue to explore, invest in, and refine these technologies. With careful management and responsible use, they hold the promise of a more sustainable and secure food future.

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