Post-harvest Biotechnology or Genetic Engineering Solutions: Extending Shelf Life and Reducing Food Waste

Nilesh Ninama [a++], Lakshmi Gangal [b#*], Arshad Khayum [c†], Harshitha S B [d‡], Divya C [e++], Sowmya H M [f†], Abhishek Singh [g^] and Anushi [h##]

[a] *Department of Vegetable Science, Rajmata Vijayaraje Scindia krishi Vishwavidyalaya, Gwalior, Madhya Pradesh – 474002, India.*
[b] *Department of Postharvest Management, College of Horticulture, Bagalkot, (University of Horticultural Sciences, Bagalkot), 587104, India.*
[c] *Department of Postharvest Technology, College of Horticulture, Mudigere-577132 (University: KSNUAHS, Shivamogga-577412), India.*
[d] *Division of Post-Harvest Technology and Agricultural engineering, ICAR-IIHR, Hesaragatta, Bengaluru-560089, India.*
[e] *Department of Food Science and Nutrition, University of Agricultural Sciences, Bangalore, India.*
[f] *Department of Genetics and Plant Breeding, Sri Krishnadevaraya College of Horticultural Sciences, Ananthapuramu, Andhra Pradesh (Affiliated to Dr.YSR Horticultural University, West Godavari, VR Gudem (A.P.), India.*
[g] *Department of Agricultural Economics, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh -208002, India.*
[h] *Department of Fruit Science, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh -208002, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

_____

[++] *Ph.D. Scholar;*
[#] *Ph.D. Student;*
[†] *Assistant Professor;*
[‡] *YP-II;*
[^] *Ph.D. (Research Scholar);*
[##] *Ph.D. Student;*
Corresponding author: E-mail: lakshgangal6@gmail.com;

Review Article

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.

1. 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.

2. 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-methylciclopropene (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].
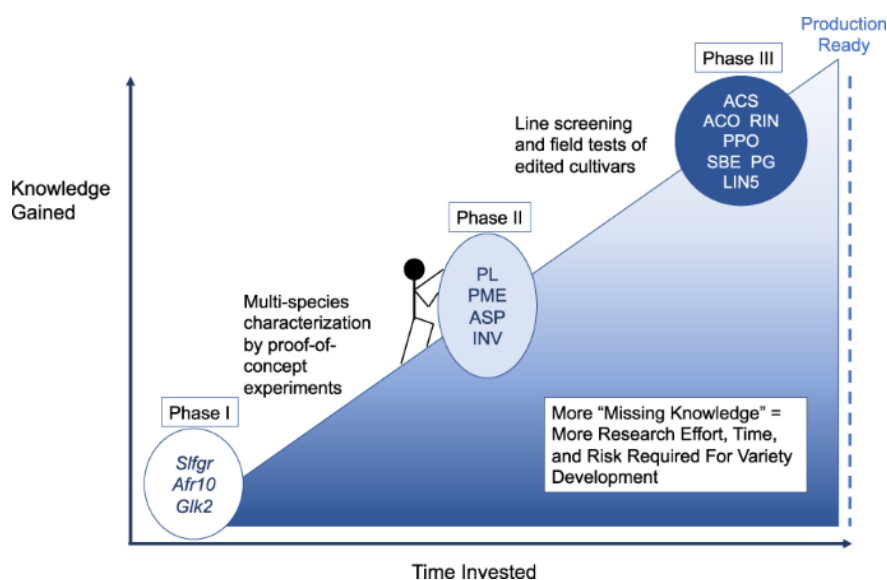

Fig. 1. Technology-assisted breeding for new and enhanced fruit

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].
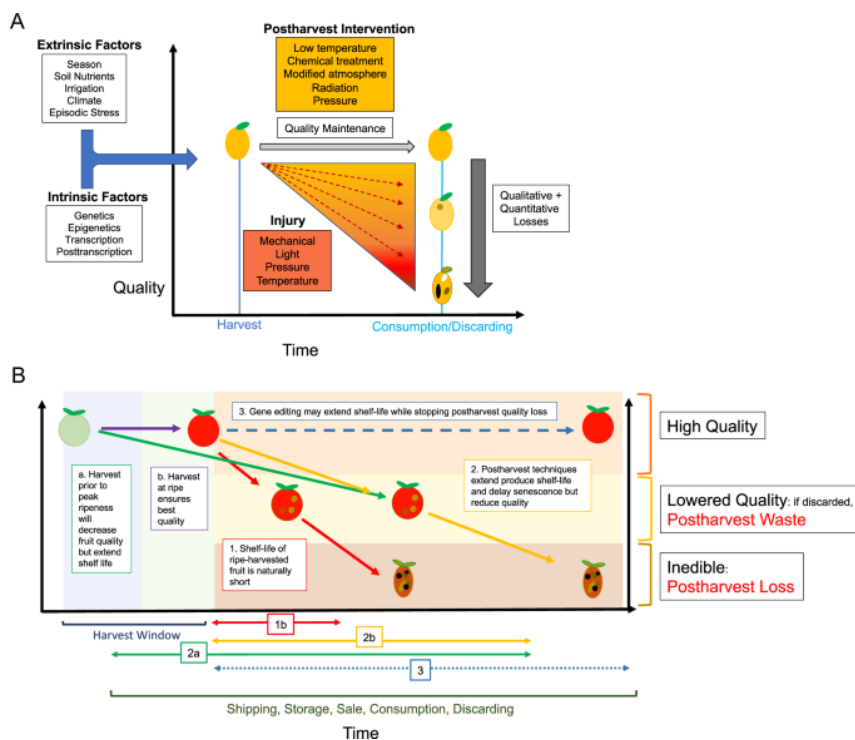

Fig. 2. Climacteric and non-climacteric principles

3. 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].

4. 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].

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].

5. 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].
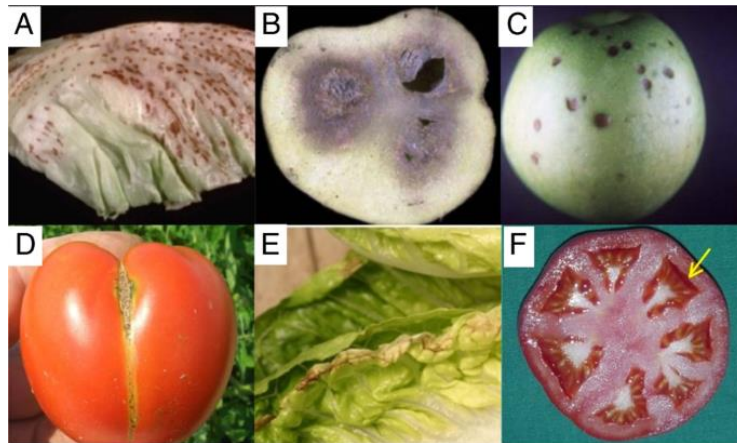
Fig. 3. Conventional breeding operations struggle with sterility, self-incompatibility, high heterozygosity, poor allele recovery, and long life cycles
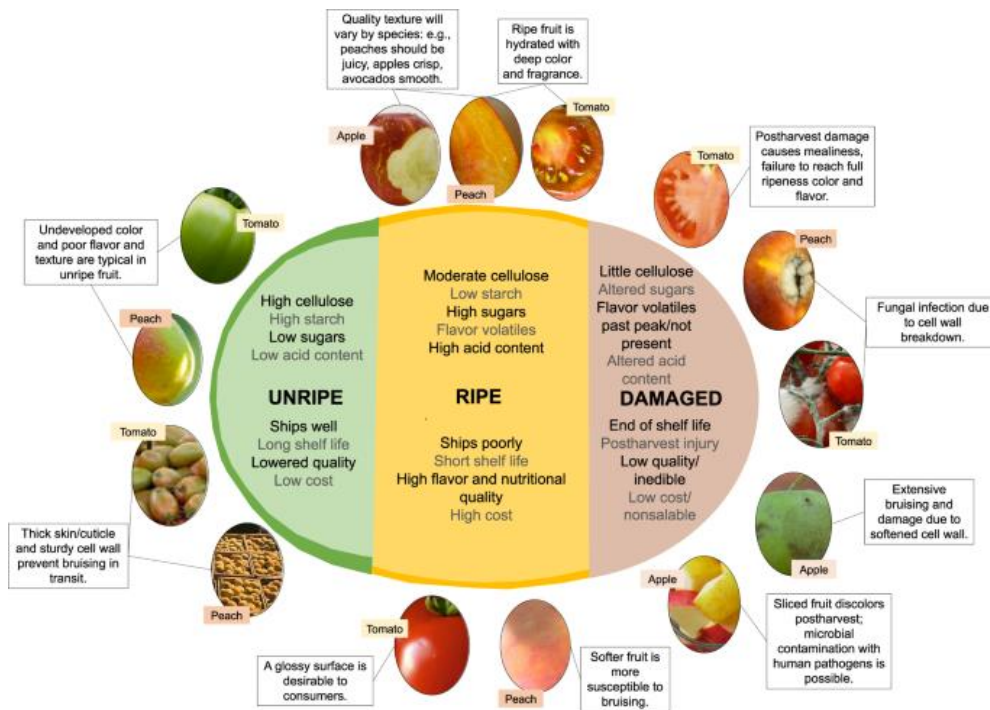

Fig. 4. Gene editing in post-harvest management

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].

6. METHOD ADOPTED

Non-thermal physical technologies have grown in favour 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 flavour-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 flavour, 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. [133] 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, aloevera 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. [133] 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. 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 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].

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].
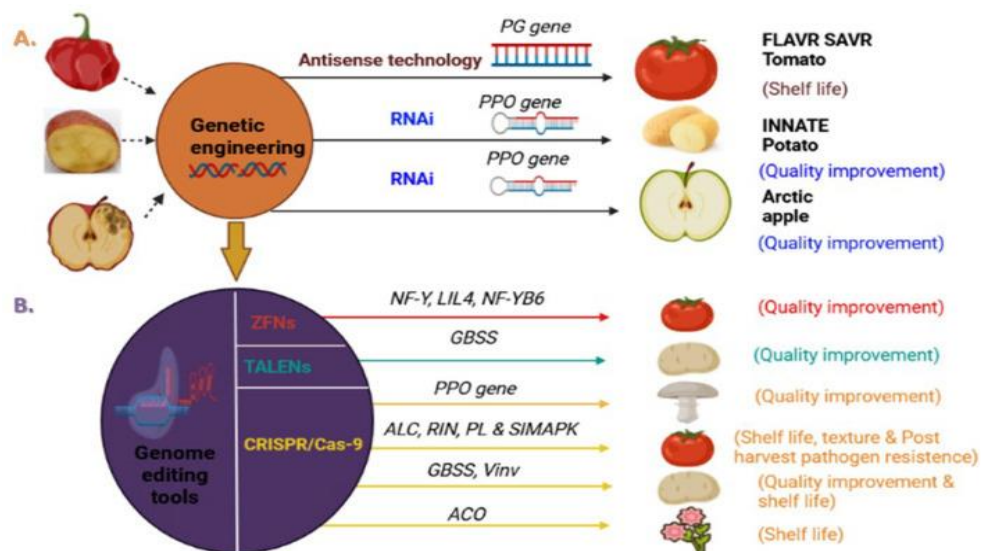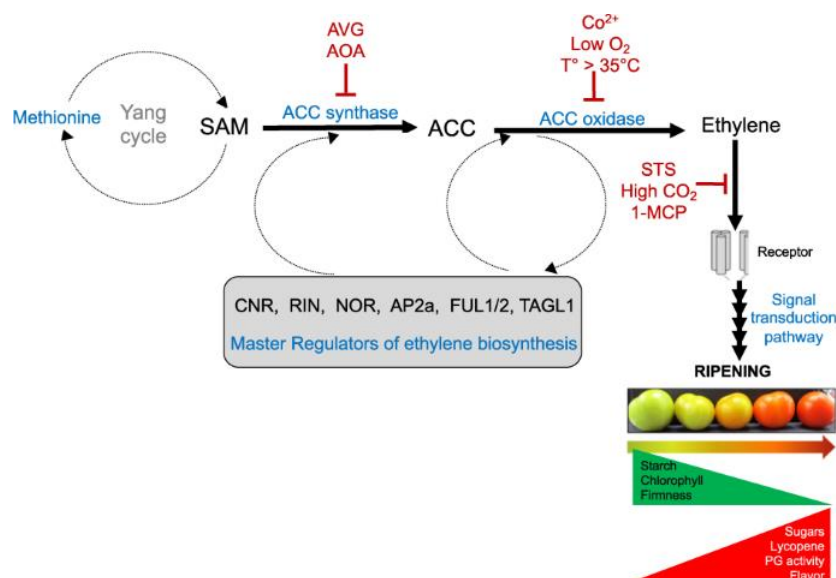

Fig. 5. Antisense technology

Fig. 6. biocontrol projections for fresh plant products

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].

7. 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 colour 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].
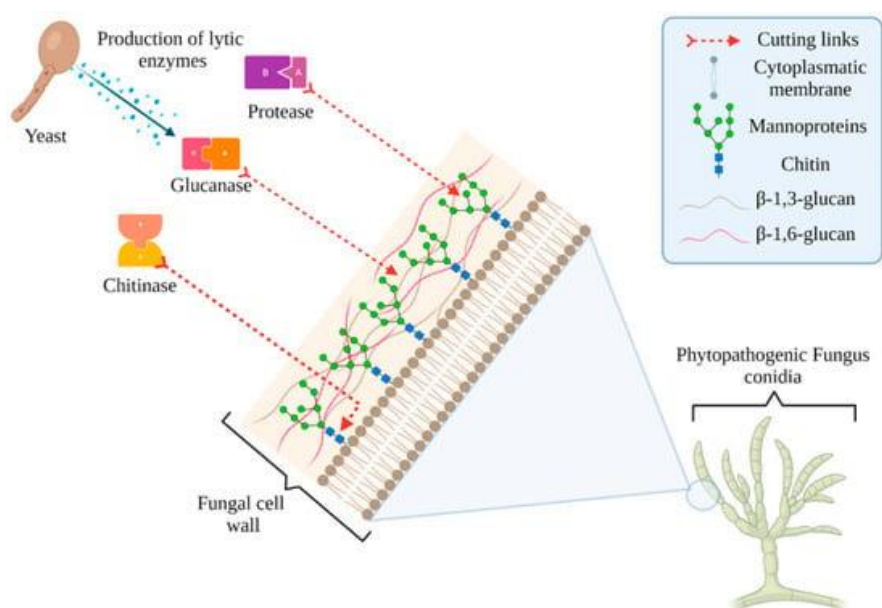

Fig. 7. Computer based technologies

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 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].
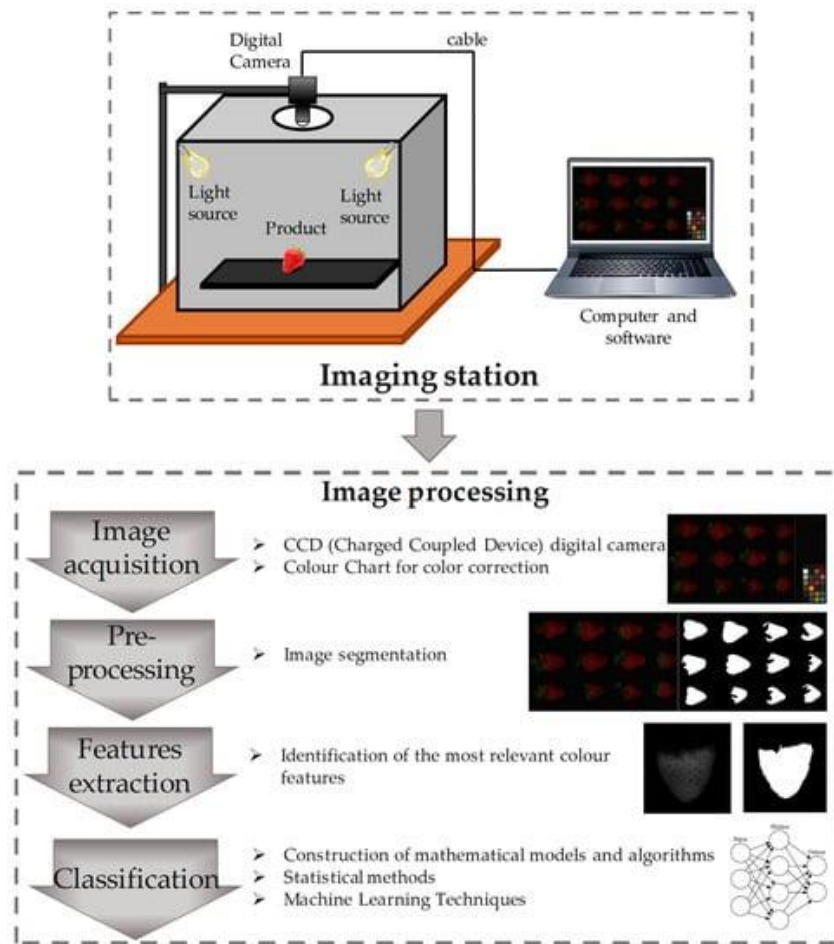
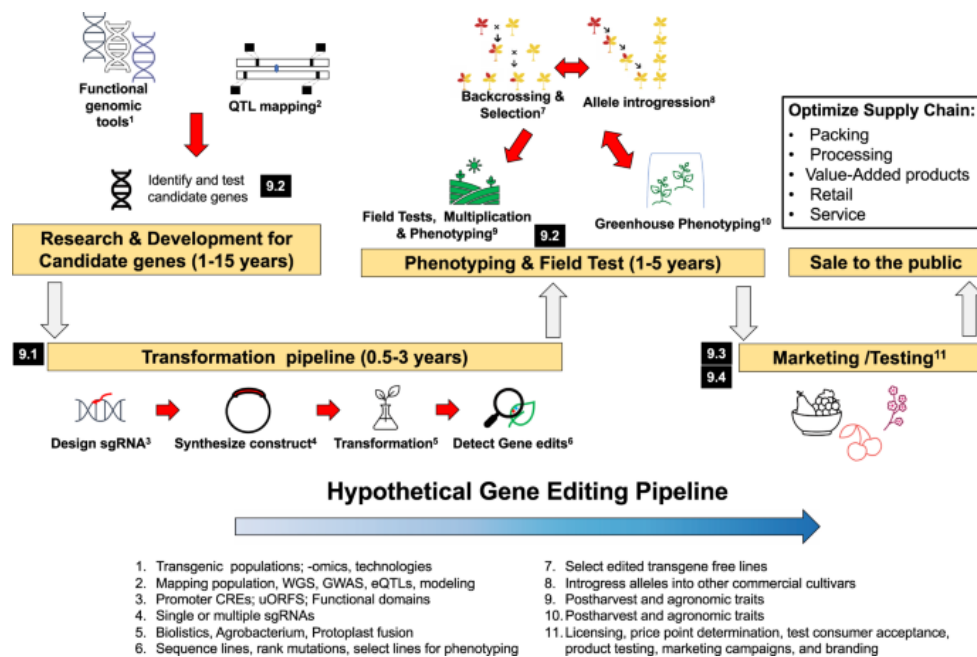**Fig. 8. solid-phase microextraction**

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

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].

8. POST-HARVEST MANAGEMENT THROUGH GENE EDITING IN VEGETABLES

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 Flavr Savr, 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), colorless nonripening (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].
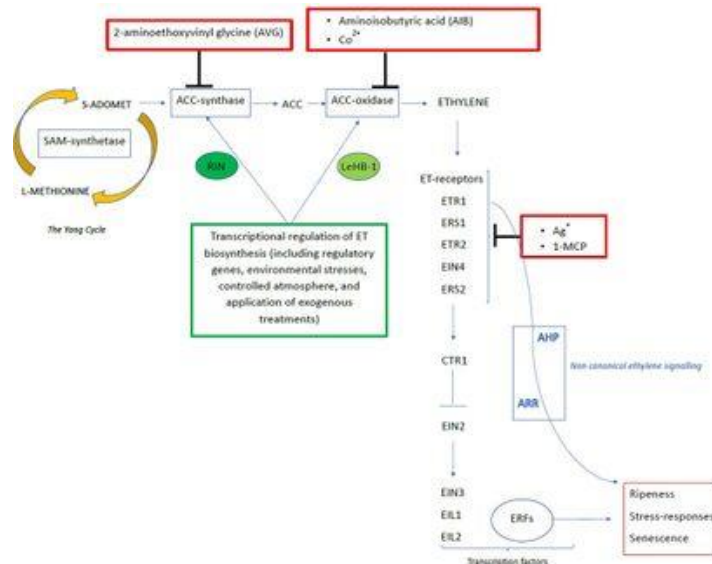
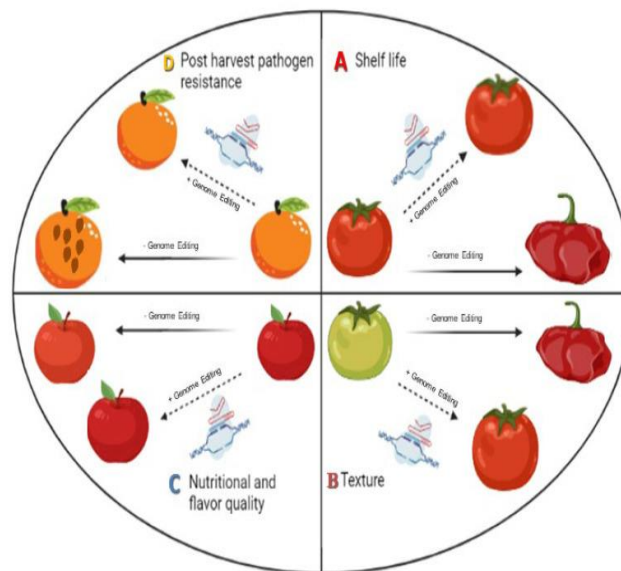**Fig. 10. CRISPR/Cas9-induced mutations for ET in breeding**

Fig. 11. Benefits of biotechnologies inventions in post-harvest

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.

9. BENEFITS OF BIOTECHNOLOGIES INVENTIONS IN POST-HARVEST

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 [132,133].

10. 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 Flavr Savr 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.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Mahajan PV, Caleb OJ, Singh Z, Watkins CB, Geyer M. Postharvest treatments of fresh produce. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 2014;372:20130309.
2. Brasil IM, Siddiqui MW. Postharvest quality of fruits and vegetables: An overview. In preharvest modulation of postharvest fruit and vegetable quality. Elsevier: Amsterdam, The Netherlands, 2018; 1–40. ISBN 978-0-12-809807-3.
3. Chauhan OP, Lakshmi S, Pandey AK, Ravi N, Gopalan N, Sharma RK. Non-destructive quality monitoring of fresh fruits and vegetables. Def. Life Sci. J. 2017;2:103.
4. Barth M, Hankinson TR, Zhuang H, Breidt F. Microbiological spoilage of fruits and vegetables. In compendium of the microbiological spoilage of foods and beverages; Sperber WH, Doyle MP, Eds.; Springer New York: New York, NY, USA. 2009;135–183. ISBN 978-1-4419-0825-4.
5. De Corato U. Improving the shelf-life and quality of fresh and minimally-processed fruits and vegetables for a modern food industry: A comprehensive critical review from the traditional technologies into the most promising advancements. Crit. Rev. Food Sci. Nutr. 2020;60:940–975.
6. Berger CN, Sodha SV, Shaw RK, Griffin PM, Pink D, Hand P, Frankel G. Fresh fruit and vegetables as vehicles for the transmission of human pathogens: Fresh produce as vehicles for transmission of human pathogens. Environ. Microbiol. 2010;12:2385–2397.
7. Srisamran J, Atwill ER, Chuanchuen R, Jeamsripong S. Detection and analysis of indicator and pathogenic bacteria in conventional and organic fruits and vegetables sold in retail markets. Food Qual. Saf. 2022;6:fyac013.
8. Gustavsson J, Cederberg C, Sonesson U. The methodology of the FAO study: Global food losses and food waste—extent, causes and prevention—FAO. Available:https://www.diva-portal.org/smash/get/diva2:944159/FULLTEXT01.pdf Accessed on 29 August 2022.
9. Bourne M. Post harvest food losses—The neglected dimension in increasing the world food supply. In Cornell International Agriculture Mimeograph 53; Cornell University: Ithaca, NY, USA; 1977.
10. SOFA—The state of food and agriculture in the world; 2019. Available:https://www.fao.org/state-of-food-agriculture/2019/en/ Accessed on 1 October 2022.
11. Singh V, Hedayetullah M, Zaman P, Meher J. Postharvest technology of fruits and vegetables: An overview, journal of post harvest technology. J. Postharvest Technol. 2014;2:124–135.
12. Ali A, Yeoh WK, Forney C, Siddiqui MW. Advances in postharvest technologies to extend the storage life of minimally processed fruits and vegetables. Crit. Rev. Food Sci. Nutr. 2018;58:2632–2649.
13. Fatchurrahman D, Amodio ML, Colelli G. Quality of goji berry fruit (*Lycium barbarum* L.) stored at different temperatures. Foods 2022;11:3700.
14. Kader AA. Postharvest technology of horticultural crops; university of california agriculture and natural resources: Oakland, CA, USA. 2002; ISBN 978-1-879906-51-8.
15. Fahmy K, Nakano K. Effective transport and storage condition for preserving the quality of 'Jiro' persimmon in export market. Agric. Agric. Sci. Procedia 2016;9:279–290.
16. Bhargava A, Bansal A. Fruits and vegetables quality evaluation using computer vision: A Review. J. King Saud Univ. - Comput. Inf. Sci. 2021;33:243–257.
17. García-Oliveira P, Fraga-Corral M, Pereira AG, Prieto MA, Simal-Gandara J. Solutions

for the sustainability of the food production and consumption system. Crit. Rev. Food Sci. Nutr. 2022;62: 1765–1781.

18. Fan X, Wang W. Quality of fresh and fresh-cut produce impacted by nonthermal physical technologies intended to enhance microbial safety. Crit. Rev. Food Sci. Nutr. 2022;62:362–382.

19. Ganesan AR, Tiwari U, Ezhilarasi PN, Rajauria G. Application of cold plasma on food matrices: A review on current and future prospects. J. Food Process. Preserv. 2021;45:e15070.

20. Dar AH, Shams R, ul Eain Hyder Rizvi Q, Majid I. Microwave and ohmic heating of fresh cut fruits and vegetable products; Elsevier Inc.: Amsterdam, The Netherlands, 2019; ISBN 9780128161845.

21. Usall J, Ippolito A, Sisquella M, Neri F. Physical treatments to control postharvest diseases of fresh fruits and vegetables. Postharvest Biol. Technol. 2016;122:30–40.

22. Martínez-Hernández GB, Amodio ML, Colelli G. Potential use of microwave treatment on fresh-cut carrots: physical, chemical and microbiological aspects. J. Sci. Food Agric. 2016;96:2063–2072.

23. Song L, Luo H, Cheng X, Yan F, Yang Z, Yu Z. Effects of microwave treatment on physiology and quality of minimally processed bok choy (*Brassica campestris* L.) during storage at 5 °C. *J.* Food Meas. Charact. 2018;12:913–922.

24. Colelli G, Amodio ML, de Chiara MLV. Operating conditions for microwave application throughout production process to reduce microbial load of fresh-cut apples. Acta Hortic. 2021;1319:223–230.

25. Vadivambal R, Jayas DS. Non-uniform temperature distribution during microwave heating of food materials—A review. Food Bioprocess Technol. 2010;3:161–171.

26. Li J, Shi J, Huang X, Wang T, Zou X, Li Z, Zhang D, Zhang W, Xu Y. Effects of pulsed electric field pretreatment on frying quality of fresh-cut lotus root slices. LWT. 2020;132:109873.

27. López-Gámez G, Elez-Martínez P, Martín-Belloso O, Soliva-Fortuny R. Pulsed electric fields affect endogenous enzyme activities, respiration and biosynthesis of phenolic compounds in carrots. Postharvest Biol. Technol. 2020;168:111284.

28. López-Gámez G, Elez-Martínez P, Martín-Belloso O, Soliva-Fortuny R. Enhancing phenolic content in carrots by pulsed electric fields during post-treatment time: effects on cell viability and quality attributes. Innov. Food Sci. Emerg. Technol. 2020;59:102252.

29. López-Gámez G, Elez-Martínez P, Martín-Belloso O, Soliva-Fortuny R. Changes of carotenoid content in carrots after application of pulsed electric field treatments. LWT 2021;147:111408.

30. Rux G, Gelewsky R, Schlüter O, Herppich WB. High hydrostatic pressure treatment effects on selected tissue properties of fresh horticultural products. Innov. Food Sci. Emerg. Technol. 2020;61: 102326.

31. Ramos-Parra PA, García-Salinas C, Rodríguez-López CE, García N, García-Rivas G, Hernández-Brenes C, Díaz de la Garza RI. High hydrostatic pressure treatments trigger de novo carotenoid biosynthesis in papaya fruit (*Carica papaya* Cv. Maradol). Food Chem. 2019;277:362–372.

32. Hu X, Ma T, Ao L, Kang H, Hu X, Song Y, Liao X. Effect of high hydrostatic pressure processing on textural properties and microstructural characterization of fresh-cut pumpkin (*Cucurbita pepo*). *J.* Food Process Eng. 2020;43:e13379.

33. Hu K, Peng D, Wang L, Liu H, Xie B, Sun Z. Effect of mild high hydrostatic pressure treatments on physiological and physicochemical characteristics and carotenoid biosynthesis in postharvest mango. Postharvest Biol. Technol. 2021; 172:111381.

34. Kundukulangara Pulissery S, Kallahalli Boregowda S, Suseela S, Jaganath B. A comparative study on the textural and nutritional profile of high pressure and minimally processed pineapple. J. Food Sci. Technol. 2021;58:3734–3742.

35. Paciulli M, Rinaldi M, Rodolfi M, Ganino T, Morbarigazzi M, Chiavaro E. Effects of high hydrostatic pressure on physico-chemical and structural properties of two pumpkin species. Food Chem. 2019;274:281–290.

36. Paciulli M, Medina Meza IG, Rinaldi M, Ganino T, Pugliese A, Rodolfi M, Barbanti D, Morbarigazzi M, Chiavaro E. Improved physicochemical and structural properties of blueberries by high hydrostatic pressure processing. Foods. 2019;8:272.

37. Paciulli M, Ganino T, Meza IGM, Rinaldi M, Rodolfi M, Morbarigazzi M, Chiavaro E. High pressure and thermal processing on

the quality of zucchini slices. Eur. Food Res. Technol. 2021;247:475–484.

38. Tappi S, Ramazzina I, Rizzi F, Sacchetti G, Ragni L, Rocculi P. Effect of plasma exposure time on the polyphenolic profile and antioxidant activity of fresh-cut apples. Appl. Sci. 2018;8:1939.

39. Tappi S, Ragni L, Tylewicz U, Romani S, Ramazzina I, Rocculi P. Browning response of fresh-cut apples of different cultivars to cold gas plasma treatment. Innov. Food Sci. Emerg. Technol. 2019;53:56–62.

40. Zhou D, Li T, Cong K, Suo A, Wu, C. Influence of cold plasma on quality attributes and aroma compounds in fresh-cut cantaloupe during low temperature storage. LWT 2022;154:112893.

41. Ahmadnia M, Sadeghi M, Abbaszadeh R, Ghomi Marzdashti H.R. Decontamination of whole strawberry via dielectric barrier discharge cold plasma and effects on quality attributes. J. Food Process. Preserv. 2021;45:e15019.

42. Rana S, Mehta D, Bansal V, Shivhare US, Yadav SK. Atmospheric Cold Plasma (ACP) treatment improved in-package shelf-life of strawberry fruit. J. Food Sci. Technol. 2020;57:102–112.

43. Li X, Li M, Ji N, Jin P, Zhang J, Zheng Y, Zhang X, Li F. Cold plasma treatment induces phenolic accumulation and enhances antioxidant activity in fresh-cut pitaya (*Hylocereus Undatus*) Fruit. LWT. 2019;115:108447.

44. Zhang Y, Zhang J, Zhang Y, Hu H, Luo S, Zhang L, Zhou H, Li P. Effects of In-package atmospheric cold plasma treatment on the qualitative, metabolic and microbial stability of fresh-cut pears. J. Sci. Food Agric. 2021;101:4473–4480.

45. Giannoglou M, Stergiou P, Dimitrakellis P, Gogolides E, Stoforos NG, Katsaros G. Effect of cold atmospheric plasma processing on quality and shelf-life of ready-to-eat rocket leafy salad. Innov. Food Sci. Emerg. Technol. 2020;66:102502.

46. Hu X, Sun H, Yang X, Cui D, Wang Y, Zhuang J, Wang X, Ma R, Jiao Z. Potential use of atmospheric cold plasma for postharvest preservation of blueberries. Postharvest Biol. Technol. 2021;179:111564.

47. Gavahian M, Sheu F, Tsai M, Chu Y. The effects of dielectric barrier discharge plasma gas and plasma-activated water on texture, color, and bacterial characteristics of shiitake mushroom. J. Food Process. Preserv. 2020;44:e14316.

48. Liu C, Chen C, Jiang A, Sun X, Guan Q, Hu W. Effects of plasma-activated water on microbial growth and storage quality of fresh-cut apple. Innov. Food Sci. Emerg. Technol. 2020;59:102256.

49. Perinban S, Orsat V, Raghavan V. Influence of plasma activated water treatment on enzyme activity and quality of fresh-cut apples. Food Chem. 2022;393: 133421.

50. Vanga SK, Wang J, Jayaram S, Raghavan V. Effects of pulsed electric fields and ultrasound processing on proteins and enzymes: A Review. Processes 2021;9:722.

51. González-Casado S, Martín-Belloso O, Elez-Martínez P, Soliva-Fortuny R. Enhancing the carotenoid content of tomato fruit with pulsed electric field treatments: Effects on respiratory activity and quality attributes. Postharvest Biol. Technol. 2018;137:113–118.

52. Sotelo KAG, Hamid N, Oey I, Pook C, Gutierrez-Maddox N, Ma Q, Ying Leong S, Lu J. Red Cherries (*Prunus avium* Var. Stella) processed by pulsed electric field—physical, chemical and microbiological analyses. Food Chem. 2018;240: 926–934.

53. Ribas-Agustí A, Martín-Belloso O, Soliva-Fortuny R, Elez-Martínez P. Enhancing hydroxycinnamic acids and flavan-3-ol contents by pulsed electric fields without affecting quality attributes of apple. Food Res. Int. 2019;121:433–440.

54. Pokhrel PR, Boulet C, Yildiz S, Sablani S, Tang J, Barbosa-Cánovas GV. Effect of high hydrostatic pressure on microbial inactivation and quality changes in carrot-orange juice blends at varying PH. LWT. 2022;159:113219.

55. Bagheri H, Abbaszadeh S. Effect of cold plasma on quality retention of fresh-cut produce. J. Food Qual. 2020;8866369.

56. Li M, Li X, Han C, Ji N, Jin P, Zheng Y. Physiological and metabolomic analysis of cold plasma treated fresh-cut strawberries. J. Agric. Food Chem. 2019;67:4043–4053.

57. Ziuzina D, Misra NN, Han L, Cullen PJ, Moiseev T, Mosnier JP, Keener K, Gaston E, Vilaró I, Bourke P. Investigation of a large gap cold plasma reactor for continuous in-package decontamination of fresh strawberries and spinach. Innov.

Food Sci. Emerg. Technol. 2020;59: 102229.

58. Hozák P, Jirešová J, Khun J, Scholtz V, Julák J. Shelf life prolongation of fresh strawberries by nonthermal plasma treatment. J. Food Process. Preserv. 2022;46Le16150.

59. Puligundla P, Lee T, Mok C. Effect of intermittent corona discharge plasma treatment for improving microbial quality and shelf life of kumquat (*Citrus Japonica*) Fruits. LWT. 2018;91:8–13.

60. Guo J, Qin D, Li W, Wu F, Li L, Liu X. Inactivation of *Penicillium Italicum* on kumquat via plasma-activated water and its effects on quality attributes. Int. J. Food Microbiol. 2021;343:109090.

61. Tan J, Karwe MV. Inactivation of enterobacter aerogenes on the surfaces of fresh-cut purple lettuce, kale, and baby spinach leaves using Plasma Activated Mist (PAM). Innov. Food Sci. Emerg. Technol. 2021;74:102868.

62. Laurita R, Gozzi G, Tappi S, Capelli F, Bisag A, Laghi G, Gherardi M, Cellini B, Abouelenein D, Vittori S, et al. Effect of Plasma Activated Water (PAW) on rocket leaves decontamination and nutritional value. Innov. Food Sci. Emerg. Technol. 2021;73:102805.

63. Silvetti T, Pedroni M, Brasca M, Vassallo E, Cocetta G, Ferrante A, De Noni I, Piazza L, Morandi S. Assessment of possible application of an atmospheric pressure plasma jet for shelf life extension of fresh-cut salad. Foods. 2021;10:513.

64. Sudarsan A, Keener K. Inactivation of spoilage organisms on baby spinach leaves using High Voltage Atmospheric Cold Plasma (HVACP) and assessment of quality. Innov. Food Sci. Emerg. Technol. 2022;79:103023.

65. Dong XY, Yang YL. A novel approach to enhance blueberry quality during storage using cold plasma at atmospheric air pressure. Food Bioprocess. Technol. 2019;12:1409–1421.

66. Ji Y, Hu W, Liao J, Jiang A, Xiu Z, Gaowa S, Guan Y, Yang X, Feng K, Liu C. Effect of atmospheric cold plasma treatment on antioxidant activities and reactive oxygen species production in postharvest blueberries during storage. J. Sci. Food Agric. 2020;100:5586–5595.

67. Pathak N, Grossi Bovi G, Limnaios A, Fröhling A, Brincat J, Taoukis P, Valdramidis VP, Schlüter O. Impact of cold atmospheric pressure plasma processing on storage of blueberries. J. Food Process. Preserv. 2020;44:e14581.

68. Segura-Ponce LA, Reyes JE, Troncoso-Contreras G, Valenzuela-Tapia G. Effect of Low-Pressure Cold Plasma (LPCP) on the wettability and the inactivation of *Escherichia Coli* and *Listeria Innocua* on Fresh-Cut Apple (Granny Smith) Skin. Food Bioprocess Technol. 2018;11:1075–1086.

69. Zhou R, Zhou R, Mai-Prochnow A, Zhang X, Xian Y, Cullen PJ, Ostrikov K. (Ken) Surface plasma discharges for the preservation of fresh-cut apples: Microbial inactivation and quality attributes. J. Phys. Appl. Phys. 2020;53:174003.

70. Chen C, Liu C, Jiang A, Guan Q, Sun X, Liu S, Hao K, Hu W. The effects of cold plasma-activated water treatment on the microbial growth and antioxidant properties of fresh-cut pears. Food Bioprocess Technol. 2019;12:1842–1851.

71. Zhao Z, Wang X, Ma T. Properties of plasma-activated water with different activation time and its effects on the quality of button mushrooms (*Agaricus Bisporus*). LWT. 2021;147:111633.

72. Lee T, Puligundla P, Mok C. Intermittent corona discharge plasma jet for improving tomato quality. J. Food Eng. 2018;223:168–174.

73. Zhao Y, Chen R, Liu D, Wang W, Niu J, Xia Y, Qi Z, Zhao Z, Song Y. Effect of nonthermal plasma-activated water on quality and antioxidant activity of fresh-cut kiwifruit. IEEE Trans. Plasma Sci. 2019;47:4811–4817.

74. Limnaios A, Pathak N, Grossi G, Fr A, Valdramidis P, Taoukis PS, Schlüter O. Effect of cold atmospheric pressure plasma processing on quality and shelf life of red currants. LWT. 2021;151: 112213.

75. Siddiqui W, Chakraborty I, Ayala-Zavala JF, Dhua RS. Advances in minimal processing of fruits and vegetables: A review. *J.* Sci. Ind. Res. 2011;70:12.

76. Escobedo-Avellaneda Z, García-García R, Valdez-Fragoso A, Mújica-Paz H, Welti-Chanes J. Fruit preservation and design of functional fruit products by vacuum impregnation. In Fruit Preservation; Rosenthal A, Deliza R, Welti-Chanes J., Barbosa-Cánovas GV, Eds.; Food Engineering Series; Springer New York: New York, NY, USA, 2018;335–349. ISBN 978-1-4939-3309-9.

77. Chinnaswamy S, Rudra SG, Sharma RR. Texturizers for fresh-cut fruit and vegetable products. In fresh-cut fruits and vegetables. Elsevier: Amsterdam, The Netherlands, 2020;121–149. ISBN 978-0-12-816184-5.

78. Joshi A, Prajapati U, Sethi S, Arora B, Sharma RR. Fortification in fresh and fresh-cut horticultural products. In fresh-cut fruits and vegetables; Elsevier: Amsterdam, The Netherlands, 2020;183–204. ISBN 978-0-12-816184-5.

79. Martín-Diana AB, Rico D, Frías JM, Barat JM, Henehan GTM, Barry-Ryan C. Calcium for extending the shelf life of fresh whole and minimally processed fruits and vegetables: A Review. Trends Food Sci. Technol. 2007;18:210–218.

80. Soliva-Fortuny RC, Martín-Belloso O. New advances in extending the shelf-life of fresh-cut fruits: A review. Trends Food Sci. Technol. 2003;14:341–353.

81. Alzamora SM, Salvatori D, Tapia MS, López-Malo A, Welti-Chanes J, Fito P. Novel functional foods from vegetable matrices impregnated with biologically active compounds. J. Food Eng. 2005;67;205–214.

82. Mu B, Xue J, Zhang S, Li Z. Effects of the use of different temperature and calcium chloride treatments during storage on the quality of fresh-cut "Xuebai" cauliflowers. Foods. 2022;11:442.

83. Mola S, Uthairatanakij A, Srilaong V, Aiamla-or S, Jitareerat P. Impacts of sodium chlorite combined with calcium chloride, and calcium ascorbate on microbial population, browning, and quality of fresh-cut rose apple. Agric. Nat. Resour. 2016;50:331–337.

84. Giacalone G, Chiabrando V. Effect of different treatments with calcium salts on sensory quality of fresh-cut apple. J. Food Nutr. Res. 2013;52:79–86.

85. Albertini S, Lai Reyes AE, Trigo JM, Sarriés GA, Spoto MHF. Effects of chemical treatments on fresh-cut papaya. Food Chem. 2016;190: 1182–1189.

86. Yan R, Han C, Fu M, Jiao W, Wang W. Inhibitory effects of CaCl2 and pectin methylesterase on fruit softening of raspberry during cold storage. Horticulturae. 2021;8:1.

87. Hamdan N, Lee CH, Wong SL, Fauzi CENCA, Zamri NMA, Lee TH. Prevention of enzymatic browning by natural extracts and genome-editing: A review on recent progress. Molecules. 2022;27:1101.

88. Martínez-Hernández GB, Castillejo N, Artés-Hernández F. Effect of fresh–cut apples fortification with lycopene microspheres, revalorized from tomato by-products, during shelf life. Postharvest Biol. Technol. 2019;156:110925.

89. Supapvanich S, Mitsang P, Srinorkham P. Effects of 'Queen' and 'Smooth Cayenne' pineapple fruit core extracts on browning inhibition of fresh-cut wax apple fruit during storage. Int. Food Res. J. 2017;24:559–564.

90. Turrini F, Malaspina P, Giordani P, Catena S, Zunin P, Boggia R. Traditional decoction and puae aqueous extracts of pomegranate peels as potential low-cost anti-tyrosinase ingredients. Appl. Sci. 2020;10:2795.

91. Jirasuteeruk C, Theerakulkait C. Ultrasound-assisted extraction of phenolic compounds from mango (*Mangifera Indica* Cv. Chok Anan) peel and its inhibitory effect on enzymatic browning of potato puree. Food Technol. Biotechnol. 2019;57:350–357.

92. Supapvanich S, Mitrsang P, Srinorkham P, Boonyaritthongchai P, Wongs-Aree C. Effects of fresh aloe vera gel coating on browning alleviation of fresh cut wax apple (*Syzygium Samarangenese*) fruit Cv. Taaptimjaan. J. Food Sci. Technol. 2016;53:2844–2850.

93. Wessels B, Damm S, Kunz B, Schulze-Kaysers N. Effect of selected plant extracts on the inhibition of enzymatic browning in fresh-cut apple. J. Appl. Bot. Food Qual. 2014;87:16–23.

94. Supapvanich S, Yimpong A, Srisuwanwichan J. Browning inhibition on fresh-cut apple by the immersion of liquid endosperm from mature coconuts. J. Food Sci. Technol. 2020;57:4424–4431.

95. Gras M, Vidal-Brotóns N, Betoret A, Chiralt, Fito P. The response of some vegetables to vacuum impregnation. Innov. Food Sci. Emerg. Technol. 2002;3:263–269.

96. Fito P. Modelling of vacuum osmotic dehydration of food. J. Food Eng. 1994;22:313–328.

97. Andrés A, Salvatori D, Albors A, Chiralt A, Fito P. Vacuum impregnation viability of some fruits and vegetables. In osmotic dehydration & vacuum impregnation; Fito P, Chiralt A, Barat JM, Spiess WEL,

Behsnilian D, Eds.; CRC Press: Boca Raton, FL, USA. 2019;53–60. ISBN 978-0-429-13221-6.

98. Kang J-W, Kang D-H. Enhanced antimicrobial effect of organic acid washing against foodborne pathogens on broccoli by vacuum impregnation. Int. J. Food Microbiol. 2016;217:85–93.

99. Yılmaz FM, Ersus Bilek S. Ultrasound-assisted vacuum impregnation on the fortification of fresh-cut apple with calcium and black carrot phenolics. Ultrason. Sonochem. 2018;48:509–516.

100. Santana Moreira M, de Almeida Paula D, Maurício Furtado Martins E, Nascif Rufino Vieira É, Mota Ramos A, Stringheta PC. Vacuum impregnation of β-carotene and lutein in minimally processed fruit salad. J. Food Process. Preserv. 2018;42:e13545.

101. Lech K, Michalska A, Wojdyło A, Nowicka P, Figiel A. The influence of physical properties of selected plant materials on the process of osmotic dehydration. LWT. 2018;91:588–594.

102. Peng J, Bi J, Yi J, Allaf K, Besombes C, Jin X, Wu X, Lyu J, Asghar Ali MNH. Apple juice concentrate impregnation enhances nutritional and textural attributes of the instant controlled pressure drop (DIC)-dried carrot chips. J. Sci. Food Agric. 2019;99:6248–6257.

103. Derossi A, Ricci I, Fiore AG, Severini C. Apple sclices enriched with aloe vera by vacuum impregnation. Ital. J. Food Sci. 2017;30:256–257.

104. González-Pérez JE, Jiménez-González O, Ramírez-Corona N, Guerrero-Beltrán JA, López-Malo A. Vacuum impregnation on apples with grape juice concentrate: Effects of pressure, processing time, and juice concentration. Innov. Food Sci. Emerg. Technol. 2022;77:102981.

105. Zhang L, Wang P, Chen F, Lai S, Yu H, Yang H. Effects of calcium and pectin methylesterase on quality attributes and pectin morphology of jujube fruit under vacuum impregnation during storage. Food Chem. 2019;289:40–48.

106. Yang H, Wu Q, Ng LY, Wang S. Effects of vacuum impregnation with calcium lactate and pectin methylesterase on quality attributes and chelate-soluble pectin morphology of fresh-cut papayas. Food Bioprocess Technol. 2017;10:901–913.

107. Pandey VK, Islam RU, Shams R, Dar AH. A comprehensive review on the application of essential oils as bioactive compounds in nano-emulsion based edible coatings of fruits and vegetables. Appl. Food Res. 2022;2:100042.

108. M Rangaraj V, Rambabu K, Banat F, Mittal V. Natural antioxidants-based edible active food packaging: An overview of current advancements. Food Biosci. 2021;43:101251.

109. Zam W. Effect of alginate and chitosan edible coating enriched with olive leaves extract on the shelf life of sweet cherries (*Prunus avium* L.). J. Food Qual. 2019;2019:8192964.

110. Robles-Sánchez RM, Rojas-Graü MA, Odriozola-Serrano I, González-Aguilar G, Martin-Belloso O. Influence of alginate-based edible coating as carrier of antibrowning agents on bioactive compounds and antioxidant activity in fresh-cut kent mangoes. LWT - Food Sci. Technol. 2013;50: 240–246.

111. Özdemir KS, Gökmen V. Effect of chitosan-ascorbic acid coatings on the refrigerated storage stability of fresh-cut apples. Coatings. 2019;9:503.

112. Liu J, Liu S, Zhang X, Kan J, Jin C. Effect of gallic acid grafted chitosan film packaging on the postharvest quality of white button mushroom (*Agaricus Bisporus*). Postharvest Biol. Technol. 2019;147:39–47.

113. Carvalho RL, Cabral MF, Germano TA, de Carvalho WM, Brasil IM, Gallão MI, Moura CFH, Lopes MMA, de Miranda MRA. Chitosan coating with trans-cinnamaldehyde improves structural integrity and antioxidant metabolism of fresh-cut melon. Postharvest Biol. Technol. 2016;113:29–39.

114. Jagannath JH, Nanjappa C, Gupta DD, Bawa AS. Studies on the stability of an edible film and its use for the preservation of carrot (*Daucus Carota*). Int. J. Food Sci. Technol. 2006;41:498–506.

115. Imeneo V, Piscopo A, Martín-Belloso O, Soliva-Fortuny R. Efficacy of pectin-based coating added with a lemon byproduct extract on quality preservation of fresh-cut carrots. Foods. 2022;11:1314.

116. Perdones A, Sánchez-González L, Chiralt A, Vargas M. Effect of chitosan–lemon essential oil coatings on storage-keeping quality of strawberry. Postharvest Biol. Technol. 2012;70:32–41.

117. Ghafoor K, Al-Juhaimi FY, Babiker EE, Mohamed Ahmed IA, Shahzad SA, Alsawmahi ON. Quality attributes of

refrigerated barhi dates coated with edible chitosan containing natural functional ingredients. Foods. 2022;11:1584.

118. Vieira TM, Alves VD, Moldão Martins M. Application of an eco-friendly antifungal active package to extend the shelf life of fresh red raspberry (*Rubus idaeus* L. Cv. 'Kweli'). Foods. 2022;11:1805.

119. Jurburg SD, Eisenhauer N, Buscot F, Chatzinotas A, Chaudhari NM, Heintz-Buschart A, Kallies R, Küsel K, Litchman E, Macdonald CA, et al. Potential of microbiome-based solutions for agrifood systems. Nat. Food. 2022;3:557–560.

120. Wassermann B, Müller H, Berg G. An apple a day: Which bacteria do we eat with organic and conventional apples? Front. Microbiol. 2019;10:1629.

121. Kłapeć T, Wójcik-Fatla A, Farian E, Kowalczyk K, Cholewa G, Cholewa A, Dutkiewicz J. Mycobiota of berry fruits—levels of filamentous fungi and mycotoxins, composition of fungi, and analysis of potential health risk for consumers. Ann. Agric. Environ. Med. 2022;29:28–37.

122. Vermote L, Verce M, Mozzi F, De Vuyst L, Weckx S. Microbiomes associated with the surfaces of northern argentinian fruits show a wide species diversity. Front. Microbiol. 2022;13:872281.

123. Sellitto VM, Zara S, Fracchetti F, Capozzi V, Nardi T. Microbial biocontrol as an alternative to synthetic fungicides: Boundaries between Pre- and postharvest applications on vegetables and fruits. Fermentation. 2021;7:60.

124. Zhang H, Zhang Q, Chen S, Zhang Z, Song J, Long Z, Yu Y, Fang H. Enterobacteriaceae predominate in the endophytic microbiome and contribute to the resistome of strawberry. Sci. Total Environ. 2020;727:138708.

125. De Simone N, Pace B, Grieco F, Chimienti M, Tyibilika V, Santoro V, Capozzi V, Colelli G, Spano G, Russo P. Botrytis cinerea and table grapes: A review of the main physical, chemical, and bio-based control treatments in post-harvest. Foods. 2020;9:1138.

126. De Simone N, Capozzi V, Amodio ML, Colelli G, Spano G, Russo P. Microbial-based biocontrol solutions for fruits and vegetables: Recent insight, patents, and innovative trends. Recent Pat. Food Nutr. Agric. 2021;12:3–18.

127. Capozzi V, Fragasso M, Bimbo F. Microbial resources, fermentation and reduction of negative externalities in food systems: Patterns toward sustainability and resilience. Fermentation. 2021;7: 54.

128. Díaz MA, Pereyra MM, Picón-Montenegro E, Meinhardt F, Dib JR. Killer yeasts for the biological control of postharvest fungal crop diseases. Microorganisms. 2020;8:1680.

129. Hernandez-Montiel LG, Droby S, Preciado-Rangel P, Rivas-García T, González-Estrada RR, Gutiérrez-Martínez P, Ávila-Quezada GD. A sustainable alternative for postharvest disease management and phytopathogens biocontrol in fruit: Antagonistic yeasts. Plants. 2021;10:2641.

130. Carmona-Hernandez S, Reyes-Pérez J, Chiquito-Contreras R, Rincon-Enriquez G, Cerdan-Cabrera C, Hernandez-Montiel L. Biocontrol of postharvest fruit fungal diseases by bacterial antagonists: A review. Agronomy. 2019;9:121.

131. Aiello D, Restuccia C, Stefani E, Vitale A, Cirvilleri G. Postharvest biocontrol ability of *Pseudomonas Synxantha* against *Monilinia Fructicola* and *Monilinia Fructigena* on Stone Fruit. Postharvest Biol. Technol. 2019;149:83–89.

132. Bu S, Munir S, He P, Li Y, Wu Y, Li X, Kong B, He P, He Y. *Bacillus Subtilis* L1-21 as a biocontrol agent for postharvest gray mold of tomato caused by *Botrytis Cinerea*. Biol. Control. 2021;157: 104568.

133. Cocetta G, Natalini A. Ethylene: Management and breeding for postharvest quality in vegetable crops. A review. Frontiers in Plant Science. 2022;13:96831