Chapter

Perspective Chapter: Traditional, Innovative and Eco-Friendly Methods for Postharvest Storage of Fruits

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Abstract

Fruits are among the most important elements of human diet. It is also well known and scientifically confirmed that fruit-based diet helps to protect human health and prevent many human diseases, mainly because of the high contents of vitamins, minerals, and phytochemicals. Since the human population on the earth is increasing, the need for fruits is also increasing. However, at the same time, the main factors of fruit production, that is, soil, water, and climate, are being damaged by human activities. Therefore, the production of the fruits and vegetables is becoming difficult. Furthermore, nearly 30% of fruits do not reach the consumers because of the postharvest losses along the fruit value chain. Therefore, prevention of the postharvest losses is highly important for ensuring the sustainability of life through consumption of wholesome fruits. In this chapter, we aim to list and discuss the traditional, innovative, and eco-friendly methods for postharvest storage of fruits. We also aim to provide most current information about these methods and provide practical information for students, scientists, farmers, food packers & sellers, and entrepreneurs engaged in fruit storage.

Keywords: agrochemicals, edible film packaging, innovative packaging, modified atmosphere packaging, traditional storage

1. Introduction

Food insecurity is reported to be the world's most crucial problem in the near future. Shifts in human diet, non-diversification in production and consumption (selection of nearly 200 crops for horticultural production), monoculture, excessive and mis-use of pesticides and fertilizers, reduction in soil fertility, reduction in water quality and quantity and increase in human population are the most important causes of food insecurity [1–3]. For example, only four crops (sugar cane, maize, wheat and rice) accounts half of global primary crop production and consumption in 2019. However, fruits are a major part of human diet and of horticultural production. They are very important for healthy life [3]. The most commonly produced fruits globally include bananas, apples, grapes and citrus [4]. Agricultural activities have significantly changed over the last 10 decades. Most of these changes, such as use of high yielding varieties and agrochemicals, cause an increase in the crop yield and quality in the beginning. However, excessive and mis-use of these activities resulted into negative impacts on soil, water and biodiversity, and adversely affected agricultural sustainability [5]. Aside the problems of production and storage, the uneven distribution among population also drive food insecurity [6].

The total agricultural primary products was 9.2 billion tons in 2018 [4], which is 50% more than the total agricultural primary products recorded in year 2000. Fruits and vegetables accounted for 10% and 12% of the global primary products for year 2018, respectively. Although there is an increase in the amount of production, the hunger is on the rise, which is estimated to be 690 million people undernourished in 2019 [4]. It is noteworthy that as hunger is increasing, food losses (from postharvest o distribution, excluding retail level and homes) is also increasing. The Food Loss Index (FLI) of Food and Agriculture Organization (FAO), based on the models developed by official records, noted 13.8% and 13.3% food loss globally in year 2016 and 2020, respectively. Among the crop groups, fruits and vegetables accounted for about 22%, which is highly related to their perishable nature [4]. The addition of the losses at retail level and homes, the postharvest losses may reach up to 50%, which means about half of the quantity of fruits and vegetables produced were not consumed and lost due to several factors such as poor postharvest handling practices, high physiological and respiration activities, high moisture content, microbial infection etc. This loss is highly crop dependent and handling practices are very important for the prevention of these losses [7, 8].

The main causes of the postharvest losses (senescence and deterioration) are the respiration, transpiration and diseases and these are highly dependent on prevailing temperature, relative humidity, light, atmospheric composition and ethylene concentration of the surrounding environment [8, 9]. Since the beginning of agriculture, human beings have developed several practices for reducing postharvest losses of fruits and vegetables. Additionally, agrochemicals have important role in controlling postharvest pathogens. In today's world, where there is an increasing negative awareness on agrochemicals, the eco-friendly methods are having more attention by the consumers. The developments in technology also made it possible to better understand fruit physiology and develop some innovative techniques for fruit storage. However, there is not a clear distinction among the traditional, innovative and eco-friendly methods for storage of fruits and vegetables (**Figure 1**). This chapter therefore aimed to discuss and summarize up-to-date information about these traditional, innovative and eco-friendly methods for fruit storage for practical information for readers.

2. Traditional methods

Since the beginning of horticulture and production of horticultural crops, human beings are trying to find suitable ways for different products to improve their storability. Most of these traditional techniques are mainly simple and in line with ecocentric philosophies of the adopted societies. These techniques mostly aim to convert these perishable products to more stable products for improving storage life and to eliminate toxicity. Some of these traditional methods are listed below in separate headings and discussed briefly.

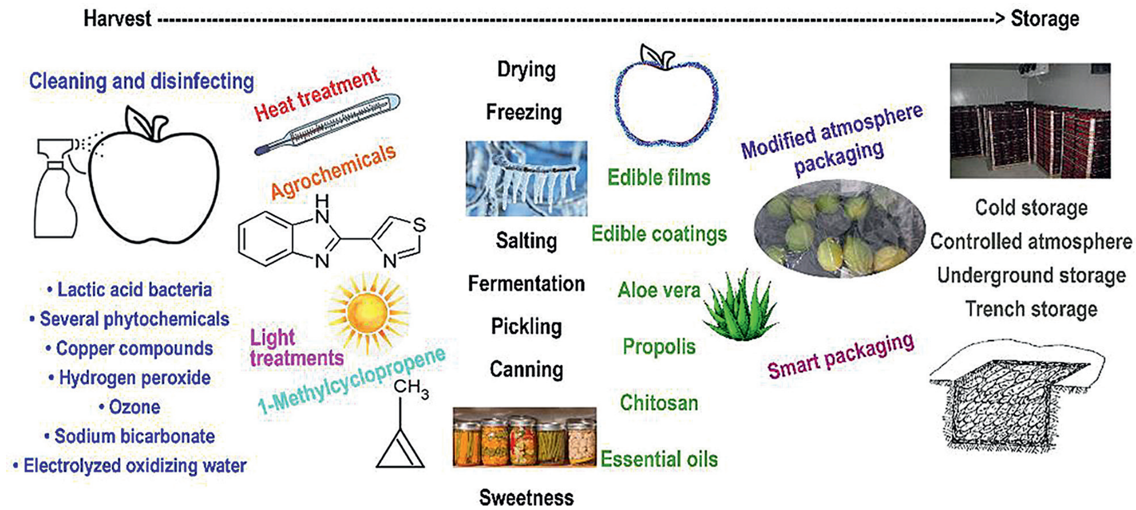

Figure 1.
List of different traditional, innovative and eco-friendly methods for postharvest storage.

2.1 Underground storage

Temperature is one of the most crucial environmental factor affecting the postharvest storability of products, by stimulating/reducing pathogen development and fruit ripening/senescence. Increase in temperature increases the pathogen growth rate and stimulates fruit ripening. Thus, reduction of the temperature is so crucial during postharvest storage. However, lowering temperature too much (below 7 C) for a longer duration may cause chilling injury on many subtropical fruits [8].

People have historically learned how to preserve/store foods (including fruits and vegetables) and developed some techniques for food preservation. This was necessary, because the climate was/is not suitable for growing same fruits and vegetables throughout the year on the same place. People have understood that harvested fruits and vegetables are alive and they can be stored longer if the respiration and transpiration can be stopped or slowed which reduce the spoilage. During the colonial era, the use of cold storage, ice boxes or ice houses were not common. The ice houses and temporary food storage emerged during the beginning of nineteenth century. However, ice was difficult and expensive to obtain at that time. Hence, the underground rooms were more common to keep fruits cool [10].

2.2 Cold storage

Storage is the act of storing fruits and vegetables in a safety place being ready for consumption but not being used at that time. It aims to prevent fruits and vegetables from deterioration for a specific time period [11]. Moreover, cold storage is so crucial and important way of fruit storage, which helps to reduce respiration and transpiration and so delays senescence and prevent deterioration [8]. Therefore, the idea of cold storage was reported to date back to ancient times. The first forms of cold rooms were formed from the ice blocks which lead to the developments in ice industry in 1800s. During 1830s, ice became among the most important marketing items. After the works of Benjamin Franklin and John Hadley in 1758 (about cooling an object with the help of evaporation on volatile liquids), in 1820 Michael Faraday liquefied ammonia by applying high and low pressures, and then in 1834 Jacob Perkins invented the first vapor-compression cooling system. Then the refrigeration equipment became popular in meat industry [12]. The mass production and use of the refrigerators were reported to begin around 1918 in USA [13].

2.3 Drying

Drying is among the most used traditional methods for food preservation. In this method, the fruits and vegetables were dried to reduce the water content (dehydration). Removal of water helps to inhibit the growth of food pathogens. According to Nummer [14], drying of fruits dates back to ancient times in Middle East and Asia around 12.000 BC. Mostly, sun drying, air drying or wind drying had been used for evaporation purposes for dehydration. Nowadays, with the help of technology, food dehydrators can be used for same purpose, which provides quick and consistent results than traditional methods [15]. Drying the fruits results with a reduced water and increased sugar concentration, which ensure longer storage duration and sweeter taste. However, drying the fruits significantly changes the structure of fruits and makes them different than the fresh ones. For example, grapes become raisin, while plums transform into prune. Besides to freeze-drying, some forms of light (ultraviolet light, X-rays or ionizing radiations) can also be used for sterilization and dehydration [16].

2.4 Freezing

Freezing fruits and vegetables for ensuring preservation dates back to prehistoric times. People used ice and snow for preserving their hunts and then used for fruits and vegetables. It slows the movement of molecules and enzyme activity in the fruits and pathogens, and delays spoilage by causing pathogens to enter into dormant stage. The frozen water in the fruits and vegetables become unavailable for the pathogens. However, it is known that most of the pathogens remain dormant during frozen and can be problem after thawing. Frozen fruits became popular after 1930s [14]. Depending on the physiology of the products, the fruits and vegetables can be kept safely for 3–12 months. The critical temperature is −18°C and products should be kept at or below this level. Packaging is also recommended in suitable (i.e. plastic) bags to prevent freezer burn. It is not recommended to freeze hot fruits and the refrozen the thawed products [17]. Freezing alone does not change the nutrient contents of the fruits. On the other hand, freezing slows the activity of several enzymes (which may increase deterioration, if active) but not halt their activity. Enzyme activity can be neutralized in frozen fruits by the acids but not in the vegetables which are low acidic. Therefore, partial cooking in boiling water is recommended for vegetables to slow/prevent deterioration. This process is known as blanching. Lack of oxygen or freezer burn, especially under longer storage may cause change in color. Slow freezing may be problematic for several fruits, especially for pomegranate arils. It creates large ice crystals in the fruits, which may damage the cells during thawing and dissolve emulsions. Therefore, fast freezing is recommended in such products. Thawing is as important as with freezing. The most safety way of thawing was reported to be under cool conditions, such as refrigerator or cold water. After thawing, the products must be cared carefully as they are perishable and consumed in a short time as possible [18].

2.5 Salting

Salting is a type of drying, mainly used before refrigeration. It is used to draw water out of the fruits and vegetables which provides similar advantages with drying and prevents food deterioration [19]. Sodium plays an important role in reducing pathogen growth and improves texture. A number of other sodium-containing compounds are also used for increasing the safety and shelf life of foods or creating physical properties [20]. There are two ways of salting. In the dry method, the fruits or vegetables are surrounded in salt and left till dry (water is drawn out into the salt). The second method is wet curing. In this method, salt is dissolved in water and is called as brine. Then the fruits or vegetables are placed in brine and left in cool dry place [21]. Salt reduces the activity of water in foods. This is because the sodium and chloride ions tents to associate with water molecules [22]. Salt also cause osmotic shock on microbial cells, loss of water from microbe cells and finally death of the pathogens [23].

2.6 Fermentation

It is the process of converting carbohydrates to alcohol or other organic acids by using microorganisms (mostly yeasts) or oxygen-free conditions. This process is used to produce alcoholic drinks including wine and beer. This is not well used in fresh fruit industry but most commonly used for bread, cheese, yoghurt, wine, beer, vinegar and olives [14]. Salt has an important role in food fermentation. Products like pickles and cheese obtain most of their characteristics from the lactic acid bacteria. Salt inhibits the growth of many spoilage bacteria while favoring the growth of salt-tolerant lactic acid bacteria [24].

2.7 Pickling

Pickling is another method of fruit or vegetable preservation which takes place in acids, especially vinegar. Vinegar is an end product of fermentation. Firstly, the carbohydrates are fermented into alcohol and next the alcohol is oxidized into acetic acid by some bacteria. Wines and beers can be used to produce vinegars [14]. Pickling is most commonly performed by placing the fruits or vegetables in water, salt, some herbs and vinegar or lemon. Pickling may require boiling the fruits or vegetables in the salt mixture. After the food is infused by the pickling solution, it must be placed in an airtight container [10].

2.8 Canning

Another important method for food preservation is the application of canning technology. In this method, the fruits or vegetables are placed in cans or similar materials and heated to destroy pathogens and inactivate enzymes. The cans are being cooled after heating and this creates a vacuum seal. Thus, the entrance of external pathogens is also being prevented [14]. This method was firstly developed in France, between 1795 and 1809, with the aid of French government to feed their citizens during the wars [10].

2.9 Sweetness (jam)

Boiling the fruits (whole, pulp or parts) in sugar mixture or sealing those in honey are among the other methods of food preservation. The use of honey is not new and has been used for thousands of years for fruit preservation [10]. For this purpose, fruits should be ripe and firm. After harvest, fruits should be washed, generally peeled, pulped (removing seeds), and sugar (generally in the proportion of 1:1 or 1:0.5 w/w) is added. Then the mixture is being boiled with continuous stirring. Sometimes citric acid can be added. The fruit-sugar mixture is cooked till the soluble solids concentration reached 65–70%. Hereafter, the jam is filled hot into sterilized bottles, capped and stored (even at ambient temperatures). High sugar content of jams makes the moisture unavailable for the growth of postharvest pathogens and other microorganisms.

2.10 Trench storage

Trench is an excavation in the ground, commonly deeper than is wide and narrow than its length. Trench storage is a traditional method for food preservation. It is suitable for preserving late-maturing varieties of different fruits [25]. In these systems, the trenches are filled with wet sand (3–7 cm), then the fruits are placed in (30–60 cm) and finally covered with maize straw or reed mat to control temperature. This method is beneficial for especially apples [25]. In this method, the trench (together with wet sand) provides moisture for the fruits and keep the fruits cold. It is the traditional way of modern cold storage rooms.

2.11 Heat treatment

Postharvest heat treatments (mostly as air or water) have a long history in fruit preservation. Although it is a traditional method, there are numerous recent studies about innovative applications of heat. Heat treatments have several advantages on fruit storage, (1) regulating products' response to cold, (2) direct control of pathogens, (3) improving products' tolerance against pathogens, (4) cleaning products and (5) maintaining products' quality during storage [26–28]. Empirical studies are required for determination of the best temperature and duration for different types of heat application for different varieties of crops. Mostly temperatures from 30 to 40°C for hot air treatments (HAT) for a duration of range from hours to days were reported to be effective in conditioning treatments for different product varieties [26]. Moreover, hot water treatments (HWD), are generally applied at temperatures from 45 to 55°C for a few minutes (3–5 min) for controlling postharvest pathogens [29]. Biochemical reactions in living organisms are highly affected by temperature. Change in the temperature around the plants and/or fruits signals the metabolism to make regulations in cell function and metabolism for preventing heat-related harms [30]. Heat stress cause metabolic imbalance in crops, affects cell membranes and proteins and alters several enzymatic reactions, including reactive oxygen species (ROS) [31, 32]. These changes in the metabolism improves products' tolerance against pests and helps to maintain products' quality. The heat can also directly damage the existing pathogens' cells and control the growth and development of diseases. Peroxidase (POD) and superoxide dismutase (SOD) enzymes can alleviate lipid peroxidation, thus the chilling injury [33, 34] and polyphenol oxidase (PPO) enzymes enhance fruits' resistance against pathogens [35, 36]. Heat treatments also prevent or delay the occurrence of chilling injury [26]. The heat-shock proteins (HSPs) increase after heat stress and protects products against chilling injury. However, these HSPs disappear quickly when the fruits are placed in ambient air conditions [37]. Not only in traditional application, but also for commercial applications today, the heat treatment is commonly used and known as safe, effective and physical [29].

2.12 Agrochemicals

The first use of fungicides dates back to seventeenth century. Firstly salty water treatment on grain and then copper sulphate (1760) took place for controlling grain bunt. Sulfur (1824) and lime sulfur (1833) were then used for pathogen controlling of food [38]. The developments in the fungicide history was continued with bordeaux mixture (1885) and mercury chloride (1891). This was continued with farmer prepared inorganic preparations till 1940s and the industrial & commercial fungicides were developed in 1940 with chloranil and dichlone active ingredients [38]. Since then, fungicides are widely used in controlling funguses during production and after harvest, mainly because of their easy to use and ability to bring about quick results in the food products. It is important to note that most of the pathogens which damage the products after harvest require a field application is also necessary to reduce/eliminate infections [39]. Fungicides applications can be done for controlling the infections on the fruits and/or vegetables, and also can be done in cold rooms or storage rooms to reduce/eliminate the sources of infections. Application of fungicides to the products can be done in different ways, mostly as dipping the products into the solutions, spraying onto the products, as volatiles/gas into the environment (fumigants), treating as wraps or embedded in coatings/films. Dipping and spraying are the two most common applications. The active ingredients of thiabendazole (from benzimidazoles group) and imazalil (from triazoles group) are among the most common fungicides which have been widely used against several important pathogens including *Penicillium* and *Colletotrichum*. Both fungicides are approved by European Union and are in use as of February 2022 [40]. Moreover, sulfur dioxide as fumigant is widely used against gray mold (*Botrytis cinerea*). For each and every application of the fungicides, it is a must for checking the suitability of the active ingredients and the chemical against the target pathogens and product. This is very important for the elimination of the chemical residues on the products. The doses of the chemicals must be used correctly according to the recommendations and fungicide rotation must be done in store houses to prevent fungicide resistance in the pathogens. Similar with the other agrochemicals, the fungicides have permitted limits on crops as the maximum residual limit (MRL) [41].

2.13 Cleaning and disinfecting

Cleaning and disinfecting are among the most important measures for better storage of fruits and vegetables. It is highly recommended to be carried before other handling practices for fruits and vegetables. This is a traditional measure but is being innovated continuously and several eco-friendly methods are also being used for cleaning. Hygiene is very important for the products health and quality both during production and storage. It is very critical to reduce (if possible eliminate) the sources of pathogens before storage. For this reason, a good knowledge is required about the type of the pathogen, its characteristics and life cycle. Therefore, cleaning of the pathogen sources prior to storage is strongly recommended for each product [39]. Chlorine was among the most widely used chemicals for product disinfection. The chlorine dioxide has ability to penetrate into the cell membrane of the target microorganisms and inhibit the metabolic functions [42]. However, it is now prohibited in many European countries because of its potential harms on human health and increased public concern about its use [43]. It was reported that there can be some by-products of chlorine, such as chloroform and chloramines, which are carcinogenic [44]. There are some biological or chemical alternatives of chlorine in which some of them are more effective and safer than chlorine. Some of them are listed below and explained briefly. Some of these techniques are not traditional, but are listed below:

- Lactic acid bacteria (LAB) are classified as Generally Recognized as Safe (GRAS) and produce some antimicrobial compounds, which help them to be used as disinfecting agent [45]. An example of these compounds is *Bacteriocin nisin*. This may form pores on the cell membrane and cause cell death [46]. In a study, Bari et al. [47] used nisin at 50 ppm for 1 min on broccoli and reported high efficiency against *Listeria monocytogenes*.

- Several phytochemicals. In their natural structures, a lot of plants are capable of producing phytochemicals (secondary metabolites) which have several roles in plants body, including control of pathogens. Phytochemicals are mainly divided into three groups as terpenes, phenolics and nitrogen/sulfur containing compounds [48]. The mod of action of these phytochemicals vary widely, but main impact takes place by increasing membrane permeability of the cells and leading leakage of cell compounds. Essential oils cover the most important part of these phytochemicals, such as carvacrol from thyme, citral from vitrus and etc. [48, 49].

- Copper compounds. Copper is essential for many microorganisms at very low concentrations. However, its higher concentrations may damage membrane integrity and stimulate the development of free radicals, which results with the cell death [50]. On the other hand, its high concentrations can be toxic and this limits its use in food industry. Because of this, the combination of copper with other compounds, i.e. lactic acid or hydrogen peroxide is suggested [51].

- Hydrogen peroxide (H_2O_2) is a reactive oxygen species which has antimicrobial characteristics due to its ability to form cytotoxic species [52]. The most important disadvantage of this compound is its fast decomposition, which is being not effective in cross-contamination [53]. Moreover, it may cause browning onto the vegetables, i.e. lettuce [54].

- Ozone (O_3) is a gas which can be dissolved in water. Ozone fumigation is among the important sanitizing agents having high potential against a wide range of pathogens [55]. Very small concentrations (1–5 ppm) are enough when dissolved in water for controlling most of the pathogens, but higher concentrations are necessary for gas applications [56]. It has several important disadvantages and higher attention is required during application. First of all, it can be toxic because of its respiratory tract and irritation ability [57], it decomposes rapidly and unstable [58] and corrosive for equipment [59]. However, it was approved as a disinfectant for water and decontaminant for products [60].

- Sodium bicarbonate. It is another important GRAS food additive. Palou et al. [61] suggested that it can be used for controlling molds at citrus fruits caused by

Penicillium italicum and *Penicillium digitatum*. In a recent study, Vilaplana [62] reported that the postharvest application of 298 mM (2.5%) sodium bicarbonate is effective in improving the storability and shelf life of pitaya fruits, by reducing weight loss, retaining color and firmness, slowing down the changes in solible solids concentration, titretable acidity and pH and most important controlling the black rot caused by *Alternaria alternata*. It was also suggested that the combination of sodium bicarbonate with hot water or *Bacillus amyloliquefaciens* improves the efficacty against pathogenic decay at mandarin fruits [63].

- Electrolyzed oxidizing water (EOW) is a new, innovative technique for food storage industry. It is an activated water. It is formed by electrolysis of sodium chloride by passing it from chamber containing an anode and a cathode [64]. EOW is low-cost, eco-friendly and safe method [65, 66]. Its ability to be produced on-site is important for the elimination of exposure risks [67]. It is deactivated when contacts and reacts with organic matter and tap water can easily dilute it from the environment [66].

3. Innovative methods

The above listed traditional methods have been still using in handling practices and still have important role in product preservation. As described above, some of these techniques have been developed and some innovations were applied to the techniques. Besides to that, there are some other newly developed innovative techniques in postharvest handling. Some of these methods are listed and described below.

3.1 Controlled atmosphere (CA) storage

Respiration rate of the products is strongly related with the product senescence [68]. The increase in the respiration increases the fruit senescence. Thus, the reduction of the respiration rate is known to improve products storability by delaying the fruit ripening and product senescence. This can be achieved by modifying the atmosphere surrounding the product. The modification must achieve a reduced oxygen level and increased carbon dioxide level for being able to reduce respiration rate. However, it is also strongly important not to eliminate oxygen level in the surrounding atmosphere, which can cause anaerobic respiration and alcohol production in the products, which could result into bad smell and decreased marketability [68].

Since the beginning of technological developments, people have tried to modify surrounding atmosphere of the products for increasing storability [69]. Controlled atmosphere (CA) storage is among these technical, which simply aims to monitor and adjust of the O_2 and CO_2 levels within gas-tight cold rooms [70]. The combination of CA rooms (so control of temperature and relative humidity) with ethylene control lowers the metabolic activity of products and improves storability. In these systems/rooms, the atmospheric composition inside the air-tight room must be controlled regularly and maintained during storage. In the CA storage rooms, there are two common ways of regulation of the room atmospheric composition, these are: static and dynamic. Products generates the atmosphere by respiration in cold rooms and it is being regulated by ventilation and scrubbing in the static method, whereas a supply of gas concentration is required in the dynamic system. There are different systems used for controlling/regulating oxygen and carbon dioxide concentrations. Simply the oxygen level inside the room is reduced to pre-defined (well-studied) desired level by nitrogen flushing, and then carbon dioxide is being injected with a gas generator [71]. CA storage is reported to be an advantageous method for the preservation of climacteric fruits (having increased respiration rate after harvest), i.e. apples, mangoes, bananas, papayas, etc. The effectiveness of CA storage is not very high on the non-climacteric fruits and some others with slow respiration rate [68].

3.2 Modified atmosphere packaging (MAP)

Respiration is the basic process in freshly harvested fruits and vegetables causing deterioration and it is mainly dependent on the atmospheric composition (mostly the level of O_2 and so CO_2) as well as on the temperature, ethylene and water vapor. Therefore, regulating the gas concentrations in the surrounding atmosphere of the fruits (or other food products) is highly important for reducing respiration and increasing storability of the products. Reduction of O_2 and elevation of CO_2 can delay deterioration of fresh horticultural crops [72]. However, it is highly dependent on the type of commodity, cultivar, maturity and temperature. At this time, some important methods are coming to forefront to regulate atmospheric composition around the fresh products. When the generation and stabilization of favorable atmosphere are obtained by packaging refrigerated produce in closed polymeric films of reduced dimensions (bags, boxes, pallets), the technique is called MAP. Modified atmosphere packaging (MAP) is a dynamic process of altering gaseous composition (mainly oxygen and carbon dioxide) inside a package. If the volume of gas with a different atmospheric concentration was introduced at the time of sealing the package (active MAP) or simply the bag was sealed with atmospheric air (passive MAP). The passive MAP is an old technique and is not used well, while the active MAP constitutes the most important share in the MAP use. The interaction between the respiration rate (RR) of the crop and the permeability of packaging material are the two important elements of modified atmosphere packaging, with no further control exerted over the initial gas composition [73]. The permeability coefficients of the materials for O_2, CO_2, N_2, and H_2O is very important. Also the type of the crop, growing conditions, physiological stage and storage time are important for the selection of appropriate packaging material. The most used materials for MAP are low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), high-density polyethylene (HDPE), polypropylene (PP), polyvinyl chloride (PVC), ethylene-vinyl alcohol (EVOH), ethylene vinyl acetate (EVA), and etc. Each of these polymeric materials offers different mechanical characteristics and fundamentally different permeability to O_2, CO_2 and water vapor. Such as: polyamide has very low permeability to O_2 and CO_2, polypropylene and EVA has moderate permeability and LDPE has high permeability [74]. It is also reported to be successful for the prolongation of storage duration of several fruits by slowing down respiration, reducing weight loss, reducing sensitivity to ethylene, reducing development of some physiological disorders (i.e. chilling injury), maintaining product quality and preventing decay [75, 76]. This techniques (MAP bags) is an important way for extending the storability of fresh products.

3.3 1-Methylcyclopropene (1-MCP)

1-Methylcyclopropene (1-MCP) is an ethylene inhibitor. Ethylene is a colorless gas (plant hormone) which plays an important role in the postharvest life of horticultural crops, especially the climacteric ones. It is also known as the ripening hormone. It is produced by the climacteric plants during ripening and it speed up the ripening and respiration of climacteric fruits (apples, banana, mangoes, apricot, tomato, etc.), while it damages the postharvest quality of non-climacteric fruits (grape, lemon, eggplant, cherry, watermelon, etc.) at the same time. It can also be produced by petrol combustion engines [77]. However, the higher concentration or continuous production/supply of ethylene damage the quality of the climacteric fruits too. Therefore, the control of ethylene is important to improve the storability of fresh horticultural crops. Thus, 1-MCP interact irreversibly with ethylene receptors and avoids its physiological stimulus [78]. The active ingredient of 1-MCP is currently (as of February 2022) approved by European Union and can be used in postharvest storage of fruits and vegetables [40]. Therefore, it is used in postharvest storage to down regulate the ripening of fruits. Its postharvest and preharvest application was reported to delay ripening of many fruits [79].

3.4 Light treatments

Light has fundamental roles in many biochemical reactions, including well-known photosynthesis. It also has important impacts on physical and chemical process and its range and dose are the most important factor. The higher energy of the light might be toxic, while the lower doses can be ineffective [80]. The electromagnetic spectrum of light ranges from long radio waves to gamma (γ) rays [81]. The different ranges of the spectrum has been tested for different purposes in horticulture, including production and postharvest storage [82]. With the help of the LED technology, which has ability to produce light from a narrow bandwidth of wavelengths, including UV LEDs, IR LEDs, and LED blue lights [82]. The non-ionizing irradiations (UV-C [100–280 nm], UV-B [280–315 nm], UV-A [315–400 nm] and blue light [400–500 cn]) of the light and ionizing irradiations (gamma (γ) and X-rays) may have different impact on the products' quality. This impact can be direct, by inhibiting the growth of postharvest pathogens, or indirect by inducing the resistance of products to the several pathogens and/or storage stress conditions [80, 83]. UV-C is the most tested light treatment in postharvest studies, especially against postharvest pathogens and was reported to be very effective [84, 85]. The duration and intensity of the light is so crucial and there are numerous different studies with different fruits and vegetables. Besides to UV light, blue light is also reported to have high efficacy in postharvest studies. It is mostly absorbed by plant tissues and have job in several metabolic reactions [86]. It has both role in growth promotion in plants and damages in fungal cells. It was reported to induce ferroptosis (nonapoptotic type of iron-dependent cell death) in fungal cell by activating ROS production in the cell wall and damaging the DNA [87]. Therefore, the light irradiation, especially the UV-C and blue light have significant advantages in postharvest studies and are powerful tools in postharvest handling with the help of technology [80].

3.5 Smart packaging

In these systems, the packaging is embedded intelligent (agri 4.0) sensor technology is embedded in the packaging material to monitor the status of the products during storage. The data generated about the quality is used to regulate storage conditions for improving product and customer safety [88]. Several different principles (sensors, indicators or radio frequency identification-RFID) are being used in these systems to monitor the temperature, atmospheric composition, microbial growth, integrity indicators and freshness indicators of the products [89]. Monitoring of these factors and quality parameters enables the active and quick response to the changing factors. For example, adjusting of the atmospheric composition is so crucial for prevention of the respiration rate and so the postharvest losses. Similarly, control and management of temperature and relative humidity are crucial both for fruit quality and for the control of pathogens. Thus, the smart and innovative technology makes this possible without the need for mental control, but with the artificial intelligence. Therefore, smart packaging may help to actively prevent fruit spoilage, improve/maintain the fruits' characteristics (i.e. taste, aroma, appearance, etc.), hence extending the storability of products. However, the integrity of artificial intelligence into these systems is new, where some doubts exist about its performance and it is more expensive than traditional methods [90]. Sooner or later, smart packaging techniques will be highly developed and introduced into the market; which is hoped to reduce postharvest losses.

4. Eco-friendly methods

Because of the negative impacts of agrochemicals on the environment and human health and the damages on the ecosystem caused by the petroleum-based packaging materials, there is a trend in postharvest studies to develop and introduce the use of eco-friendly alternatives in postharvest handling of fruits and vegetables. Some eco-friendly alternatives which are promising alternatives to agrochemicals and petroleum-based packaging materials have been listed and discussed. It is believed that these methods will be upgraded, modified appropriately in postharvest handling of fruits and vegetables globally in future.

4.1 Edible film packaging and edible coatings

Edible film packaging is a thin layer (with less than 0.3 mm thickness) [91] formed from the combination of biopolymers and various additives which is prepared before application and then adhered to the product surface and can be consumed as an integral part of the food product [92]. Edible coating is similar with the edible films, but formed as thin layer directly on the product surface [93]. Their application onto the products is differs from the edible films, and are applied in liquid form by dipping the products into the solutions. Both the edible films and edible coatings have high attraction by the consumers and environmentalist, because of their biodegradable characteristics as compared with the plastic packaging materials. These materials, similar with the plastic packaging materials, creates a modified atmosphere around the products and helps to regulate respiration and transpiration [94, 95]. Several other benefits of the biomaterials used in the edible film industry are prevention of microbial decay (both by inducing product resistance or direct control of pathogens), reducing weight loss, improving product appearance, maintaining the composition and concentration of phytochemicals and etc. [96]. Proteins, polysaccharides, lipids and the secondary metabolites of plants are being used for the production and use of edible films [95, 96].

Wheat gluten, corn zein and soy protein are important protein sources for edible films and coatings, where oils and waxes are the most used lipid-based materials. Plant- (cellulose, gums, starch, pectin, etc.) or animal- (chitosan and chitin) based polysaccharides are on the other hand are being highly used for production of edible films and coatings [95]. The mechanical characteristics (elasticity, elongation and tensile strength) are among the most important characteristics of edible films and coatings [97]. Starch, with its gelatinization characteristics has been used in bio-packaging universally. Another important bio-polymer is the alginate, which has ability to form hydrogels and encapsulation barrier [98]. Chitosan (discussed below separately) has recently been involved in food packaging industry for edible films and coatings. The ability of the materials to provide a barrier for the transfer of gaseous and water vapor, ability to improve food storability and processing techniques are the most important points to consider for the selection of the right material. The polysaccharide-based materials and chitosan have are nonpolar to the aroma compounds and produce a good barrier [99]. Alginate and cellulose, on the other hand, are hydrocolloid-based materials which have higher ability to retain moisture [100]. To sum up, edible films and coatings helps to reduce transpiration and respiration, retard ethylene biosynthesis, stimulate the biosynthesis of several enzymes (i.e. PPO), stimulate antifungal activity of products, enhance the activity of secondary metabolites and so protect the products' storability.

4.2 *Aloe vera* application

The perennial *A. vera* plant, belonging to the family of Xanthorrhoeaceae, has been widely used in medicine and traditional medicine for curing several human diseases. Besides to that, the gels of *A. vera* have an important role in food industry, mostly as a source of edible film or coating [101]. It has ability to reduce respiration and transpiration and delay food deterioration. Besides to this general advantage of edible films and coatings, the *A. vera* plant extracts or gels, have antimicrobial ability to control several microorganisms, including postharvest fungi. In a research by Nabigol and Asghari [102], it was found that the A. vera gel have high ability to stop the mycelium growth of *Penicillium digitatum* and *Aspergillus niger*. Similarly, Kator et al. [103], suggested that *A. vera* gel application prevents decay at tomato fruits. The number of examples can be extended to several other fruits, including pineapples, nectarine, grape, plum, strawberry and etc. [104–108].

4.3 Propolis application

Propolis (bee-glue) is a natural resinous produced by honeybees from plant exudates. Previous studies revealed that the propolis includes wide variety of phytochemical compounds including phenolic which have been linked with its beneficial characteristics [109]. The sources of plants and the season are highly affecting the chemical composition of the propolis. It has been using in traditional and scientific medicine for several decades and noted to have wound healing ability since 300 BC [109]. Moreover, it was reported to have high benefits in postharvest handling of fruits and vegetables. Studies suggested that the high concentrations of cinnamic acid, ferulic acid and caffeic acids provides anti-microbial ability for the propolis extract [110]. Similar with the light and edible materials, the positive impacts of propolis on the control of pathogens can be in two modes of action as direct control or improving resistance of the products [109]. Extracts of propolis had been suggested to reduce gray mold (*Botrytis cinera*) at pomegranate fruits [76], anthracnose at mango fruits [111] and *Penicillium digitatum* at orange fruits [112]. Besides to the control of postharvest pathogens, several studies suggested that the propolis extracts reduce weight loss and chilling injury, maintains soluble solids concentration, titratable acidity, ascorbic acid, total phenolic content, antioxidant activity, textural quality and overall acceptability of several fruits, including pomegranates, mango, papaya, banana and orange [76, 111, 113–115].

4.4 Chitosan application to stored fruits

Chitosan is a linear polysaccharide which is obtained from the exoskeleton of insects and the shells of crustaceans (i.e. crab, shrimp, lobster, etc.). It has a wide area of use in different sectors including agriculture, medicine, cosmetics, textile, food and biotechnology. The use of chitosan as a supplement to edible films and coating had been reported to have high potential for maintain product quality and reducing pathogen growth. It is a biocompatible polysaccharide with intrinsic antimicrobial characteristic [116]. The chitosan was approved in the European Union (Reg. EU 662014/563) for plant protection purposes. It was suggested that chitosan have three separate characteristics, which makes it an important alternative in postharvest. It has an ability to produce biofilms on the applied surface [117], it has high antimicrobial ability [118] and it has ability to stimulate the defense mechanism of the products [119, 120]. The exact mechanism behind the antimicrobial activity of chitosan has not been completely understood yet. The polycationic structure of the chitosan has been suggested as one of the reasons of the mechanism. The chitosan is positively charged which causes it react with cell membranes which are negatively charged [121]. This connection then damages the membrane permeability, inhibits DNA replication and finally cause cell death [122]. As mentioned above, chitosan stimulate the defense mechanism of products against pathogens. Several different defense related mechanisms have been reported to be stimulated by the application of chitosan, including pathogenesis-related (PR) proteins [123], several secondary metabolites (i.e. chitinase, lignin, phytoalexins, etc.) [124, 125] and reactive oxygen species (ROS) [126].

4.5 Essential oils application to stored fruits

Essential oils (EO) are complex and concentrated hydrophobic liquid containing volatile aromatic substances derived from plants. These oils are mostly composed of terpenes, phenols, esters, alcohols, nitrogen and sulfur compounds [127]. EOs are commonly extracted by steam distillation and can also be derived by cold pressing, solvent extraction and wax embedding. EOs can be used in different industries including cosmetics, perfumes, air fresheners and as food additive. Several studies have reported that the different EOs have higher efficacy in controlling postharvest diseases [128]. The application of the EOs can be as direct application (as vapor) or incorporation into films, coatings or washing materials [41]. Some recent research noted that the essential oils of myrtle (*Myrtus communis* L.) leaves [129], black cumin oil [130], and lemongrass oil [131] have high potential of promoting storability of loquat, apricot and strawberry fruits, respectively.

4.6 Plant-derived methods

Besides to the essential oils, several different plant extracts or plant-derived materials have been reported to have significant positive influence on the prevention of product quality and preventing the growth and development of several postharvest pathogens [132]. For example, ethanolic extracts of garlic have been reported to control *Penicillium* sp. in citrus fruits [133]. In a different study, the extracts of guava leaves and lemon have been suggested to improve the storability of banana fruits [134]. In another study, the aqueous extracts (10% and 20%) of neem, chinaberry, and marigold were noted to improve the storability of guava fruits [135]. On the other hand, cinnamon, pimento, and laurel extracts were tested against postharvest gray mold at apple fruits. The in vitro studies were found to be effective, while the in vivo studies with fruits were found to be ineffective [136]. The success of the plant extracts might be because of the essential oils (explained above) or other forms of secondary metabolites. It is clear from the above examples that the plant-derived biomaterials have significant positive impact on the storage quality of fruits and vegetables. Therefore, the development and use of plant-derived materials is a promising alternative for synthetic chemicals which can improve the storage quality of the products.

5. Conclusions and recommendations

Reduction of the postharvest losses is so crucial for ensuring food security on the earth and eco-friendly management of postharvest losses is so important for its sustainability and ensuring food safety. Thus, the use of eco-friendly postharvest technologies, i.e. edible films, is valuable for reducing postharvest losses throughout the value chain. Aside from the selection and use of traditional and innovative techniques in postharvest handling is so crucial, where a proper postharvest handling includes at least cleaning, selection, grading, packing and storage. Where applicable, curing and/or heat treatment before storage; pre-cooling; packaging with plastic or edible materials; and regulation of the surrounding atmospheric composition are essential and highly recommended for successful postharvest handling. They have vital role in keeping products' quality and storability during supply chain. It is highly important to focus on eco-friendly alternatives in all kind of application for every step and to develop eco-friendly & innovative technologies to overcome postharvest losses.

Conflict of interest

The authors declare no conflict of interest.

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References

[1] Godfray HC, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, et al. Food security: The challenge of feeding 9 billion people. Science. 2010;**327**(5967):812-818. DOI: 10.1126/science.1185383

[2] Kahramanoğlu İ, Wan C. Determination and improvement of the postharvest storability of little mallow (*Malva parviflora* L.): A novel crop for a sustainable diet. HortScience. 2020;**55**(8):1378-1386. DOI: 10.21273/HORTSCI15179-20

[3] Kahramanoğlu İ, Rengasamy KR, Usanmaz S, Alas T, Helvacı M, Okatan V, et al. Improving the safety and security of fruits and vegetables during COVID-19 pandemic with postharvest handling. Critical Reviews in Food Science and Nutrition. 2021;1-11. DOI: 10.1080/10408398.2021.1935703

[4] FAO. Sustainable Development Goals—Indicators. Available from: https://www.fao.org/sustainable-development-goals/indicators/1231/en/ [Accessed: August 01, 2022]

[5] Sannigrahi S, Pilla F, Zhang Q, Chakraborti S, Wang Y, Basu B, et al. Examining the effects of green revolution led agricultural expansion on net ecosystem service values in India using multiple valuation approaches. Journal of Environmental Management. 2021;**277**:111381. DOI: 10.1016/j.jenvman.2020.111381

[6] Wood SA, Smith MR, Fanzo J, Remans R, DeFries RS. Trade and the equitability of global food nutrient distribution. Nature Sustainability. 2018;**1**(1):34-37. DOI: 10.1038/s41893-017-0008-6

[7] Gunders D. Wasted: How America is losing up to 40 percent of its food from farm to fork to landfill. Natural Resources Defense Council. 2012;**26**:1-26

[8] Kahramanoğlu İ. Introductory chapter: Postharvest physiology and technology of horticultural crops. In: Kahramanoğlu İ, editor. Postharvest Handling. London, United Kingdom: IntechOpen; 2017:1-5. DOI: 10.5772/intechopen.69466

[9] Yahia EM, Ornelas-Paz JD, Elansari A. Postharvest technologies to maintain the quality of tropical and subtropical fruits. In: Postharvest Biology and Technology of Tropical and Subtropical Fruits. Cambridge, England: Woodhead Publishing; 2011. pp. 142-195. DOI: 10.1533/9780857093622.142

[10] Kittredge J. Food Preservation through the Ages. 2021. Available from: https://thenaturalfarmer.org/article/food-preservation-through-the-ages/ [Accessed: October 27, 2021]

[11] Kiaya V. Post-harvest losses and strategies to reduce them. In: Technical Paper on Postharvest Losses. Paris, France: Action Against Hunger (AAH); 2014. p. 25

[12] Anonymous [Internet]. 2021. Available from: http://www.coldstoragechiller.com/evolution/ [Accessed: October 27, 2021]

[13] Wilhite H. Refrigerating India. [Internet]. Science Museum Group Journal. 2018;**9**(09):1-13. Available from: http://journal.sciencemuseum.ac.uk/browse/issue-09/refrigerating-india/ [Accessed: October 27, 2021]

[14] Nummer BA. Historical Origins of Food Preservation: National Center for Home Food Preservation. University of Illinois Extension, Illinois, United Stated of America; 2002. Available from:

https://nchfp.uga.edu/publications/nchfp/factsheets/food_pres_hist.html [Accessed: October 27, 2021]

[15] Rahman MS, editor. Handbook of Food Preservation. Boca Raton, Florida: CRC Press; 2007. ISBN 9781420017373

[16] Onwude DI, Hashim N, Chen G. Recent advances of novel thermal combined hot air drying of agricultural crops. Trends in Food Science & Technology. 2016;**57**:132-145. DOI: 10.1016/j.tifs.2016.09.012

[17] Fellows PJ. Food Processing Technology: Principles and Practice. Woodhead, London: Elsevier; 2009. ISBN: 978-1-84569-21w6-2

[18] USDA. Freezing and Food Safety [Internet]. 2021. Available from: https://www.fsis.usda.gov/food-safety/safe-food-handling-and-preparation/food-safety-basics/freezing-and-food-safety [Accessed: October 27, 2021]

[19] He FJ, MacGregor GA. Dietary Salt, High Blood Pressure and Other Harmful Effects on Health. Reducing Salt in Foods. Cambridge, UK: Woodhead; 2007. pp. 18-54

[20] Henney JE, Taylor CL, Boon CS. Institute of Medicine (US) committee on strategies to reduce sodium intake. Preservation and physical property roles of sodium in foods. In: Strategies to Reduce Sodium Intake in the United States. US: National Academies Press; 2010

[21] Binici A, Kaya GK. Effect of brine and dry salting methods on the physicochemical and microbial quality of chub (*Squalius cephalus* Linnaeus, 1758). Food Science and Technology. 2017;**38**:66-70. DOI: 10.1590/1678-457X.15717

[22] Fennema OR. Food Chemistry. 3rd ed. New York: Marcel Dekker; 1996

[23] Davidson PM. In: Doyle MP, Beauchat LR, Montville TJ, editors. Chemical Preservatives and Natural Antimicrobial Compounds, Food Microbiology: Fundamentals and Frontiers. Washington, DC: ASM Press; 2001

[24] Doyle MP, Beuchat LR, Montville TJ, editors. Food Microbiology: Fundamentals and Frontiers. 2nd ed. Washington, DC: ASM Press; 2001

[25] Bhad SA, Khan F. Traditional wisdom in post harvest management of food commodities. Researchgate. 2017;**1**:1-8. DOI: 10.13140/RG.2.2.17350.88644

[26] Lurie S. Postharvest heat treatments. Postharvest Biology and Technology. 1998;**14**(3):257-269

[27] Paull RE, Chen NJ. Heat treatment and fruit ripening. Postharvest Biology and Technology. 2000;**21**(1):21-37

[28] Tang J, editor. Heat Treatments for Postharvest Pest Control: Theory and Practice. Wallingford, Oxfordshire, England: CABI; 2007

[29] Fallik E. Prestorage hot water treatments (immersion, rinsing and brushing). Postharvest Biology and Technology. 2004;**32**(2):125-134. DOI: 10.1016/j.postharvbio.2003.10.005

[30] Kotak S, Larkindale J, Lee U, von Koskull-Döring P, Vierling E, Scharf KD. Complexity of the heat stress response in plants. Current Opinion in Plant Biology. 2007;**10**(3):310-316. DOI: 10.1016/j.pbi.2007.04.011

[31] Ruelland E, Zachowski A. How plants sense temperature. Environmental

and Experimental Botany. 2010;**69**(3):225-232. DOI: 10.1016/j.envexpbot.2010.05.011

[32] Suzuki N, Koussevitzky SH, Mittler RO, Miller GA. ROS and redox signalling in the response of plants to abiotic stress. Plant, Cell & Environment. 2012;**35**(2):259-270. DOI: 10.1111/j.1365-3040.2011.02336.x

[33] Ballester AR, Lafuente MT, González-Candelas L. Spatial study of antioxidant enzymes, peroxidase and phenylalanine ammonia-lyase in the citrus fruit–*penicillium digitatum* interaction. Postharvest Biology and Technology. 2006;**39**:115-124. DOI: 10.1016/j.postharvbio.2005.10.002

[34] Huang Q, Ruopeng Y, Chuying C, Chunpeng W, Kahramanoğlu İ. Postharvest hot air treatment to maintain fruit quality of Nanfeng mandarins during storage. International Journal of Agriculture Forestry and Life Sciences. 2021;**5**(1):122-128

[35] Gao Y, Kan C, Wan C, Chen C, Chen M, Chen J. Quality and biochemical changes of navel orange drufits during storage as affected by cinnamaldehyde-chitosan coating. Scientia Horticulturae. 2018;**239**:80-86. DOI: 10.1016/j.scienta.2018.05.012

[36] Wan C, Kahramanoğlu İ, Chen J, Gan Z, Chen C. Effects of hot air treatments on postharvest storage of Newhall navel orange. Plants. 2020;**9**(2):170. DOI: 10.3390/plants9020170

[37] Sevillano L, Sola MM, Vargas AM. Induction of small heat-shock proteins in mesocarp of cherimoya fruit (*Annona cherimola* Mill.) produces chilling tolerance. Journal of Food Biochemistry. 2010;**34**(3):625-638. DOI: 10.1111/j.1745-4514.2009.00304.x

[38] Morton V, Staub T. A short history of fungicides. In: APSnet Features, 308 [Internet]. 2008. Available from: https://www.apsnet.org/edcenter/apsnetfeatures/Pages/Fungicides.aspx [Accessed: October 30, 2021]

[39] Coates L, Johnson G. Postharvest diseases of fruit and vegetables. In: Brown JF and Ogle HJ, editors. Plant Pathogens and Plant Diseases. Australia: Australasian Plant Pathology Society; 1997;**99**:533-548

[40] European Union Pesticide Database. Search Active Substances, Safeners and Synergists [Internet]. 2022. Available from: https://ec.europa.eu/food/plant/pesticides/eu-pesticides-database/active-substances/?event=search.as [Accessed February 24. 2022]

[41] González-Estrada R, Blancas-Benítez F, Velázquez-Estrada RM, Montaño-Leyva B, Ramos-Guerrero A, Aguirre-Güitrón L, et al. Alternative eco-friendly methods in the control of post-harvest decay of tropical and subtropical fruits. In: Modern Fruit Industry. London, UK: IntechOpen; 2019. DOI: 10.5772/intechopen.85682

[42] Joshi K, Mahendran R, Alagusundaram K, Norton T, Tiwari BK. Novel disinfectants for fresh produce. Trends in Food Science & Technology. 2013;**34**(1):54-61. DOI: 10.1016/j.tifs.2013.08.008

[43] Meireles A, Giaouris E, Simões M. Alternative disinfection methods to chlorine for use in the fresh-cut industry. Food Research International. 2016;**82**:71-85. DOI: 10.1016/j.foodres.2016.01.021

[44] Bull RJ, Reckhow DA, Li X, Humpage AR, Joll C, Hrudey SE. Potential carcinogenic hazards of non-regulated disinfection by-products: Haloquinones, halo-cyclopentene and

cyclohexene derivatives, N-halamines, halonitriles, and heterocyclic amines. Toxicology. 2021;**286**(1-3):1-19. DOI: 10.1016/j.tox.2011.05.004

[45] Rodgers S. Novel applications of live bacteria in food services: Probiotics and protective cultures. Trends in Food Science & Technology. 2008;**19**(4):188-197. DOI: 10.1016/j.tifs.2007.11.007

[46] Arevalos-Sánchez M, Regalado C, Martin SE, Domínguez-Domínguez J, García-Almendárez BE. Effect of neutral electrolyzed water and nisin on listeria monocytogenes biofilms, and on listeriolysin O activity. Food Control. 2012;**24**(1-2):116-122. DOI: 10.1016/j.foodcont.2011.09.012

[47] Bari ML, Ukuku DO, Kawasaki T, Inatsu Y, Isshiki K, Kawamoto S. Combined efficacy of nisin and pediocin with sodium lactate, citric acid, phytic acid, and potassium sorbate and EDTA in reducing the listeria monocytogenes population of inoculated fresh-cut produce. Journal of Food Protection. 2005;**68**(7):1381-1387. DOI: 10.4315/0362-028x-68.7.1381

[48] Kahramanoğlu İ, Usanmaz S. Roles of citrus secondary metabolites in tree and fruit defence against pests and pathogens. Natural Resources for Human Health. 2021;**1**(2):51-62. DOI: 10.53365/nrfhh/141637

[49] Roller S, Seedhar P. Carvacrol and cinnamic acid inhibit microbial growth in fresh-cut melon and kiwifruit at 4 and 8 C. Letters in Applied Microbiology. 2002;**35**(5):390-394. DOI: 10.1046/j.1472-765x.2002.01209.x

[50] Ibrahim SA, Yang H, Seo CW. Antimicrobial activity of lactic acid and copper on growth of salmonella and Escherichia coli O157: H7 in laboratory medium and carrot juice. Food Chemistry. 2008;**109**(1):137-143. DOI: 10.1016/j.foodchem.2007.12.035

[51] Cerioni L, de los Ángeles Lazarte M, Villegas JM, Rodríguez-Montelongo L, Volentini SI. Inhibition of *Penicillium expansum* by an oxidative treatment. Food Microbiology. 2013;**33**(2):298-301. DOI: 10.1016/j.fm.2012.09.011

[52] Rahman SM, Jin YG, Oh DH. Combined effects of alkaline electrolyzed water and citric acid with mild heat to control microorganisms on cabbage. Journal of Food Science. 2010;**75**(2):M111-M115. DOI: 10.1111/j.1750-3841.2009.01507.x

[53] Van Haute S, Tryland I, Veys A, Sampers I. Wash water disinfection of a full-scale leafy vegetables washing process with hydrogen peroxide and the use of a commercial metal ion mixture to improve disinfection efficiency. Food Control. 2015;**50**:173-183. DOI: 10.1016/j.foodcont.2014.08.028

[54] Rico D, Martin-Diana AB, Barat JM, Barry-Ryan C. Extending and measuring the quality of fresh-cut fruit and vegetables: A review. Trends in Food Science & Technology. 2007;**18**(7):373-386. DOI: 10.1016/j.tifs.2007.03.011

[55] Chauret CP. Sanitization. In: Batt CA, Tortorello ML, editors. Encyclopedia of Food Microbiology. 2nd ed. Oxford: Academic Press; 2014. pp. 360-364

[56] Horvitz S, Cantalejo MJ. Application of ozone for the postharvest treatment of fruits and vegetables. Critical Reviews in Food Science and Nutrition. 2014;**54**(3):312-339. DOI: 10.1080/10408398.2011.584353

[57] Artés F, Gómez P, Aguayo E, Escalona V, Artés-Hernández F. Sustainable sanitation techniques for keeping quality and safety of fresh-cut

plant commodities. Postharvest Biology and Technology. 2009;**51**(3):287-296. DOI: 10.1016/j.postharvbio.2008.10.003

[58] Chawla AS, Kasler DR, Sastry SK, Yousef AE. Icrobial decontamination of food using ozone. In: Demirci A, Ngadi MO, editors. Microbial Decontamination in the Food Industry. Cambridge, England: Woodhead Publishing; 2012. pp. 495-532

[59] Sapers GM. Disinfection of contaminated produce with conventional washing and sanitizing technology. In: The Produce Contamination Problem. Cambridge, Massachusetts, United States of America: Academic Press; 2014. pp. 389-431. DOI: 10.1016/B978-0-12-374186-8.00016-1

[60] Foong-Cunningham S, Verkaar ELC, Swanson K. Microbial decontamination of fresh produce. In: Demirci A, Ngadi MO, editors. Microbial Decontamination in the Food Industry. Cambridge, England: Woodhead Publishing; 2012. pp. 3-29

[61] Palou L, Smilanick JL, Usall J, Viñas I. Control of postharvest blue and green molds of oranges by hot water, sodium carbonate, and sodium bicarbonate. Plant Disease. 2001;**85**(4):371-376. DOI: 10.1094/PDIS.2001.85.4.371

[62] Vilaplana R, Alba P, Valencia-Chamorro S. Sodium bicarbonate salts for the control of postharvest black rot disease in yellow pitahaya (*Selenicereus megalanthus*). Crop Protection. 2018;**1**(114):90-96. DOI: 10.1016/j.cropro.2018.08.021

[63] Hong P, Hao W, Luo J, Chen S, Hu M, Zhong G. Combination of hot water, *Bacillus amyloliquefaciens* HF-01 and sodium bicarbonate treatments to control postharvest decay of mandarin fruit. Postharvest Biology and Technology. 2014;**1**(88):96-102. DOI: 10.1016/j.postharvbio.2013.10.004

[64] Demirci A, Bialka KL. Electrolyzed Oxidizing Water. Nonthermal Processing Technologies for Food. Hoboken, New Jersey, United States of America: Wiley-Blackwell; 2010. pp. 366-376

[65] Al-Haq MI, Sugiyama J, Isobe S. Applications of electrolyzed water in agriculture & food industries. Food Science and Technology Research. 2005;**11**(2):135-150

[66] Huang YR, Hung YC, Hsu SY, Huang YW, Hwang DF. Application of electrolyzed water in the food industry. Food Control. 2008;**19**(4):329-345. DOI: 10.1016/j.foodcont.2007.08.012

[67] RajeshwarK, IbanezJG. Environmental Electrochemistry: Fundamentals and Applications in Pollution Sensors and Abatement. Amsterdam, The Netherlands: Elsevier; 1997

[68] Bodbodak S, Moshfeghifar M. Advances in controlled atmosphere storage of fruits and vegetables. In: Eco-Friendly Technology for Postharvest Produce Quality. Cambridge, Massachusetts, United States of America: Academic Press; 2016. pp. 39-76. DOI: 10.1016/B978-0-12-804313-4.00002-5

[69] Fragoso AV, Mújica-Paz H. Controlled atmosphere storage: Effect on Fruit and Vegetables. In: Caballero B, Finglas PM, Toldrá F, editors. Encyclopedia of Food and Health. Amsterdam, The Netherlands : Elsevier; 2016. pp. 308-311. DOI: 10.1016/B978-0-12-384947-2.00197-5

[70] Pinhero RG, Coffin R, Yada RY. Post-harvest storage of potatoes. In: Advances in Potato Chemistry and Technology. Cambridge, Massachusetts: Academic Press; 2009. pp. 339-370. DOI: 10.1016/B978-0-12-374349-7.00012-X

[71] Escobedo-Avellaneda Z, Welti-Chanes J. Controlled Atmosphere Storage: Applications for Bulk Storage of Foodstuffs. In: Caballero B, Finglas PM, Toldrá F, editors. Encyclopedia of Food and Health. Amsterdam, The Netherlands: Elsevier; 2016. pp.301-307. DOI: 10.1016/B978-0-12-384947-2.00196-3

[72] Embleni A. Modified atmosphere packaging and other active packaging systems for food, beverages and other fast-moving consumer goods. In: Farmer N, editor. Trends in Packaging of Food, Beverages and Other Fast-Moving Consumer Goods (FMCG). Amsterdam, The Netherlands: Elsevier; 2013. pp. 22-34. DOI: 10.1533/9780857098979.22

[73] Caleb OJ, Opara UL, Witthuhn CR. Modified atmosphere packaging of pomegranate fruit and arils: A review. Food and Bioprocess Technology. 2012;**5**(1):15-30. DOI: 10.1007/s11947-011-0525-7

[74] Castellanos DA, Herrera AO. Modified atmosphere packaging: Design and optimization strategies for fresh produce. In: Kahramanoğlu İ, editor. Postharvest Handling. London, United Kingdom: IntechOpen; 2017. pp. 85-106. DOI: 10.5772/intechopen.68498

[75] Kader AA. Regulation of fruits physiology by controlled and modified atmosphere. Acta Horticulturae. 1995;**398**:59-70. DOI: 10.17660/ActaHortic.1995.398.6

[76] Kahramanoğlu İ, Aktaş M, Gündüz Ş. Effects of fludioxonil, propolis and black seed oil application on the postharvest quality of "Wonderful" pomegranate. PLoS One. 2018;**13**(5):e0198411. DOI: 10.1371/journal.pone.0198411

[77] Baswal AK, Ramezanian A. 1-methylcyclopropene potentials in maintaining the postharvest quality of fruits, vegetables, and ornamentals: A review. Journal of Food Processing and Preservation. 2021;**45**(1):e15129. DOI: 10.1111/jfpp.15129

[78] Brasil IM, Siddiqui MW. Postharvest quality of fruits and vegetables: An overview. In: Siddiqui MW, editor. Preharvest modulation of postharvest fruit and vegetable quality. Cambridge, Massachusetts: Academic Press; 2018:1-40. DOI: 10.1016/B978-0-12-809807-3.00001-9

[79] Khan AS, Ali S. Preharvest sprays affecting shelf life and storage potential of fruits. In: Preharvest Modulation of Postharvest Fruit and Vegetable Quality. Cambridge, Massachusetts: Academic Press; 2018. pp. 209-255. DOI: 10.1016/B978-0-12-809807-3.00009-3

[80] Kahramanoğlu İ, Nisar MF, Chen C, Usanmaz S, Chen J, Wan C. Light: An alternative method for physical control of postharvest rotting caused by fungi of citrus fruit. Journal of Food Quality. 2020;**8821346**:1-12. DOI: 10.1155/2020/8821346

[81] Nikita P, Kevin V, Mateo H. Electromagnetic Radiation. Chemistry LibreTexts [Internet]. 2015. Available from: https://chem.libretexts.org/Bookshelves/General_Chemistry/Map%3A_General_Chemistry_(Petrucci_et_al.)/08%3A_Electrons_in_Atoms/8.01%3A_Electromagnetic_Radiation#:~:text=Electromagnetic%20radiation%20consists%20of%20two,in%20their%20frequencies%20and%20wavelengths [Accessed: October 29, 2021]

[82] D'Souza C, Yuk HG, Khoo GH, Zhou W. Application of light-emitting diodes in food production, postharvest preservation, and microbiological food safety. Comprehensive Reviews in Food Science and Food Safety. 2015;**14**(6):719-740. DOI: 10.1111/1541-4337.12155

[83] Papoutsis K, Mathioudakis MM, Hasperué JH, Ziogas V. Non-chemical treatments for preventing the postharvest fungal rotting of citrus caused by *penicillium digitatum* (green mold) and *penicillium italicum* (blue mold). Trends in Food Science & Technology. 2019;**86**:479-491. DOI: 10.1016/j.tifs.2019.02.053

[84] Arcas MC, Botía JM, Ortuño AM, Del Río JA. UV irradiation alters the levels of flavonoids involved in the defence mechanism of *Citrus aurantium* fruits against *penicillium digitatum*. European Journal of Plant Pathology. 2000;**106**(7):617-622. DOI: 10.1023/A:1008704102446

[85] Porat R, Lers A, Dori S, Cohen L, Weiss B, Daus A, et al. Induction of chitinase and β-1, 3-endoglucanase proteins by UV irradiation and wounding in grapefruit peel tissue. Phytoparasitica. 1999;**27**(3):233-238. DOI: 10.1007/BF02981463

[86] Lafuente MT, Alférez F. Effect of LED blue light on *Penicillium digitatum* and *Penicillium italicum* strains. Photochemistry and Photobiology. 2015;**91**(6):1412-1421. DOI: 10.1111/php.12519

[87] Stockwell BR, Angeli JP, Bayir H, Bush AI, Conrad M, Dixon SJ, et al. Ferroptosis: A regulated cell death nexus linking metabolism, redox biology, and disease. Cell. 2017;**171**(2):273-285. DOI: 10.1016/j.cell.2017.09.021

[88] Schaefer D, Cheung WM. Smart packaging: Opportunities and challenges. Procedia CIRP. 2018;**72**:1022-1027. DOI: 10.1016/j.procir.2018.03.240

[89] Rodino S. Postharvest handling practices for fruit crops. In: Agrarian Economy and Rural Development - Realities and Perspectives for Romania. 8th Edition of the International Symposium, November 2017, Bucharest; 279-284

[90] Joshi U, Bisht TS, Mamgain LR. Smart packaging: Modern way for reducing post-harvest losses of horticultural produce. International Journal of Agricultural Sciences. 2021;**17**:297-305. DOI: 10.15740/HAS/IJAS/17-AAEBSSD/297-305

[91] Embuscado ME, Huber KC. Edible Films and Coatings for Food Applications. Vol. 9. New York, NY, USA: Springer; 2009

[92] Jeevahan J, Chandrasekaran M. Nanoedible films for food packaging: A review. Journal of Materials Science. 2019;**54**(19):12290-12318. DOI: 10.1007/s10853-019-03742-y

[93] Guimaraes A, Abrunhosa L, Pastrana LM, Cerqueira MA. Edible films and coatings as carriers of living microorganisms: A new strategy towards biopreservation and healthier foods. Comprehensive Reviews in Food Science and Food Safety. 2018;**17**(3):594-614. DOI: 10.1111/1541-4337.12345

[94] Falguera V, Quintero JP, Jiménez A, Muñoz JA, Ibarz A. Edible films and coatings: Structures, active functions and trends in their use. Trends in Food Science & Technology. 2011;**22**(6):292-303. DOI: 10.1016/j.tifs.2011.02.004

[95] Wan C, Kahramanoğlu İ, Okatan V. Application of plant natural products for the management of postharvest diseases in fruits. Folia Horticulturae. 2021;**33**(1):203-215. DOI: 10.2478/fhort-2021-0016

[96] Ncama K, Magwaza LS, Mditshwa A, Tesfay SZ. Plant-based edible coatings for managing postharvest quality of fresh horticultural produce: A review. Food Packaging and Shelf Life. 2018;**16**:157-167. DOI: 10.1016/j.fpsl.2018.03.011

[97] Zhang Y, Liu Z, Han J. Starch-based edible films. In: Environmentally Compatible Food Packaging. Cambridge, England: Woodhead Publishing; 2008. pp. 108-136

[98] Lee KY, Mooney DJ. Alginate: Properties and biomedical applications. Progress in Polymer Science. 2012;**37**(1):106-126. DOI: 10.1016/j.progpolymsci.2011.06.003

[99] Hambleton A, Fabra MJ, Debeaufort F, Dury-Brun C, Voilley A. Interface and aroma barrier properties of iota-carrageenan emulsion–based films used for encapsulation of active food compounds. Journal of Food Engineering. 2009;**93**(1):80-88. DOI: 10.1016/j.jfoodeng.2009.01.001

[100] Lacroix M, Vu KD. Edible coating and film materials: Proteins. In: Innovations in Food Packaging. Cambridge, Massachusetts: Academic Press; 2014. pp. 277-304

[101] Kahramanoğlu İ, Chen C, Chen J, Wan C. Chemical constituents, antimicrobial activity, and food preservative characteristics of *Aloe vera* gel. Agronomy. 2019;**9**(12):831. DOI: 10.3390/agronomy9120831

[102] Nabigol A, Asghari A. Antifungal activity of *Aloe vera* gel on quality of minimally processed pomegranate arils. International Journal of Agronomy and Plant Production. 2013;**4**(4):833-838

[103] Kator L, Hosea ZY, Ene OP. The efficacy of Aloe-vera coating on postharvest shelf life and quality tomato fruits during storage. Asian Research Journal of Agriculture. 2018;**8**(4):1-9

[104] Adetunji CO, Fawole OB, Arowora KA, Nwaubani SI, Ajayi ES, Oloke JK, et al. Effects of edible coatings from Aloe vera gel on quality and postharvest physiology of *Ananas comosus* (L.) fruit during ambient storage. Global Journal of Science Frontier Research Bio-Tech & Genetics. 2012;**12**(5):39-43

[105] Ahmed MJ, Singh Z, Khan AS. Postharvest Aloe vera gel-coating modulates fruit ripening and quality of 'Arctic Snow' nectarine kept in ambient and cold storage. International Journal of Food Science & Technology. 2009;**44**(5):1024-1033. DOI: 10.1111/j.1365-2621.2008.01873.x

[106] Castillo S, Navarro D, Zapata PJ, Guillén F, Valero D, Martínez-Romero D, et al. Using Aloe vera as a preharvest treatment to maintain postharvest organic table grape quality. Acta Horticulturae. 2012;**933**:621-625

[107] Martínez-Romero D, Zapata PJ, Guillén F, Paladines D, Castillo S, Valero D, et al. The addition of rosehip oil to aloe gels improves their properties as postharvest coatings for maintaining quality in plum. Food Chemistry. 2017;**217**:585-592. DOI: 10.1016/j.foodchem.2016.09.035

[108] Nasrin TA, Rahman MA, Hossain MA, Islam MN, Arfin MS. Postharvest quality response of strawberries with aloe vera coating during refrigerated storage. The Journal of Horticultural Science and Biotechnology. 2017;**92**(6):598-605. DOI: 10.1080/14620316.2017.1324326

[109] Kahramanoğlu İ, Okatan V, Wan C. Biochemical composition of propolis and its efficacy in maintaining postharvest storability of fresh fruits and vegetables. Journal of Food Quality. 2020;**8869624**: 1-9. DOI: 10.1155/2020/8869624

[110] Borges A, Ferreira C, Saavedra MJ, Simões M. Antibacterial activity and mode of action of ferulic and gallic acids against pathogenic bacteria. Microbial

Drug Resistance. 2013;**19**(4):256-265. DOI: 10.1089/mdr.2012.0244

[111] Mattiuz BH, Ducamp-Collin MN, Mattiuz CF, Vigneault C, Marques KM, Sagoua W, et al. Effect of propolis on postharvest control of anthracnose and quality parameters of 'Kent' mango. Scientia Horticulturae. 2015;**184**:160-168. DOI: 10.1016/j.scienta.2014.12.035

[112] Badawy IF. Effect of ethanol-extracted propolis on fruit quality and storability of balady oranges during cold storage. Assiut Journal of Agricultural Sciences. 2016;**47**(4):156-166

[113] da Cunha MC, Passos FR, Mendes FQ, Pigozzi MT, de Carvalho AM. Propolis extract from different botanical sources in postharvest conservation of papaya. Acta Scientiarum. Technology. 2018;**40**:e31074. DOI: 10.4025/actascitechnol.v40i1.31074

[114] Passos FA, Mendes FI, da Cunha MC, da Cunha MI, de Carvalho AE. Propolis extract coated in Pera orange fruits: An alternative to cold storage. African Journal of Agricultural Research. 2016;**11**(23):2043-2049

[115] Passos FR, Mendes FQ, Cunha MC, Pigozzi MT, Carvalho AM. Propolis extract in postharvest conservation banana 'Prata'. Revista Brasileira de Fruticultura. 2016;**38**(2):1-11. DOI: 10.1590/0100-29452016931

[116] Sharma S, Barman K, Siddiqui MW. Chitosan: Properties and roles in postharvest quality preservation of horticultural crops. In: Eco-friendly Technology for Postharvest Produce Quality. Cambridge, Massachusetts: Academic Press; 2016. pp. 269-296. DOI: 10.1016/B978-0-12-804313-4.00009-8

[117] Romanazzi G, Feliziani E, Sivakumar D. Chitosan, a biopolymer with triple action on postharvest decay of fruit and vegetables: Eliciting, antimicrobial and film-forming properties. Frontiers in Microbiology. 2018;**9**:2745. DOI: 10.3389/fmicb.2018.02745

[118] Duan C, Meng X, Meng J, Khan MI, Dai L, Khan A, et al. Chitosan as a preservative for fruits and vegetables: A review on chemistry and antimicrobial properties. Journal of Bioresources and Bioproducts. 2019;**4**(1):11-21. DOI: 10.21967/jbb.v4i1.189

[119] Landi L, De Miccolis Angelini RM, Pollastro S, Feliziani E, Faretra F, Romanazzi G. Global transcriptome analysis and identification of differentially expressed genes in strawberry after preharvest application of benzothiadiazole and chitosan. Frontiers in Plant Science. 2017;**8**:235. DOI: 10.3389/fpls.2017.00235

[120] Xoca-Orozco LÁ, Aguilera-Aguirre S, Vega-Arreguín J, Acevedo-Hernández G, Tovar-Pérez E, Stoll A, et al. Activation of the phenylpropanoid biosynthesis pathway reveals a novel action mechanism of the elicitor effect of chitosan on avocado fruit epicarp. Food Research International. 2019;**121**:586-592. DOI: 10.1016/j.foodres.2018.12.023

[121] Kong M, Chen XG, Xing K, Park HJ. Antimicrobial properties of chitosan and mode of action: A state of the art review. International Journal of Food Microbiology. 2010;**144**(1):51-63. DOI: 10.1016/j.ijfoodmicro.2010.09.012

[122] Divya K, Vijayan S, George TK, Jisha MS. Antimicrobial properties of chitosan nanoparticles: Mode of action and factors affecting activity. Fibers and Polymers. 2017;**18**(2):221-230. DOI: 10.1007/s12221-017-6690-1

[123] Beatrice C, Linthorst JH, Cinzia F, Luca R. Enhancement of PR1 and PR5 gene expressions by chitosan treatment in kiwifruit plants inoculated with

Pseudomonas syringae pv. actinidiae. European Journal of Plant Pathology. 2017;**148**(1):163-179. DOI: 10.1007/s10658-016-1080-x

[124] Landi L, Feliziani E, Romanazzi G. Expression of defense genes in strawberry fruits treated with different resistance inducers. Journal of Agricultural and Food Chemistry. 2014;**62**(14):3047-3056. DOI: 10.1021/jf404423x

[125] Malerba M, Cerana R. Chitosan effects on plant systems. International Journal of Molecular Sciences. 2016;**17**(7):996. DOI: 10.3390/ijms17070996

[126] Singh RK, Soares B, Goufo P, Castro I, Cosme F, Pinto-Sintra AL, et al. Chitosan upregulates the genes of the ROS pathway and enhances the antioxidant potential of grape (*Vitis vinifera* L. 'Touriga Franca' and 'Tinto Cão') tissues. Antioxidants. 2019;**8**(11):525. DOI: 10.3390/antiox8110525

[127] Johannessen GS. Post-harvest strategies to reduce enteric bacteria contamination of vegetable, nut and fruit products. In: Handbook of Organic Food Safety and Quality. Cambridge, England: Woodhead Publishing; 2007. pp. 433-453. DOI: 10.1533/9781845693411.4.433

[128] Boubaker H, Karim H, El Hamdaoui A, Msanda F, Leach D, Bombarda I, et al. Chemical characterization and antifungal activities of four Thymus species essential oils against postharvest fungal pathogens of citrus. Industrial Crops and Products. 2016;**86**:95-101. DOI: 10.1016/j.indcrop.2016.03.036

[129] Bahadırlı NP, Kahramanoğlu İ, Wan C. Exposure to volatile essential oils of Myrtle (Myrtus communis L.) leaves for improving the postharvest storability of fresh loquat fruits. Journal of Food Quality. 2020;**8857669**:1-10. DOI: 10.1155/2020/8857669

[130] Kahramanoğlu İ. Use of black cumin oil and liquorice syrup to maintain the postharvest quality of fully ripe apricot fruits var. 'Thyrinte'. European Journal of Horticultural Science. 2021;**86**(3):260-269. DOI: 10.17660/eJHS.2021/86.3.5

[131] Kahramanoğlu İ. Effects of lemongrass oil application and modified atmosphere packaging on the postharvest life and quality of strawberry fruits. Scientia Horticulturae. 2019;**256**:108527. DOI: 10.1016/j.scienta.2019.05.054

[132] Chen J, Shen Y, Chen C, Wan C. Inhibition of key citrus postharvest fungal strains by plant extracts in vitro and in vivo: A review. Plants. 2019;**8**(2):26. DOI: 10.3390/plants8020026

[133] Gong M, Guan Q, Xu S. Inhibitory effects of crude extracts from several plants on postharvest pathogens of citrus. In: AIP Conference Proceedings. Vol. 1956(1). Melville, NY, United States of America: AIP Publishing LLC; 2018. p. 020043

[134] Tabassum P, Khan SA, Siddiqua M, Sultana S. Effect of guava leaf and lemon extracts on postharvest quality and shelf life of banana cv. Sabri (*Musa sapientum* L.). Journal of the Bangladesh Agricultural University. 2018;**16**(3):337-342. DOI: 10.3329/jbau.v16i3.39489

[135] Malik AA, Bhat A, Ahmed N, Kaul R. Effect of postharvest application of plant extracts on physical parameters and shelf life of guava. Asian Agri-History. 2015;**19**(3):185-193

[136] Šernaitė L, Rasiukevičiūtė N, Valiuškaitė A. Application of plant extracts to control postharvest gray mold and susceptibility of apple fruits to *B. cinerea* from different plant hosts. Food. 2020;**9**(10):1430. DOI: 10.3390/foods9101430