Chapter

An Overview of Ripening Processes

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Abstract

The chapter aims to address an overview of the new discoveries regarding the methods of ripening processes. The chapter presents the latest methods used in fruit and vegetable ripening processes, ripening processes in the food industry, enzymatic ripening processes, and artificial ripening processes. Nowadays everyone wants all kinds of food to be available in every season. Naturally, we find fruits and vegetables in their ripening season, but in order to provide the population with fruit out of season, we import them from different countries, which are not harvested at full maturity, and different adjuvant ripening methods are used. Processed foods are also subjected to ripening processes, the most used being cheese and meat products. These foods are some of the most valued foods nowadays, they are considered luxury products with superior nutritional and taste properties. To achieve these ripening processes, enzymatic processes or artificial ripening are also involved. The purpose of using these processes is to provide consumers with fresh out-of-season food or food with a high degree of sensory and nutritional properties, and at the same time with a superior degree of quality and safety, because the safety of the consumer comes first.

Keywords: ripening fruits, ripening food, enzymatic ripening processes, artificial ripening processes, ripening vegetables

1. Introduction

Fruit ripening is a complex developmental process that includes significant changes in texture, color, flavor, smell, nutrient metabolism, and other quality characteristics that ultimately make the fruit attractive, desirable, and edible to consumers [1, 2]. In fruit ripening, hormonal regulation plays a crucial role, and ethylene is the main hormone involved in the process of triggering and accelerating the ripening process of many fruits [3]. Also, temperature, light, and humidity can influence the fruit ripening process. Thus, higher temperatures can accelerate ripening, while lower temperatures delay the process [4]. Fruit ripening is based on crucial metabolic processes, such as changes in carbohydrate metabolism, hormone synthesis, stress response, or defense mechanisms. All these mechanisms are involved in the stimulation or inhibition of certain genes and proteins [5]. In addition to the previously mentioned, defense mechanisms against pathogens and responses to oxidative stress are also involved in fruit ripening. These processes help to protect the fruits from the action of pathogens and to maintain their quality during the ripening process [6]. Depending on the fruit type, they may have specific characteristics and ways of ripening. In the case of climacteric fruits, such as tomatoes and peaches, they undergo a rapid increase in respiration and ethylene production during ripening, while non-climacteric fruits, such as strawberries, have a gradual ripening process [5, 7].

The production of fruits involves a meticulous selection of practices, ranging from the conventional ones like pruning and thinning, which are essential for supporting healthy growth and optimal fruit maturation, to the application of nowadays irrigation and fertilization techniques that provide appropriate moisture levels and nutrient supply. Furthermore, the integration of pest and disease control methods using sustainable strategies like integrated pest management underscores the industry's priority for environmental protection, also ensuring the food safety of the consumers. For example, pruning is a widespread and essential technique used to enhance the quality of fruits and to maintain the health of plants. Pruning shapes not only the canopy but also enhances light penetration and air circulation within the plant, both of which are crucial for photosynthesis. Furthermore, shaping the plant and improving its phytosanitary health, productivity, and fruit quality makes this activity essential for several crops [8]. Plant thinning at early stages, especially before the cell division is completed, is important for optimizing the density of fruits and producing both good quality fruits and high yields. Since fruits require a substantial utilization of plant carbohydrates and mineral nutritional resources [9] in the first stage of fruit development, this method basically prevents resource competition among fruits. Of all the techniques used in fruit production, hand and chemical thinning are the most prevalent [10].

It is well known that crop growth is heavily dependent on the availability of nutrients and water. Research on precision fertilization and irrigation has long been an important area of study, and with the progress of science and technology, precision fertilization and irrigation have been considerably developed. In this regard, conventional irrigation systems can be substituted with innovative and smart irrigation strategies that can further enhance crop yield. In dry areas, drip irrigation is a suitable alternative due to its low-rate water supply and efficient water savings. On the other hand, in horticulture, sprinkler systems are extensively utilized as they do not necessitate big pipes and disperse water droplets across the area, like rainfall [11]. Fertilizers are necessary for increasing crop productivity, preserving soil fertility, and ensuring a consistent supply of essential nutrients for plant needs. According to Jariwala H. et al., the utilization of controlled-release fertilizers can mitigate nutrient loss, increase nutrient utilization efficiency, and improve soil health [12].

Alongside methods that provide the foundation for robust and optimal fruit development, as well as strategies for irrigation and fertilization, it is crucial to prioritize sustainable approaches to controlling pests and diseases. This is critically important for both environmental protection and ensuring food safety. Integrated pest management includes a wide range of strategies to mitigate the harmful effects caused by pests. Pesticide application is considered as the final resort when alternative methods such as biological, behavioral, or other management strategies have proven ineffective in maintaining pest populations below a specified threshold, leading to substantial crop damage. Integrated pest management of fruit trees is an example of the utilization of several strategies to reduce primary pests while preserving natural enemies that offer indirect or secondary pest control [13].

The emergence and development of genetic engineering, along with precision agriculture, have fundamentally shifted the limits of what may be achieved in horticulture. In addition to improving the productivity and efficacy of fruit cultivation, these technologies also provide novel approaches to address the limitations arising from a continually changing global climate and an increasing population. Digitization in this industry includes various technical innovations, including drone technology, robotics, Internet of Things-based automation, and smartphone applications. These technologies consistently monitor, evaluate, and control soil conditions, water supplies, and weather changes [14]. Preserving the quality of ripened fruits requires proper handling and storage after harvesting. This stage integrates a range of good practices and technologies designed to preserve the fruit's freshness, prevent spoilage, and modulate the fruit's ripening process postharvest. For efficient management, understanding of physiological changes during harvesting is a priority [15]. The fruits continue to breathe, ripen, and go through specific metabolic changes even after they have been harvested. Therefore, extending shelf life and assuring quality requires effective management of these changes. Ideal timing and methods for harvesting are key elements of postharvest handling practices, as they effectively mitigate losses and promote optimal fruit maturation. Additionally, fruits are sorted according to their quality, size, and maturity and cleaned to remove soil and detritus after harvesting [16, 17]. Particularly for specific fruits, rapidly cooling after their harvesting lowers respiration and delays the process of ripening, which is essential for these types of fruits. An extensively used method in this field involves storing the fruit in a controlled atmosphere, where the levels of oxygen, carbon dioxide, and humidity are adjusted. This method aims to prolong the fruit's shelf life and delay the ripening process. Furthermore, since ethylene serves as a catalyst for the ripening process, it is important to remove or regulate its presence in storage facilities for fruits that are susceptible to this hormone. In addition to low temperatures and proper handling, modified-atmosphere packaging is a preservation method that can further minimize the physiological and microbiological degradation of perishable fruits [18, 19]. The postharvest processing and packaging of ripe fruits prolong not only their shelf life but also improve their value by converting them into various forms while maintaining their nutritional and sensory attributes. Fruits are frequently preserved to prolong their shelf life. This method involves cleaning and, in certain situations, heat treatment of the fruits prior to their packing in hermetically sealed containers. The aim of heat treatment is to destroy the microorganisms, although this operation has the drawback of negatively impacting the texture and some heat-sensitive nutrients [18]. By drying/dehydrating fruits by the sun or mechanically, microbial growth and enzymatic reactions are inhibited. Although the objective of this method is to enhance flavor concentration, it comes with the loss of valuable nutrients, particularly vitamins [20]. Freezing produce, on the other hand, effectively maintains the nutritional value and flavor of the fruits. A potential drawback of this approach is the appearance of ice crystals under certain circumstances, which can result in cellular structure impairment and subsequent texture degradation during the thawing process [21]. In the context of packaging, modified atmosphere packaging implies the act of modifying the inside conditions to slow down the rate of ripening and spoilage of fruits [22]. Edible coatings represent another method used to apply a protective barrier to fruits, thereby regulating gas exchange and diminishing water loss. Antimicrobial agents may be specifically incorporated into edible coatings [23]. Increasingly prevalent is smart packaging, involving sensors and indicators that deliver data regarding the ripening and spoilage of fruits [24]. In relation to the impact of processing on the ripening process of fruits, modifications can appear in texture, flavor, nutritional value, or chemical agents. Thus, the flavor and texture of fruits can be influenced by the processing techniques, which determine whether the fruits become softer or harder. Although processing can result in the depletion of specific nutrients, it can also enhance the bioavailability of others, as illustrated by the increased availability of lycopene in tomatoes that have undergone processing [25]. The processing and packing of ripened fruits are crucial for converting them into varied edible forms, prolonging their shelf life, and ensuring their year-round availability. However, the optimization of these processes is difficult as it is necessary to preserve the sensory and nutritional proprieties of the fruit, which are crucial for the well-being and satisfaction of customers.

2. New discoveries in fruits and vegetables ripening processes

The postharvest area of vegetables includes an important part of agricultural production. Fresh produce suffers changes in various characteristics between harvest and consumption, resulting in a significant drop in total quality. The postharvest and storage changes of plants can result in food waste and major economic damage. Approximately 24% of all vegetables produced globally are lost in developed countries during the postharvest process and 50% in developing countries [26]. The degree of postharvest losses depends on environmentally friendly agents, techniques, commodities, as well as the season and location of production. However, investments in high-tech postharvest management practices are still a challenge for low-income countries, where politics with efforts for nonhazardous and safe food management are taking place gradually [27].

Vegetables ripening and senescence are degradative processes focused on metabolic disruption and cellular disintegration mediated by genetically regulated programs [28]. Moreover, the vegetables ripening involves oxidative as well as hydrolytic degradation [29]. Tomato fruit has evolved into a model system for understanding the fundamentals of ripening and quality, due to five features: (1) short life cycle plant, (2) collection of mutants affected in ripening, (3) genomic resources, (4) ripening program regulated by ethylene, and (5) was accompanied by increased H2O2 concentrations and the oxidation of lipids and proteins [28, 30].

The control of vegetables ripening is essential to maintain quality and to reduce the losses during the postharvest shelf-life. A crucial factor determining the postharvest qualities of fresh vegetables and the potential to keep these postharvest qualities, is the biology of the parent plant [26]. Respiration rate and cold sensitivity are two physiological characteristics with significant postharvest implications. Plants that have higher rates of respiration tend to have a more limited postharvest life. Respiration is crucial in the postharvest life of fresh produce because it shows the metabolic processes of the tissue [31]. Plants' inherent cold sensitivity is genetically encoded. Cold sensitivity of vegetables constraints our ability to use low-temperature storage [26].

Ethylene relation to postharvest quality of vegetables produced, were subject to several reviews [19, 22, 32–36]. Ethylene (C2H4) is a naturally present plant hormone which is linked to postharvest quality maintenance in storage. Postharvest-related processes in which ethylene activity is present are: texture changes, taste, development of physiological disorders, bioactive value, and fruit–pathogen interactions [26]. One of the main challenges in food packaging for modifying ethylene biosynthesis is the use of appropriate regulatory elements (silica gel, clays, zeolite, or activated carbon) for optimal postharvest benefit. The impregnation inside the packaging matrix with ethylene scavenging agents (contain catalysts to enhance in situ oxidation) has caused a reduction in the amount of ethylene scavenging agents. The results of this procedure have been proven to increase the product's shelf life while preserving physical quality and freshness [19].

The occurrence of abscission has a large postharvest implication, as well as during the storage of fresh products. Abscission in vegetables depends on the type of plants and it is necessary to either inhibit or induce [26].

Low-temperature postharvest storage is widely used because it slows down the cell metabolism rate and delays senescence and ripening processes. However, low temperatures may induce a disorder "chilling injury" of vegetables [37]. The cell membrane is regarded to be the area of initial events leading to chilling injuries that occur because of membrane structure and permeability (lipids undergo enzymatic peroxidation).

The use of emerging technology for future improvement of postharvest quality and reduction of losses could potentially have a profound effect on supplying the growing demand for food. Currently, it seems that there are some main approaches: efficiently distribute professional knowledge about postharvest to disadvantaged areas but with high potential plant production potential; The other strategy is to utilize emerging technology for the development of new crop varieties, thus becoming more adapted to postharvest storage [32–34].

3. New discoveries in ripening food processes

Ripened foods derived from animals can be categorized into two primary groups: meat products, which encompass dry-cured pieces and dry-cured fermented goods often prepared through mincing and stuffing techniques, and dairy products, which primarily consist of ripened cheeses. These conventional food items are widely recognized and held in high regard globally [38].

The ripening process of animal-derived products is influenced by environmental circumstances that promote the growth of various microbial communities, which significantly contribute to their transformation. The majority of these microorganisms, including some molds, yeasts, gram-positive catalase-positive cocci (GCC+), and lactic acid bacteria (LAB), exert a beneficial influence on the formation of the desired sensory attributes. State that the appearance of these beneficial bacteria is not exclusive to these goods, as they are usually exposed to the indigenous microbiota of the processing environment [38–40].

Nowadays, various efficacious treatments can be employed in the preservation of matured animal-derived food products. These treatments encompass physical techniques like heat treatments, ionizing radiation, and high hydrostatic pressures, as well as chemical preservatives such as organic acids, antifungal compounds, nitrates, and nitrites. Nevertheless, it should be noted that these techniques may not always be congruent with the natural ripening process and may potentially compromise the sensory attributes of the end product. This is mostly due to their non-selective nature, which can result in the detriment of the beneficial bacteria present in these matured food items [41]. Furthermore, there have been reports indicating that the improper or excessive utilization of various synthetic chemicals for the purpose of managing pathogenic bacteria may contribute to the development of resistance among these organisms. In addition, there is a current consumer preference for clean-label items that are devoid of chemical additives and preservatives [42]. Consequently, the implementation of preventative measures in the management of pathogenic or spoilage microorganisms in ripened foods of animal origin relies on the utilization of biocontrol agents (BCAs) derived from either microbial sources or plant-based sources, such as essential oils (EOs) and spices. It is imperative that these treatments have minimal environmental consequences and demonstrate a neutral or favorable effect on the sensory attributes of matured animal-derived food products. This is particularly crucial, as the organoleptic qualities of such products are clearly defined and greatly valued by customers [40].

3.1 Cheese ripening

Cheese is a category of dairy products that undergo fermentation, utilizing milk as the primary ingredient. It encompasses a diverse range of cheese varieties, characterized by their distinct flavors and physical compositions, which are found across the globe. Each geographical region contributes to the development of its own unique cheese products, influenced by cultural practices and available resources. Cheese can be considered a biocomplex ecosystem that is inhabited by a vast array of microorganisms, referred to as cheese flora. These microorganisms are introduced into the cheese through raw milk, as well as starter and adjunct cultures. The flora present in cheese has a significant role in determining the sensory characteristics of various cheese kinds. This is due to their intricate interaction with milk proteins, carbohydrates, and lipids, which mostly takes place during the crucial cheese manufacturing process known as "ripening" [43].

Therefore, the assessment of cheese quality can be conducted by the examination of ripening levels and the corresponding flavor components [43]. Technological incentives exist to optimize the rate of cheese ripening and save costs, potentially impacting the taste characteristics and overall quality of cheese. The variability in cheese qualities may also be attributed to the uncontrolled proliferation and interaction of cheese flora [44].

To make cheese, ripening is an important technological step that involves a series of biochemical and microbiological events regulated by the metabolic flow of main and adjunct cultures [45]. This process needs to be looked into in more detail so that cheese products can be made with better, more consistent quality at the lowest cost and with the most customer acceptance. Changes that happen during ripening decide the organoleptic quality of cheese. The level of aging is very important for shaping the smell and taste of cheese because it changes the chemicals that make it up [46, 47].

However, the process of ripening significantly influences the evolution of cheese flavor, as it encompasses a sequence of modifications in the composition of cheese, including the formation of fatty acids and the metabolism of lactose. The extent of maturation significantly influences the formation of sensory characteristics in cheese, as a result of many biochemical processes such as proteolysis, glycolysis, and lipolysis that take place during this period.

During the initial phase of ripening, the proteolytic enzyme chymosin acts with αs1-casein, leading to its destruction. The extent of this degradation plays a crucial role in determining the textural characteristics of the cheese. The utilization of robust promoters and protein engineering in biotechnological experiments is being explored to enhance the expression of chymosin. These efforts aim to optimize the production of cheese and maximize its flavor and texture attributes [48].

Numerous elements have been identified as having an influence on the quality of cheese. When these factors are carefully handled and monitored, they contribute to the development of desirable flavors. Conversely, if they are not properly addressed, they can lead to the presence of undesirable off-flavors. Numerous research have been undertaken to investigate the factors that can potentially modify the chemical and physical composition of cheese, owing to the delicate balance between flavor production and the occurrence of off-flavors. The examination of flavor, aroma, taste, and chemical constituents has been employed in the process of recognizing and distinguishing various varieties of cheese. Although it is possible that expert panelists may not always get to a definitive agreement, alternative methods are utilized to generate more tangible outcomes. In this particular scenario, the significance of expert judgments in identifying quality qualities of cheese is acknowledged, alongside the conduction of acceptability assessments by customers [46, 47].

The evaluation and surveillance of cheese maturation pose significant difficulties, yet are of utmost importance due to the complex nature of cheese as a multifactorial biological system. This system comprises many classes of substances (such as lipids, proteins, and carbohydrates) inside a complex physical matrix. The utilization of complementing sensory and analytical methodologies is highly sought after in order to adequately investigate the numerous biochemical alterations that occur during this process. In addition, several technologies including infrared (IR) technology, electronic nose (E-nose), and optical techniques such as computer vision and digital image analysis continue to hold significant potential for the analysis and quality control of cheese, as well as the estimation of its shelf life [47].

3.2 Meat and meat product ripening

The process of ripening meat/aging meat encompasses a series of modifications that occur within the muscle tissue of an animal following its slaughter. These processes lead to alterations in the meat's color, softness, and aroma. The metabolic processes that transpire during the age of meat primarily arise from endogenous enzymes, resulting in glycolysis, proteolysis, and lipolysis. During the process of glycolysis, glucose undergoes metabolic reactions resulting in the production of lactic acid. This metabolic pathway leads to a decrease in muscle pH and the depletion of ATP, which serves as the energy reserves. Energy deprivation results in the breakdown of myofibrillar proteins through the enzymatic activity of endopeptidases and exopeptidases. The proteolysis of meat is significantly influenced by endogenous proteases, namely calpains, cathepsins, and calpastatin. However, it is important to note that exogenous proteases, such as peptidylpeptidases, aminopeptidases, and carboxypeptidases, which are secreted by microorganisms participating in meat fermentation, also play a role in elevating the levels of peptides and amino acids [49]. Another chemical process that occurs with the aging of beef is known as lipolysis, which involves the breakdown of fats in both the muscle and adipose tissue [50].

4. New discoveries in enzymatic ripening processes

Fruits and vegetables are an important element of the human diet because they provide vitamins, minerals, antioxidants, carbohydrates, and fiber. The nutritional quality of fruits is heavily dependent on the ripening stage, and optimal ripeness is recommended for ingestion [51]. Moreover, fruit ripening, qualitative qualities, and numerous physiological changes are all heavily influenced by enzymatic activities. Fruits contain enzymes, which function as biological catalysts that accelerate biochemical operations and are essential to many important fruit functions.

Understanding the basic mechanisms governing fruit and vegetable growing, maturation and ripening is necessary to manipulate fruit and vegetable yield and quality [52, 53].

The following are some of the well-known enzymatic activities in fruits and modified components:

4.1 Cell wall degradation

A key component of the cell wall, pectin is broken down by pectinase enzymes, which also include pectin methylesterase and polygalacturonase. During ripening, this process makes the fruit softer. Moreover, fruit softening is facilitated by the enzymes cellulase and hemicellulose, which break down the cellulose and hemicellulose in the cell wall [54].

Fruit softening is primarily brought on by alterations in the content and structure of the cell walls, which affect the fruit's flavor, texture, scent, and appearance [55]. Xyloglucan molecules connected to cellulose's limited regions often make up cell walls [56]. It is well known that the ripening process of cell walls primarily affects pectin, hemicellulose, and cellulose. This is achieved through the coordinated and cooperative action of enzymes that modify the cell wall. These enzymes primarily consist of polygalacturonase, pectin methylesterase, cellulase, xylanase, β-galactosidase, α-arabinofuranosidase, and protease [57]. Extensive research has been conducted on the action patterns of cell wall modifying enzymes in various fruit varieties, including tomato, pears, zucchini fruit, apples, and so on, in order to investigate the internal relationship between textural properties and fruit softening. Protease enzymes break down proteins into amino acids, contributing also to the softening of fruit texture during ripening [58–61].

4.2 Starch to sugar conversion

The process of fruit ripening also involves the conversion of starch to sugars, which has a substantial impact on the taste and quality of certain fruits, by the fact that amylase enzymes convert starch into sugars, such as glucose and fructose. The development of sugars and organic acids mostly affects the flavor of fruits [62]. In addition, the same authors claim that plastidial β-amylase isoenzyme gene transcript accumulation and enzyme activity were both increased in the later stages of fruit development, suggesting that the enzyme was involved in both the reduction of starch and the rise in total soluble sugar levels in ripe tomatoes.

According to [63], amylases are the most common hydrolase enzymes that break down the glycosidic bonds found in starch molecules to create oligosaccharides and dextrins. Amylases come in two varieties: exo- and endo-amylases. Hydrolyzing the nonreducing end of starch is done by exo-amylases. According to [64], endo-amylases hydrolyze glycosidic bonds inside starch molecules. Amylase is an essential enzyme in biotechnology that is mostly derived from microbes and has a wide range of industrial uses [65].

The interaction between starch modification and other metabolic processes, such as cell wall component disintegration, resulting in the unique texture and flavor profile of ripened produce [66]. The transformation of starch during ripening impacts not only the sensory properties of fruits and vegetables but also their nutritional value. The conversion of starch to sugars adds to a rise in soluble solids, including sugars and organic acids, hence improving the nutritional content of ripe food. The change is significant not only for the fruit's appearance but also for its nutritional value, making it more delicious and accessible for ingestion [67].

4.3 Texture, flavor, and aroma development

Fatty acids are the primary antecedents of flavor in fruits and vegetables and are primarily influenced by the fruits' and vegetables' maturation level, cultivar, region, and processing techniques. The main metabolic process for producing aroma chemicals is β-oxidation, while lipoxygenase is crucial for producing taste compounds from fatty acids. For instance, the β-oxidation pathway links the formation of lactones to the development of the flavors of peaches, nectarine, pineapple (δ-octalactone), coconut (γ-octalactone), and peach (γ-decalactone and γ-dodecalactone, respectively). On the other hand, fruits and vegetables derive their flavor from the lipoxygenase pathway, which breaks down linoleic and linolenic acids into aldehydes, alcohols, acids, and esters [68, 69].

Fruit texture change during ripening is an important characteristic that makes fruit edible, palatable, and appealing for human consumption as well as vectors of fruit dispersal. Textural alterations related to ripening are complex in nature and frequently entail modifications to cell-wall components, including polysaccharides and proteins. Fruit firmness is also affected by elements such as cuticle characteristics, turgor, and free radicals [70].

As previously stated, the ripening of fruits and vegetables is characterized by a wide range of metabolic processes. The action of proteolytic enzymes, which aid in the breakdown of proteins into amino acids, is prominent among them. This enzymatic transformation affects not only the flavor profile of foods but also their nutritional composition. Proteases are enzymes that convert proteins into amino acids. During ripening, this process aids in the softening of tissues and the formation of tastes and smells [71].

The creation of volatile chemicals that give ripe fruits their distinct flavor and aroma depends heavily on enzymes. Enzymes, the molecular developers of biochemical transformations, are critical in the production of volatile chemicals that contribute to the flavor and perfume of ripe fruits. Volatile biosynthetic enzymes, which catalyze the conversion of non-volatile precursors into aroma-rich molecules, are an important group of enzymes engaged in this process.

The enzymatic process of volatile compound production is not merely a biochemical phenomenon; it profoundly influences the sensory experience of consumers. The interplay of various enzymes creates a harmonious blend of volatile chemicals, imparting a signature aroma and flavor to each ripe fruit. This sensory attraction is a result of the complex biochemical movement that occurs within the fruit during the ripening process [72].

Lipid (fat) hydrolysis is catalyzed by lipases. During the ripening phase, this mechanism may play a role in the development of volatile chemicals that give foods their distinctive scents as well as changes in texture and flavor [73].

4.4 Ethylene production and action

ACS (1-Aminocyclopropane-1-carboxylic acid synthase) and ACO (1-Aminocyclopropane-1-carboxylic acid oxidase): these enzymes are involved in the biosynthesis of ethylene, a plant hormone that plays a crucial role in fruit ripening and senescence [74]. The authors mention two specific phases in the ethylene production pathway. S-adenosyl-L-methionine (SAM) is initially metabolized by ACC-synthase (ACS) into 1-aminocyclopropane-1-carboxylic acid (ACC). In a subsequent process, ACC-oxidase (ACO) transforms ACC into ethylene.

Among these changes, the breakdown of chlorophyll is a major step, signifying the transition from the green, unripe stage to the vivid hues associated with ripeness. The main regulator of ripening processes, ethylene, also modulates chlorophyll degradation. Ethylene promotes the production and activation of genes linked with chlorophyll degradation enzymes. As fruits and vegetables mature from unripe to ripe, ethylene orchestrates a coordinated enzymatic reaction, enabling efficient chlorophyll breakdown and the appearance of vibrant hues [1].

Enzymes involved in the decomposition of cell structures, such as peroxidase and polyphenol oxidase, contribute to the breakdown of chlorophyll. As fruits ripen, the cell walls alter, allowing chloroplasts containing chlorophyll to be released. The liberated chloroplasts are then subjected to the enzyme system that breaks down chlorophyll [75]. Enzymatic chlorophyll decomposition improves not only the visual appeal of fruits and vegetables but also has culinary and nutritional ramifications. Color variations are frequently related to change in flavor and nutritional content, impacting customer preferences and perceptions of ripeness and freshness [76].

Fleshy fruits were previously classified as either climacteric or nonclimacteric. At the start of ripening, all climacteric fruits—which include both monocot and dicot species like apple, pear, banana, mango, tomato, and many more—produce an increase in ethylene production and transpiration. It is well established that ethylene and master transcription factors (TFs) with multiple gene targets regulate this "climacteric," which is a precursor to the expression of genes encoding enzymes that catalyze ripening changes. Ripeness requires alterations in gene expression in both climacteric and nonclimacteric fruits [77].

Regarding the tomato fruits among the Solanaceae, α-tomatine is a crucial secondary metabolite. Several genes and enzymes complete its metabolism and biosynthesis. The production and metabolism of α-tomatine are influenced by many transcriptional regulatory factors and hormonal pathways, such as JA, GA, ethylene, light signals, and their downstream transcriptional regulatory factors, in addition to the distinct stages of plant growth and development [78].

4.5 Antioxidant defense

The first-line antioxidant defense system, which is made up of the activities of glutathione peroxidase (GPX), catalase (CAT), and superoxide dismutase (SOD), is essential to the overall defense mechanisms and tactics in biological structures. These enzymes are part of the antioxidant defense system, helping to neutralize reactive oxygen species and preserve the quality of fruits [79].

According to [80, 81], in certain concentrations, fumigation with nitric oxide is helpful in preventing the browning of the surface of freshly cut apple slices. Both the amount of nitric oxide present and the storage temperature have an impact on efficacy. Furthermore, the results suggest that nitric oxide therapy may be used to extend the postharvest shelf life of apple slices across a range of cultivars correlated with lower temperatures.

Regarding the prevention of enzymatic browning another study suggests utilizing an immersion treatment with 0.25% gum and 0.25% sodium chloride to stop enzymatic browning and maintain the quality attributes of pear slices before the drying process is recommended based on the findings of qualitative, structural, and sensory evaluations [82].

Tannins, compounds known as antioxidants, are types of secondary metabolites in plants and enzymes play an important role in their biosynthesis. Condensed tannins, also known as proanthocyanidins, and hydrolyzable tannins are the two main groups of tannins. In addition to their well-known functions in plant defense and human health, both forms of tannins have been suggested as significant molecules for the flavor perception of various fruits and beverages, especially wine [83].

Related to *alkaloids*, modifying enzymes from several families work on a wide variety of alkaloids throughout the kingdom of plants, producing a wide range of physiologically significant alkaloid derivatives. These enzymes catalyze a variety of chemical modification reactions, principally methylation, glycosylation, oxidation, reduction, hydroxylation, and acylation. Certain alkaloids possess antibacterial and antifungal characteristics, as α-tomatin found in tomatoes, piperine found in black pepper, and protoberins and berberins found in a variety of plant species [67].

Fruit handling, storage, and processing after harvest depend on an understanding of and ability to regulate these enzymatic activities. Controlling enzymatic activity can help to prolong fruit shelf life, control ripening, and improve fruit quality for customers.

5. New discoveries in artificial ripening processes

Fruits go through a process called ripening that makes them more palatable. Fruits generally get softer, less green, and sweeter as they ripen. But even though the fruit's sweetness and acidity increase as it ripens, it still tastes sweeter. Fruits are an essential component of the human diet and are very healthy. However, because of their limited shelf life, these are extremely perishable [84]. The natural process of fruit ripening involves the fruit going through a number of chemical changes that eventually cause it to become soft, edible, sweet, and colorful [2, 52]. As science and technology have advanced, different artificial fruit ripening techniques have been noticed, primarily to satisfy customer demand and other commercial factors. When fruit traders sell their products to consumers before the fruit is in season, artificial fruit ripening becomes necessary. Fruit sellers experience a financial loss as a result, thus to reduce that loss, they occasionally choose to gather fruits before they are quite ripe and artificially mature them before selling them to customers. During the off-season, it is simpler to distinguish artificially ripened fruit. Nonetheless, it is more difficult to distinguish between naturally ripened fruits and artificially ripened fruits in terms of appearance during the ripening season. Fruit traders artificially mature green fruits even in the appropriate season in order to satisfy the increased demand and maximize profits from seasonal fruits. In order to address the problems with distribution and transportation, they also artificially ripen fruits [1, 2].

Additionally, regular consumption of artificially ripened fruits has been linked by scientists to heart-related disorders, weakness, dizziness, and skin ulcers [85, 86]. Furthermore, these ripening agents could include various contaminants that are hazardous to human health. A variety of laws and legislation have been made and put into effect in various countries to limit or outright forbid the production, sale, and distribution of artificial fruit ripening agents in response to growing health-related concerns [84, 87].

To determine the relevant health risk, it is crucial to do both qualitative and quantitative investigation of the ripening agents present in the fruit's peel and flesh. On the skin of the fruit, artificial ripening chemicals are typically present. Analyzing the chemical influence of artificially ripened fruits on their food value and quantifying the compounds present in fruit flesh are also crucial [84, 87].

The main ripening chemical that fruits naturally produce and that starts the ripening process is ethylene. Numerous ripening agents have a variety of applications that include the release of ethylene to accelerate the ripening process. Artificial ripening of fruits and vegetables is achieved through the use of chemicals such as ethanol, glycol, methanol, ethylene, ethephon, and calcium carbide [32, 88, 89].

To encourage the ripening of fruit, just 1 ppm of ethylene in the air is needed. Applying ethylene externally has the potential to induce or trigger the natural ripening process of various fruits and vegetables, including avocado, banana, mango, papaya, pineapple, and guava. As a result, these products can be provided before the schedule.

Throughout the world, calcium carbide is frequently used. Although calcium carbide, which is sold as a grayish-black powder, is mostly used in welding, it is also widely used in many developing nations to artificially ripen climacteric fruits. Calcium carbide-ripened fruits have a smooth texture and well-developed peel color, although they lose flavor. Calcium carbide, commonly referred to as masala, is widely used in papayas, bananas, and mangoes, and occasionally in apples and plums. Due to its low cost, dealers utilize it carelessly instead of adhering to other suggested methods of ripening, such as dipping fruits in ethephon solution or subjecting them to ethylene gas. When calcium carbide is applied to fruits, it reacts with moisture to release acetylene, which is similar to ethylene in how it ripens fruit. Traces of arsenic and phosphorus hydride, which are harmful to human health when in direct contact with them, are present in industrial-grade calcium carbide [16, 90].

Another substance that is used to artificially ripen fruits is ethephon. Since pineapple, banana, and tomato treated with 1000 ppm of ethephon required less time to mature (48, 32, and 50 hours, respectively) than other treated fruits as well as compared with the nontreated fruits, ethephon is frequently seen to be preferable than calcium carbide. Researchers from Bangladesh found that artificially ripened pineapples and bananas have lower nutritional values, such as protein content, vitamin C, and beta-carotene. However, the most important discovery was the presence of arsenic (As) and lead (Pb) in these artificially ripened fruits and vegetables. Although the concentrations of As and Pb were within the adult daily permitted intake limit, regular consumption of these fruits can result in major health risks for people, including skin irritation, cancer, liver illness, renal disease, and diarrhea.

Artificial ripening agents ideally should not contain metal or metallicoids and instead release ethylene or acetylene to initiate fruit ripening. However, a large amount of As, Pb, and phosphorus compounds-which are hazardous to human health and can contaminate artificially ripened fruits-may be present in nearly industrial-grade calcium carbide and ethephon. When using high-quality ripening agents, it's important to eliminate metal/metalloid contamination and use modest dosage rates [17, 22, 84].

The ripening process is accelerated by acetylene, which is released by calcium carbide and functions similarly to ethylene. It has been discovered that directly consuming acetylene is harmful since it lowers the brain's oxygen supply and may even result in chronic hypoxia [85]. Because of its alkaline nature, calcium carbide irritates the abdominal mucosal tissue. There have been cases recently of gastric distress following consumption of mangoes ripened by carbide. Although eating fruit that has ripened with carbide does not immediately cause an allergic reaction, applying these chemicals to the fruit may cause dizziness or headaches.

Both established and developing nations have passed and put into effect several statutes and rules limiting the use of artificial fruit ripening agents in order to address the growing health-related concerns. Formally recommended by the National Organic Standards Board (NOSB) to the Organic Program (NOP), ethylene is used in the United States to aid in the postharvest ripening of tropical fruit and the degreening of citrus. Soil Association Organic Standards, version 16.4, June 2011 states that ethylene can be used to ripen bananas and kiwis in the United Kingdom. Additionally, ethylene gas is included on the IFOAM Indicative List of Substances for Organic Production and Processing as being "Only for ripening fruits" by the International Federation of Organic Agriculture Movements (IFOAM).

Commercial ripening is a crucial aspect of the fruit industry since ripe fruits degrade easily and should not be carried or distributed. Thus, fruit dealers select underride fruits and apply specific techniques to prolong their shelf life. It is desirable, in this sense, to use chemical approaches that are both valid and acceptable. Anything that goes against that could be harmful to our health.

Artificial fruit ripening is a complicated problem that calls for the cooperation of government organizations, legislators, fruit suppliers, farmers, scientists, and customers to find a workable solution, particularly in developing nations. To address the problems, it is crucial to evaluate many aspects of artificial fruit ripening, look at accepted procedures, and conduct in-depth scientific research as opposed to generalizing the problem [17, 22, 84, 85, 87].

6. Conclusions

The aim of this chapter was to cover the latest methods used in fruit and vegetable ripening processes, food industry ripening processes, enzymatic ripening processes, and artificial ripening processes.

The most significant characteristics influenced by the ripening of fruits and vegetables are: texture, color, aroma, smell, nutrient metabolism, and other quality characteristics that, ultimately, make the fruit attractive, desirable, and edible for consumers. These processes are greatly influenced by temperature, water, fertilization processes, and pest control, but also new technologies such as genetic engineering, drone technology, robotics, automation based on the Internet of Things, and smartphone applications.

Postharvest processes help to reduce losses through, ethylene control, storage conditions, environmental agents, techniques, commodities, as well as the season and location of production.

The ripening processes of processed foods are dependent on microorganisms, including molds, yeasts, gram-positive catalase-positive cocci (GCC+), and lactic acid bacteria (LAB), which exert a beneficial influence on the formation of desired sensory attributes. Preservation processes include physical techniques such as heat treatments, ionizing radiation, and high hydrostatic pressures, as well as chemical preservatives such as organic acids, antifungal compounds, nitrates, and nitrites.

The best-known enzymatic activities involved in the ripening process are: cell wall degradation, starch conversion into sugar, texture, flavor, and aroma development, ethylene production and action, antioxidant defense, tannins, and alkaloids.

The most commonly used chemicals for the artificial ripening of fruits and vegetables are by using acetylene, ethanol, glycol, methanol, ethylene, ethephon, and calcium carbide.

These processes aim to provide food of superior quality, high textural, and sensory properties, at the highest level of security and safety.

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