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EMERGING TRENDS AND ADVANCEMENTS IN THE BIOPRESERVATION OF FRUITS

A review

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ABSTRACT

Fruits are natural, healthy, economically feasible, ready to eat, and provide essential nutrients such as vitamins and minerals, making them a fascinating food. Deterioration of fruits during transportation can cause food security concerns and financial losses. Globally, about 45% of horticultural crops are spoiled and wasted for numerous reasons, such as environmental contamination during growth, harvesting under unsuitable conditions, and improper storage, handling, and display. There are three groups of factors affecting the spoilage of food: physical, chemical, and microbial, which damage the size, color, taste, and texture of fruits. Conventional methods of preserving food products comprise chemical preservation, freezing, drying, and pasteurization, which can result in the loss of nutrients and the addition of unwanted chemicals produced during processing. Therefore, "green" technology is required to preserve fresh produce, which protects and enhances nutritional value in equal measure. This review will present emerging trends and advancements in the biopreservation of fruits, such as lactic acid bacteria, essential oils, herbal extracts, nanoparticles, microcapsules, edible films and coatings, bacteriocins, and bacteriophages. These biopreservative techniques should be easy, inexpensive, eco-friendly, and generally recognized as safe (GRAS) by the World Health Organization (WHO).

Key words: fruits spoilage, food security, fruit borne illnesses, fresh produce, green and natural substitutes

INTRODUCTION

Fruits are natural, healthy, economically feasible, ready to eat, and provide valuable nutrients to their consumers (Alikhani 2014; Mailafia et al. 2017). Fruits are an excellent source of bioactive compounds (Munekata et al. 2023), proteins (Allaqaband et al. 2022), vitamins, minerals, and dietary fibers, which play a significant role in human health and well-being (Karasawa & Mohan 2018; Munekata et al. 2023). Dried fruits can be used as an alternative to fresh fruits due to their extended useful life (Waheed & Siddique 2009; Rehman et al. 2018). Globally, fruits are available in many tastes and textures (Gao et al. 2022). Their size, color, smell, taste, shape, and texture attract people and their appeal spreads (Veerappan et al. 2021).

Recently, the loss and wastage of food products in the food supply chain to consumers have drawn public consideration (Read et al. 2020; Lu et al. 2022). It is not only a hazard to food safety (Lu et al. 2022), but it causes waste for farmers, and it is a nonproductive loss of water, energy, and fertilizers (Kummu et al. 2012; Vanham et al. 2015). Microorganisms are the most important factors affecting food spoilage and financial losses in the preharvesting and harvesting phases (Mailafia et al. 2017; Saleh & Al-Thani 2019; Umer et al. 2019). A study reported that annually about 45% of fruits and vegetables worldwide are spoiled and wasted due to several reasons, such as environmental contamination during growth, harvesting under the wrong conditions, and improper storage, handling, and trading (Snyder & Worobo 2018; Saleh & Al-Thani 2019).

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The main objective in preserving food is to sustain freshness, unique texture, and color. Conventional methods of preserving food products comprise chemical preservation, freezing, drying, and pasteurization, which can result in the loss of nutrients and the addition of unwanted chemicals by enzyme activity. Consequently, to preserve fresh produce, "green" technologies are required to equally protect and enhance the nutritional value (Davachi et al. 2021). The use of beneficial microbes and their metabolic products to increase the food's life and prevent contamination is known as "biopreservation" (Luz et al. 2020). This review will present emerging trends and advancements in the biopreservation of fruits, such as lactic acid bacteria, essential oils, herbal extracts, nanoparticles, microcapsules, edible films and coatings, bacteriocins, and bacteriophages.

FOOD SPOILAGE

Any change in food that is intolerable for the consumers, which can be noticed by the organoleptic properties of food (Amit et al. 2017), is referred to as "food spoilage" (Lianou et al. 2016). Physical, chemical, and microbial factors affect food spoilage (Amit et al. 2017; Ma et al. 2022).

Physical spoilage

Physical damages include mechanical damage, shrinkage, color change, and others that occur primarily in harvesting and processing. It is an effect of drying, crystallization, glass transition temperature (Amit et al. 2017) and colonization with microorganisms, water activity, and pH (Sandulachi & Tatarov 2012; Racchi et al. 2020).

Chemical spoilage

Chemical spoilage occurs due to chemical reactions during storage (Kahramanoğlu 2019) that comprise putrefaction, oxidation, proteolysis, pectin hydrolysis, hydrolytic rancidity, and the Maillard reaction (Amit et al. 2017). It is identified that chemical spoilage is directly proportional to physical impairment. Throughout storage, the color and flavor of the fruits are changed due to chemical reactions such as respiration, in which carbohydrates are broken down, affecting their quality (Kahramanoğlu 2019).

Microbiological spoilage

Microbiological spoilage is caused by bacteria, yeast, mold, etc. (Amit et al. 2017). Fruits contain high concentrations of many vitamins, minerals, amino acids, and sugars, providing an excellent environment for the development of a wide range of microbes, mainly bacteria. Initially, bacteria soften pectins, then convert them into a slimy mass, and finally, convert them through the metabolism of sugars and starches into lactic acid and alcohol, producing an unpleasant odor and taste (Hasan & Zulkahar 2018). Many microorganisms can colonize and create lesions in healthy plant tissue (Barth et al. 2009; Hasan & Zulkahar 2018). From harvesting to consumption of the fruits, the microbes may infect the fruit at any stage (Hasan & Zulkahar 2018; Kuyu & Tola 2018), converting many compounds, also making it toxic to the consumers (Hasan & Zulkahar 2018; Mohammed & Kuhiyep 2020). *Lactobacillus*, *Clostridium*, *Enterobacter*, *Pseudomonas*, *Flavobacterium*, *Bacillus*, *Erwinia*, *Chromobacterium*, and *Xanthomonas* are often stated as the causative agents for the spoilage of fruits (Hasan & Zulkahar 2018). Fungi use the extracellular lytic enzymes for the spoilage of fruits by degrading the walls of fruit cells and using their intracellular components as a nutrient for their development (Table 1) (Al-Hindi et al. 2011). To prevent the multiplication of microorganisms, controlling the temperature, which is the most significant aspect of food spoilage, is necessary (Nychas & Panagou 2011; Sandulachi & Tatarov 2012; Zhao et al. 2020). The availability of free water not only favors the growth of microorganisms (bacteria, yeast, and molds) but also promotes the production of toxins or biochemicals, such as in Maillard reactions, which can deteriorate the color, texture, flavor, shelf life, and dietary value of food products. The growth of microorganisms can be predicted by the water activity of food (Sandulachi & Tatarov 2012). At 25 °C the requirement for negligible water activity for the development of most foodborne microbes is given as 0.88–0.91 for bacteria, 0.87–0.94 for yeast, and 0.70–0.80 for molds (Hamad 2012; Zhao et al. 2020). It is essential to control the pH level and water activity during food storage because their optimal combination enables storage without refrigeration at ambient conditions (Sandulachi & Tatarov 2012).

Table 1. Causative agents in microbiological spoilage of fruits

Causative agents	Spoiled fruits	References
Escherichia coli *Klebsiella* sp.	pineapple, papaya	Hasan & Zulkahar 2018
Bacillus sp. *Staphylococcus* sp.	banana	Hasan & Zulkahar 2018
Lactobacillus plantarum *Bacillus cereus* *Bacillus subtilis* *Micrococcus luteus* *Pseudomonas aeruginosa* *Staphylococcus aureus* *Proteus vulgaris* *Streptococcus pyogenes* *Erwinia cacticida* *Serratia marcescens*	apple, watermelon, pineapple, pawpaw, tomato, orange, banana, etc.	Ajayi-Moses et al. 2019
Aspergillus flavus *Aspergillus niger* *Aspergillus oryzae* *Aspergillus tubingensis* *Aspergillus foetidus* *Aspergillus awamori* *Aspergillus japonicus* *Aspergillus phoenicis* *Rhizopus stolonifer* *Fusarium oxysporum*	mango, apple, orange, peach, kiwi, lemon, pokhara (lotus fruit), apricot, tomato, dates, banana, grapes	Al-Hindi et al. 2011
Aspergillus niger *Aspergillus fumigatus* *Aspergillus parasiticus* *Aspergillus flavus* *Mucor racemosus* *Mucor piriformis* *Fusarium solani* *Fusarium oxysporum* *Fusarium avenaceum* *Penicillium expansum* *Penicillium digitatum* *Rhizopus oryzae* *Rhizopus stolonifer* *Saccharomyces cerevisiae* *Alternaria alternata* *Kluyveromyces marxianus* *Candida krusei* *Candida tropicalis* *Torulopsis fragaria* *Pichia anomala* (*Wickerhamomyces anomalus*) *Pichia kluyveri* *Pichia fermentans* *Zygosaccharomyces bailii* *Zygosaccharomyces rouxii* *Geotrichum candidum*	apple, watermelon, pineapple, pawpaw, tomato, orange, banana, etc.	Ajayi-Moses et al. 2019

FOODBORNE DISEASES

Diseases caused by consuming contaminated food are called "foodborne diseases". From fruit production to their processing, different pathogens, parasites, and chemicals can contaminate food products and cause a comprehensive range of diseases (Schirone & Visciano 2021; Yu et al. 2021). Worldwide, there are 600 million cases and 420,000 deaths each year from foodborne illnesses due to the consumption of unsafe food. In children under the age of five, the mortality rate from foodborne diseases is generally 30% (WHO 2022). To minimize foodborne diseases, a system should be developed to monitor the trends of diseases, estimate their load, recognize and control the outbreaks, detect speculative food and their unhygienic preparation, find susceptible groups, classify the routes of transmission of foodborne pathogens, etc. (Yu et al. 2021). Several countries monitor contaminated food products and their influence on the financial burden that can cause illness and death (Flint et al. 2005; Hoffmann et al. 2012; Yu et al. 2021). Foodborne diseases related to harvest can cause infections, hospitalizations, and deaths connected with fresh-fruit eating, despite the execution of safety practices during harvesting. Fresh produce can be eaten raw and stimulate a healthy way of life, which is why it will persist to act as a vehicle for foodborne diseases (Table 2) (Strawn et al. 2013). Fruits can decrease the chance of persistent illnesses when taken regularly (Waheed & Siddique 2009; Macieira et al. 2021).

Microorganisms that cause plant and human foodborne diseases can inhabit surface water (Jones et al. 2014) through contaminated soil. However, plant pathogens can contaminate shallow water with municipal sewage, verminous dirt, cull piles, debris, water, and ground drainage tiles (Jones et al. 2014; Uyttendaele et al. 2015; Iwu & Okoh 2019). Topographical locations depend upon the nature and occurrence of sickness-causing microorganisms due to ecological circumstances, weather, and existing hosts. *Escherichia coli* and *Salmonella* species from shallow water are foodborne pathogens that enter the harvesting area of fruits and vegetables through irrigation. Both organisms have the competence to persist in the soil and survive on the surface of plants for an extended period (Jones et al. 2014). Viruses, bacteria (Jones et al. 2014), fungi, oomycetes (Jones et al. 2014; Marčiulynas et al. 2020), and nematodes are informed as plant pathogens originating in irrigation water (Jones et al. 2014; Redekar et al. 2020).

RISKS OF SYNTHETIC PRESERVATIVES

Preservatives are used to protect food products from spoilage. The selection of preservatives depends on their availability, cost, and performance. Artificial preservatives are now used globally to ensure the quality of food products (Routledge et al. 1998; Xiu-Qin et al. 2008). Currently, synthetic additives like sorbic acid, propanoic acid, benzoic acid, dehydroacetic acid and their salts, calcium (sodium), ethylparaben, methylparaben, butylparaben, propylparaben, isobutylparaben, heptylparaben, isopropylparaben, potassium sorbate, sodium benzoate, sulfur dioxide, and potassium metabisulfite are allowed in food products (Table 3) (Routledge et al. 1998; Xiu-Qin et al. 2008; Khan et al. 2014). Some articles inform that the extensive use of food preservatives increases the probability of health hazards. In recent years, the quantity of synthetic preservatives has been reduced for the sake of consumers' health. Many stabilizers might be detrimental to consumers and cause allergic contact dermatitis. In vivo and in vitro assays in current studies have testified to the estrogenic activity of ethylparaben, butylparaben, methylparaben, and propylparaben and recommended that the paraben's safety must be readdressed (Routledge et al. 1998; Xiu-Qin et al. 2008). This research showed that butylparaben and propylparaben affect the function of the male reproductive system as well as the secretion of testosterone by exerting a weak estrogenic activity, whereas parabens in food products can cause the growth of breast cancer (Oishi 2002; Darbre et al. 2002, 2003, 2004; Xiu-Qin et al. 2008).

Table 2. Foodborne diseases associated with fresh produce

Microorganisms	Years	References
Shiga toxin-producing *Escherichia coli* (STEC) *Listeria monocytogenes* *Salmonella*	2013	Strawn et al. 2013
different serotypes of *Salmonella*	2006 and 2016, 2017, 2004–2018, 2017–2019, 2019	Dyda et al. 2020
Escherichia coli *Listeria monocytogenes* *Salmonella enterica*	2019	Carstens et al. 2019

Table 3. Synthetic preservatives used in fruit preservation

Preservatives	Preserved fruits	References
salicylic acid, calcium chloride	fresh-cut mangoes	Moradinezhad 2021
ascorbic acid	pear slices, arils of pomegranate	Gorny et al. 2002; Moradinezhad et al. 2020
1-methylcyclopropene and chlorine dioxide (mixture)	strawberries	Yang et al. 2020a
benzoic acid, sorbic acid, dehydroacetic acid; ethyl-, butyl-, methyl-, isopropyl-, propyl-, and isobutyl p-hydroxybenzoate	fruits	Lin et al. 2000

BIOPRESERVATION

Eliminating contamination and expanding the shelf life of food using beneficial microbes and their metabolic products is referred to as "biopreservation" (Luz et al. 2020). The techniques used for the biopreservation of fruits include application of lactic acid bacteria (Nasrollahzadeh et al. 2022), essential oils, herbal extracts, bacteriocins (Bourdichon et al. 2021), bacteriophages (Xu 2021), etc. in the form of nanoparticles, microcapsules (Calderón-Oliver & Ponce-Alquicira 2022), edible films and coatings (Rimá de Oliveira et al. 2021).

Biopreservation using lactic acid bacteria (LAB)
Lactic acid bacteria (LAB) are the indigenous microbiota of fresh fruits, which are reported as the biocontrol agents in various food items for numerous fungi and bacteria (Batish et al. 1997; Sathe et al. 2007; Linares-Morales et al. 2018; Marín et al. 2019). They are generally recognized as safe (GRAS) (Stiles & Holzapfel 1997; Dhundale et al. 2018; Linares-Morales et al. 2018; Achi et al. 2019; Aymerich et al. 2019; Marín et al. 2019; Luz et al. 2020; Margalho et al. 2021; Zapaśnik et al. 2022) by the Food and Drug Administration (FDA) and European Union (Luz et al. 2020) with qualified presumption of safety (QPS) status (Aymerich

et al. 2019; Luz et al. 2020). LAB are Gram-positive, rod- or cocci-shaped, nonmotile, nonspore-forming (Khalil et al. 2021), microaerophilic, and catalase-negative bacteria (Akbar et al. 2016), which can ferment carbohydrates to produce lactic acid. It is a diverse group of microbes that comprises bacterial genera, including *Lactobacillus*, *Lactococcus*, *Pediococcus*, *Enterococcus*, *Streptococcus*, *Leuconostoc*, *Carnobacterium*, *Aerococcus*, *Vagococcus*, *Tetragenococcus*, *Oenococcus*, and *Weissella*. These microorganisms are more thermostable due to the presence of a low GC-ratio (<55%) in their DNA (Khalil et al. 2021). Lacto-fermentation is defined as a process to enhance the biological activity of fruits by releasing the bioactive compounds from the fruit cells using specific strains of LAB (Muhialdin et al. 2020) and reduces the availability of carbohydrates and the production of some organic compounds such as lactic acid and propionic acids (Akbar et al. 2016; Tumbarski et al. 2018; Stupar et al. 2021). The load of LAB in fresh fruits and vegetables is very high, but according to Trias et al. (2008), only some LABs had inhibitory effects (Table 4).

The role of LAB is to inhibit pathogens and spoilage bacteria (Akbar et al. 2016; Khalil et al. 2021) by producing a group of bioactive compounds. Earlier, LAB was used to preserve dairy and meat (Akbar et al. 2016). The food preservation capability of the LAB depends on the production of carbon dioxide, hydrogen peroxide, ethanol, diacetyl, organic acids, antifungal compounds such as fatty acids and phenyl-lactic acid, antibiotics, namely reutericyclin, bacteriocins (Akbar et al. 2016; Dhundale et al. 2018; Achi et al. 2019; Ouiddir et al. 2019; Mechai et al. 2020; Khalil et al. 2021; Margalho et al. 2021; Stupar et al. 2021; Zapaśnik et al. 2022), enzymes, aromatic compounds, and exopolysaccharides (Tumbarski et al. 2018; Achi et al. 2019). LAB was found to be promising against foodborne pathogens such as psychrophilic bacteria (*Brochothrix thermosphacta* and *Pseudomonas* spp.) (Akbar et al. 2016), *Listeria monocytogenes* (Akbar et al. 2016; Stupar et al. 2021), *Fusarium verticillioides*, *Aspergillus flavus*, mycotoxin production (de Melo Nazareth et al. 2020), *Fusarium graminearum*, *Fusarium culmorum* (Ouiddir et al. 2019), *Botrytis cinerea*, etc. (De Simone et al. 2021). LABs are now extensively studied for the biopreservation of bakery foodstuffs (Ouiddir et al. 2019; Wiernasz et al. 2020; Dopazo et al. 2023), dairy products (Ouiddir et al. 2019; Wiernasz et al. 2020; Bhattacharya et al. 2022), fruits, meats (Bhattacharya et al. 2022; Wiernasz et al. 2020), raw and fermented vegetables (Wiernasz et al. 2020), corns (de Melo Nazareth et al. 2020), quinoa (Nasrollahzadeh et al. 2022), seafood, etc. (Wiernasz et al. 2020; Stupar et al. 2021).

Table 4. Inhibitory effects of lactic acid bacteria against fruit-borne pathogens

Lactic acid bacteria	Inhibitory effects on pathogens	References
indigenous isolates of fruits	*Xanthomonas campestris* *Erwinia carotovora* *Penicillium expansum* *Monilinia laxa* *Botrytis cinerea*	Trias et al. 2008
Leuconostoc spp. *Lactobacillus plantarum* *Weissella* spp. *Lactococcus lactis*	*Escherichia coli* *Listeria monocytogenes* *Pseudomonas aeruginosa* *Salmonella* Typhimurium *Staphylococcus aureus*	Trias et al. 2008
Lactobacillus pentosus *Lactobacillus plantarum* *Lactobacillus brevis* *Lactobacillus delbrueckii* *Lactobacillus fermentum* *Lactococcus lactis* *Leuconostoc mesenteroides*	*Penicillium oxalicum* *Fusarium verticillioides* *Aspergillus niger*	Awah et al. 2018
Lactobacillus plantarum B2 *Lactobacillus fermentum* PBCC11.5	*Listeria monocytogenes*	Ma et al. 2017
Lactobacillus rhamnosus GG	cocktail of 5 serovars of *Listeria monocytogenes*	Iglesias et al. 2018

Biopreservation by LAB is an alternative technique to chemical preservation and is regarded as inexpensive, enhancing the quality (Khalil et al. 2022), extending the shelf life (Ibrahim et al. 2021; Khalil et al. 2022) of ready to eat and minimally processed food (Khalil et al. 2022). Sustainability (Tenea et al. 2020) improves the safety and hygienic status of food products (Ibrahim et al. 2021; Khalil et al. 2022), promotes nutritive enhancement, and is considered to be a clean additive (Ibrahim et al. 2021). The native bacterial strain CPA-6 isolated from minimally processed apples was reported to reduce the growth of *Salmonella*, *Escherichia coli* O157:H7, and *Listeria innocua* in apples and peaches (Alegre et al. 2012). Correspondingly, the antagonistic strain of *Pseudomonas graminis* CPA-7 isolated from the apple was reported to sustain antioxidant activity and was not deleterious to the nutritional value of fresh-cut melon throughout refrigerated storage (Plaza et al. 2016). *Pediococcus pentosaceus* DT016 was also described as a protective culture to suppress the growth of *Listeria monocytogenes* in stored refrigerated fresh lettuce, rocket salad, parsley, and spinach (Ramos et al. 2020). Fermentation of raw dragon fruits increases the phenolic compounds and decreases the microbial load and antioxidant activity. Due to natural preservatives such as phenolic compounds and organic acids, fermented fruit juice can be preserved for a long time and have numerous health benefits compared to fresh fruit juice (Muhialdin et al. 2020). During fermentation, certain strains of probiotics develop off-flavors, so it is necessary to select a preservative agent that does not alter the original flavor of the food products (Udayakumar et al. 2022).

Biopreservation using essential oils and plant extracts

The evaporative and aquaphobic liquid mixture attained from different plant parts of odoriferous therapeutic plants is known as “essential oils” (EOs) (Hyldgaard et al. 2012; Rios 2016; Basavegowda & Baek 2021; Angane et al. 2022). EOs can be isolated by supercritical extraction, squeezing under pressure, steam distillation, fermentation, and extraction of volatile organic solvents. Plants belonging to the families of Rutaceae, Pinaceae, Apiaceae, Lauraceae, Zingiberaceae, Lamiaceae, Asteraceae, and Myrtaceae, are rich in EOs (Kocić-Tanackov & Dimić 2013). EOs have been reported to have antimutagenic, anti-inflammatory (Basavegowda & Baek 2021), antioxidant (Basavegowda & Baek 2021; De-Montijo-Prieto et al. 2021; Coimbra et al. 2022), anticarcinogenic (Basavegowda & Baek 2021), antimycotoxigenic (De-Montijo-Prieto et al. 2021), and antimicrobial properties (Basavegowda & Baek 2021; Coimbra et al. 2022). Therefore, it is extensively used as a flavoring agent (Basavegowda & Baek 2021) and preservative (Coimbra et al. 2022) in the food industry (Basavegowda & Baek 2021), as well as in agronomic, pharmaceutical, chemical, cosmetic, and perfume industries (Coimbra et al. 2022). According to the World Health Organization (WHO) (Angane et al. 2022; Castillo et al. 2014), ingredients of EOs are GRAS (Castillo et al. 2014; Angane et al. 2022; Coimbra et al. 2022) and can be used to control fruit deterioration (Castillo et al. 2014; Angane et al. 2022). EOs are a composite assortment of numerous bioactive components such as alcohols, terpenes, phenylpropanoids, esters, aldehydes, ketones, and terpenoids (Amiri et al. 2021; Maurya et al. 2021). Due to the insignificant side effects, scientists are focused on these plant-based preservatives. A study reported that EOs have successfully controlled food spoilage bacteria (Gram-positive and Gram-negative), fungi, and their toxins (Maurya et al. 2021). Examples include *Botrytis cinerea* (De-Montijo-Prieto et al. 2021; De Simone et al. 2020), *Listeria monocytogenes*, *Staphylococcus aureus*, *Salmonella*, *Escherichia coli*, *Bacillus cereus*, *Klebsiella pneumonia*, etc. (Amiri et al. 2021).

The antioxidant activity of EOs is associated with the complex diversity of phenylpropanoids, terpenes, and terpenoids. However, antimicrobial activity depends on specific chemical components that alter the membranes, modify their dynamicity and permeability, and release cytoplasmic constituents. Nevertheless, depending on the variety of microorganisms, their composition, membrane thickness, and cellular metabolic activities, the effects are different (De-Montijo-Prieto et al. 2021). The mechanism of plant material affecting the microorganisms includes disrupting enzyme structures, attacking the cell membrane, compromising bacterial genetic material, and forming fatty acid hydroperoxide by oxygenation of unsaturated fatty acids.

However, the phenolic compounds of EOs modify the permeability of bacterial cells, damage the cytoplasmic membrane, disrupt the production of ATP, and cause cell death (Amiri et al. 2021). The EOs can be used to preserve soymilk (Akakpo et al. 2019), wheat (Belasli et al. 2020), beef (Mihin et al. 2019), cheese (Nunes Silva et al. 2020), table grapes (De Simone et al. 2020), fresh camel sausage (Moghimi et al. 2021), wheat bread (Valková et al. 2022), cereals, pulses, fruits, vegetables (Pandey et al. 2017), frozen vegetables, fresh-cut *Citrullus lanatus* (Ebabhi et al. 2019), etc. (Tao et al. 2021). EOs are natural, safe, sustainable, cost-effective, host-specific, biodegradable, low toxicity, and renewable food preservatives (Pandey et al. 2017).

Various in vitro investigations verified the fungicidal efficiency of oregano, clove, thyme, tea tree, cumin, cinnamon, and birch EOs for the inhibition of significant pathogens of citrus fruits (Arras et al. 1993; Daferera et al. 2000; Yigit et al. 2000; Plaza et al. 2004; Cháfer et al. 2012). Several reports have concluded that aliphatic aldehydes, natural botanical extracts, and EOs can be used as antimicrobial ingrediens for the postharvest preservation of citrus fruits (Table 5) (Cháfer et al. 2012). The solubilization, stabilization, and liberation of active compounds of various EOs depended on exterior conditions such as moisture, temperature, ultraviolet light, and oxidation (Hermanto et al. 2016; Ban et al. 2020). EOs have been reported as an effective alternative to extend the shelf life of perishable fruits such as strawberries and raspberries without a loss in their texture, appearance, taste, and their antimicrobial activity due to the presence of bioactive components such as aldehydes, phenolic compounds, terpenes, and terpenoids (Najmi et al. 2023). *Citrus sinensis* (commercial orange) EOs obtained using the cold press method (EOP), eventually followed by steam distillation (EOPD), have been stated as natural sources to prolong the shelf life of food products due to their antipathogenic and antioxidant properties (Manzur et al. 2023). The negative side of EOs is sometimes an unpleasant smell, low efficiency (Bouarab Chibane et al. 2019), and insolubility in water (Bouarab Chibane et al. 2019; Mutlu-Ingok et al. 2020; De-Montijo-Prieto et al. 2021). These weaknesses frequently limit their use for food preservation (Bouarab Chibane et al. 2019). The wide-scale application of EOs as a free-form food preservative is additionally limited due to rapid release from covered surfaces; oxidation by ecological factors such as moisture, temperature, and irradiation; extensive loss in biological activity (Maurya et al. 2021); and possible unpleasant changes in organoleptic properties (De-Montijo-Prieto et al. 2021; Maurya et al. 2021) of food due to intense aroma (Mutlu-Ingok et al. 2020; De-Montijo-Prieto et al. 2021; Maurya et al. 2021), high reactivity, changes in intestinal absorbance, and probable undesirable reaction with the matrices (De-Montijo-Prieto et al. 2021).

Biopreservation using nanoparticles (NPs)

Colloidal particles that measure 10 to 1000 nm are known as "nanoparticles" (NPs) (McNamara & Tofail 2017). Nanotechnology can be applied in different areas such as environmental safety, the evolution of innovative materials, agriculture, pharmaceutical, food (processing and packaging) (Chadha et al. 2022), drug delivery, biomedical engineering, textile and electronic industries, etc. (Nsengumuremyi et al. 2020). NPs are also recommended in a system "from farming to consumption" of food products (production, transporting, and conservation) (Salem et al. 2022). The NPs tested in the nutrition industry comprise organic NPs (primarily natural products), inorganic NPs (metals and metal oxides), and their combinations (e.g., clay) (He et al. 2019). Conventionally, NPs are synthesized by different physical and chemical methods, which cause atmospheric pollution due to the production of harmful byproducts (Niluxsshun et al. 2021), but nowadays, the "green synthesis" of NPs from plant extracts (Yousaf et al. 2020; Niluxsshun et al. 2021), enzymes, and microbes (Alvi et al. 2021) becomes an alternative. Among all methods, the synthesizing NPs from plants is helpful because they are simple and easy to maintain in cell culture (Jackson et al. 2018; Alvi et al. 2021). For example, copper NPs were synthesized in the aqueous extract of citrus lemons (Amer & Awwad 2021), and selenium NPs in the grapefruit and lemons extracts (Alvi et al. 2021).

Table 5. Essential oils and plant extracts in postharvest preservation of fruits

Preserved fruits	Essential oils and plant extracts	References
oranges	tea tree oil coated with chitosan	Cháfer et al. 2012
lemons	carvacrol and thymol essential oils mixture assimilated with a commercial wax	Castillo et al. 2014
Satsuma mandarins (type of mandarin orange)	grapefruit seed extract combined with the coating of carnauba wax	Won & Min 2018
Citrus sinensis (sweet orange)	red acalypha (*Acalypha wilkesiana*) leaf extract	Oladunmoye 2006; Akinde et al. 2017
avocado	pepper tree essential oil	Chávez-Magdaleno et al. 2018; Ban et al. 2020
peach, kumquat, strawberry	cinnamon, tarragon, and *Thymus capitatus* essential oils	Martínez et al. 2018; Hosseini et al. 2019; Lee et al. 2019; Ban et al. 2020

NPs have an exclusive antimicrobial potential (Lloret et al. 2012; Odetayo et al. 2022) against bacteria (Wang et al. 2017), which is why they are used in edible coatings (Lloret et al. 2012; Odetayo et al. 2022). For instance, chitosan NPs have antibacterial effects on *Escherichia coli* O157:H7 (Kuang et al. 2021), *Staphylococcus aureus*, *Salmonella* Typhimurium, and *Escherichia coli* (Tayel et al. 2020). Selenium NPs have an antifungal activity on *Sclerospora graminicola* and *Fusarium oxysporum* (Hadimani et al. 2023) on psychrophilic bacteria (Shehab et al. 2022), and nisin-loaded alginate-chitosan NPs on *Listeria monocytogenes* (Zimet et al. 2018). Zinc oxide NPs on *Staphylococcus aureus*, silver NPs on *Escherichia coli*, *Pseudomonas aeruginosa* (Wang et al. 2017), and *Lepidium sativum* mucilage. The mechanism of antimicrobial activity of NPs is defined as inducing oxidative stress, releasing metal ions, disrupting bacterial cell membranes, generating reactive oxygen species, penetrating bacterial cell membranes, and causing intracellular antibacterial effects (Wang et al. 2017). NPs are widely used as an antimicrobial compound in food preservation and packaging (predominantly MgO, ZnO, Cu/CuO, TiO_2, Ag, etc.) and as a nanosensor to detect food deterioration (Chadha et al. 2022).

NPs prolong the shelf life of food by acting as a barrier from extreme mechanical and thermal shock (Singh et al. 2017). It can be used to extend the shelf life of grapes (Hadimani et al. 2023), tomatoes (Sharma et al. 2023), and oranges (Dulta et al. 2022). The research verified that "nanotechnology" is one of the finest approaches for expanding the useful life of fresh fruits (Table 6) (Odetayo et al. 2022). The application of copper NPs (Cu-NPs) in chitosan-polyvinyl alcohol (Cs-PVA) hydrogels in tomato storage increased the contents of bioactive compounds, sustained the physiochemical quality, and prolonged storage (Hernández-Fuentes et al. 2023). Likewise, the effect of alginate-based zinc oxide NPs (Alg-ZnO NPs) coating treatment was conveyed to maintain firmness and respiration rate, reduce weight loss and microbial deterioration, and decline the rate of increase of total soluble solids, sugars, and carotenoids in the coated mango fruits 'Kiett' (Hmmam et al. 2023). The limitations of NPs include the lack of a unified standard of antibacterial mechanism, the absence of research methods for in vitro trials, the complex structure of bacterial cell membranes, size-dependent transportation, and inadequate intracellular inhibition mechanism (Wang et al. 2017). Research reported that ingestion of NPs could cause protein denaturation, DNA damage, stimulation of oxidative stress responses (Chadha et al. 2022), and accumulation in different organs such as the spleen, liver, and lungs, etc. (Angelopoulou et al. 2022), which pays attention to the toxicity problem in food products, which must be addressed before implementation of this technique (Chadha et al. 2022).

Table 6. Nanoparticles in fruit preservation

Preserved fruits	Nanoparticles	References
loquat	chitosan/nanosilica coating	Song et al. 2016
sweet cherries	nitric oxide-releasing chitosan nanoparticles	Ma et al. 2019
cherries, apricots	silver nanoparticles-locust bean gum coating	Akyüz et al. 2023
red grapes	zinc oxide nanoparticles in the starch-based edible coating	Mahardiani et al. 2022
strawberries	olive mill wastewater phenol capping zinc oxide nanoparticles	Qi et al. 2022
plum	chitosan and glycine betaine nanoparticles	Mahmoudi et al. 2022
apricots	chitosan coatings and their nanoparticles	Algarni et al. 2022
tomatoes	zinc oxide nanoparticles	Iqbal et al. 2022

Biopreservation by microencapsulation

The physiochemical method in which one component is inserted into another by creating a particle of a few nanometers to millimeters is known as "microencapsulation" (Yang et al. 2020b). The active component is designated as the "core", whereas the enfolding substance is known as the "wall" (Speranza et al. 2017). For microencapsulation, the wall materials are mostly proteins (whey proteins, maltodextrin, modified starch, etc.), polysaccharides (sodium carboxymethyl cellulose and chitosan, etc.) (Touré et al. 2011; Carneiro et al. 2013; Speranza et al. 2017; Ban et al. 2020), and lipids (EOs and triglycerides, etc.) (Speranza et al. 2017). The size of microcapsules ranges between 0.2 and 5000 μm in diameter, which depends on the nature of encapsulating material and processing method (Calderón-Oliver & Ponce-Alquicira 2022). Microencapsulating materials should be readily available, inexpensive (Ban et al. 2020; Baghi et al. 2022), nontoxic, biocompatible, and biodegradable (Saqueti et al. 2021; Baghi et al. 2022). The most encapsulated preservatives include EOs, plant extracts, polyphenols, bacteriocins, organic acids, and bacteriophages (Calderón-Oliver & Ponce-Alquicira 2022). Globally, the trends of using microparticles can be continuously increasing in many areas, such as bioremediation of the environment, food, medication, electronics (Calderón-Oliver & Ponce-Alquicira 2022), cosmetic, textile, agriculture, chemical, metallurgical, and biotechnology industries (Arenas-Jal et al. 2020).

Biopreservation by edible films and coatings

Edible films and coatings are thin layers that protect foodstuffs and can be used simultaneously (Hassan et al. 2018; Galus et al. 2020; Tavassoli-Kafrani et al. 2022). The terms films and coatings are sometimes used interchangeably, but represent different packaging concepts. Usually, the films are thin layers to wrap or cover, while coatings are formed on the product's surface (Seyedzade Hashemi et al. 2022). The advantages of edible films embrace palatability, biodegradability, inexpensiveness, ease in production, and being environment-friendly (Tavassoli-Kafrani et al. 2022). It can be formed by using different biopolymers such as proteins (e.g., wheat gluten, whey protein, zein, gelatin, casein, etc.) (Díaz-Montes & Castro-Muñoz 2021; Tavassoli-Kafrani et al. 2022), polysaccharides (e.g., chitosan, starch, cellulose, seaweed extracts, pectin, alginate, gum, agar, dextran, pullulan, whole grain material, etc.) (Galus et al. 2020; Díaz-Montes & Castro-Muñoz 2021; Zhou et al. 2021; Tavassoli-Kafrani et al. 2022), lipids (e.g., paraffin, shellac resin, bees wax, glycerides, carnauba wax, candelilla wax, etc.) (Galus et al. 2020; Díaz-Montes & Castro-Muñoz 2021; Tavassoli-Kafrani et al. 2022), and inorganic nanoparticles comprising (e.g., polyphenols, EOs, plant extracts, etc.) (Zhou et al. 2021).

Edible coatings are used extensively to protect the sensory and nutritional potential and intensify the shelf life of fruits and vegetables (fresh and fresh-cut) (Temiz & Özdemir 2021). In agricultural foodstuffs, the edible films and coatings can reduce the respiration, water evaporation, and oxidation rate by restricting oxygen interchange, humidity, and movement of solutes (Falguera et al. 2011; Ebrahimi & Rastegar 2020). Edible films and coatings can be used as carriers for probiotics, prebiotics, antioxidants, nutraceuticals, flavors, antimicrobials, and coloring agents (Seyedzade Hashemi et al. 2022). Whey protein-based edible films and coatings incorporated with *Lactobacillus buchneri* UTAD104 can control the growth of *Penicillium nordicum* in cheese (Guimarães et al. 2020), chitosan, alginate. Carboxymethyl cellulose-based probiotic edible coatings can be used to expand the shelf life of UF soft cheese (El-Sayed et al. 2021). Starch and chitosan coating prolongs the shelf life of air-dried green bananas (Alam et al. 2020). Mesoporous active edible film based on silica nanoparticles containing oregano EOs can extend shelf life by reducing the growth of aerobic mesophilic bacteria, *Escherichia coli*, *Brochothrix thermosphacta*, and *Pseudomonas* spp. (Matadamas-Ortiz et al. 2023). Edible films containing oregano EO can prolong the shelf life of fruits (Lan et al. 2022). Novel nanoemulsion-based edible coatings with a complex assortment of ε-poly-l-lysine and edible coatings combined with LAB sustain the postharvest quality of grapes by controlling the fungal growth (Marín et al. 2019). Alginate biofilms containing killer yeast (*Wickerhamomyces anomalus* and *Pichia membranifaciens*) prevent fungal decay of apples after harvest (Błaszczyk et al. 2022). The edible functional coatings can be applied directly by spraying the film-forming solution on the surface of the food or dipping the food into a film-forming solution (Zhang & Rhim 2022).

Research reported that the combination of carboxymethyl chitosan and pullulan-integrated edible film with galangal EO is a favorable and "green" substance for the preservation of fruits industrially (Table 7) (Zhou et al. 2021). The synthesis of novel chitosan nanoemulsion-coating embedded with *Valeriana officinalis* EO (Ne-VOEO) reported that it could control the respiration rate and weight loss, delay the degradation of soluble solids, phenolic contents, titratable acidity, and pH, and maintain the sensory qualities under specific storing conditions that can extend the shelf life of stored *Citrus sinensis* fruits with improved aflatoxin B_1 (AFB_1) mitigation (Das et al. 2023). Likewise, applying chitosan coating from *Cunninghamella elegans* can control the pathogenic fungi, especially *Botrytis cinerea* and *Penicillium expansum*, and preserve the physicochemical, physical, and sensory qualities of the table grapes (Vasconcelos de Oliveira et al. 2014). The disadvantages of edible films and coatings include: toxicity related to the molecular weight of biopolymers, detrimental impurities in raw materials, and penetration of nanomaterial coatings in living cells. Before implementation in food packaging, further investigations are needed to assess the effects of edible films and coatings on human health and the environment (Tavassoli-Kafrani et al. 2022).

Biopreservation by bacteriocins

Bacteriocins are stated as antimicrobial agents (Tumbarski et al. 2019; Ng et al. 2020), which are usually produced by the genus *Lactobacillus* and *Bacillus* (Tumbarski et al. 2019) or strains of other bacteria such as *Escherichia coli* and *Staphylococcus* (Ng et al. 2020). Bacteriocins destroy the target cells by penetrating the cytoplasmic membrane, releasing tiny particles of cytoplasm, making pores in the cell wall, depolarizing the membrane potential, deactivating lipids by eliminating membrane potential, and reducing ATP concentration (Noktehsanj Avval et al. 2022). Bacteriocins are possibly sensitive to pH, temperature, and certain protease enzymes. It can be applied as a food preservative to improve the sensory qualities and prolong the shelf life of foodstuffs and is stated as GRAS (Ogundare et al. 2021). The antimicrobial substances produced by LABs include bacteriocins, lactic acid, hydrogen peroxide, diacetyl, etc., which can limit both Gram-minus and Gram-plus pathogenic bacteria (Afrin et al. 2021), such as *Bacillus subtilis*, *Escherichia coli*, *Staphylococcus aureus* (Ogundare et al. 2021), *Listeria monocytogenes* (De Marco et al. 2022), *Vibrio* sp. 1T1 (Kaktcham et al. 2019), *Lactobacillus* sp., coliforms, *Vibrio* sp., and *Aeromonas* sp. (Sarika et al. 2019).

Bacteriocin produced by *Enterococcus* spp. can be used as a preservative against foodborne pathogens such as *Streptococcus mitis*, *Listeria innocua*, *Staphylococcus aureus*, *Listeria monocytogenes*, *Bacillus cereus*, vancomycin-resistant enterococci (VRE), and methicillin-resistant *Staphylococcus aureus* (Fugaban et al. 2021). Bacteriocin produced by LAB isolated from catfish and *Zea mays* can be used to preserve food and vegetables (Ogundare et al. 2021). *Lactococcus lactis* LLH20 has synthesized a bacteriocin-like inhibitory substance (BLIS) that can be used to biopreserve minimally processed lettuce (De Marco et al. 2022). *Lactobacillus casei* KLDS 1.0338 bacteriocin can be helpful in the biopreservation of soybean milk (Ma et al. 2020).

Bacteriocins are assimilated into edible coatings and enhance the shelf life of perishable fruits. It can be widely used as a biostabilizer in the nutrition industry (Table 8) (Tumbarski et al. 2019). The study of the influence of edible coatings based on celery pectin separately and in combination with a bacteriocin of *Bacillus methylotrophicus* BM47 reported that the pectin + bacteriocin coatings reduce the weight loss, deterioration, total soluble solids, protect the content of ascorbic acid and antioxidants, had no effects on pH, titratable acidity, the concentration of sugars or decrease total phenolic and anthocyanin contents, and prolong the storage period of blackberries (Tumbarski et al. 2020). The performance of bacteriocin depends upon the environmental circumstances and the targeted bacteria. Determining the most precise and effective circumstances for applying each bacteriocin is essential (Ma et al. 2017). LAB produces various bacteriocins, but not all are safe and can cause diseases like cancers, nosocomial infections, endocarditis, urinary tract infections, etc. For example, *Streptococcus thermophilus* has approved the status of GRAS, but the other species of *Streptococcus* are not considered safe (Todorov et al. 2022). The limitations of bacteriocins as a preservative include a constrained antimicrobial range, a high required dosage for the inhibition of multidrug-resistant bacteria, sensitivity to protease enzymes, expensive production, and low yield (Sidhu & Nehra 2019).

Biopreservation by bacteriophages

Bacteriophages infect bacterial cells and use them to replicate (Akbaba & Ozaktan 2021; Guerrero-Bustamante et al. 2021; Liu et al. 2022). After the yields are collected, the fresh produce is colonized initially by aerobic bacteria. Due to the sophisticated specificity and lack of any side effects for humans, plants, and animals, bacteriophages have long been used in the treatment of bacteriological infections. The phage will persist in a latent phase until the host bacteria begin to degenerate. Then the prophage will be activated, replicated, and lysed in the bacteria cells (Saleh 2020). Bacteriophages are natural, specific, eco-friendly agents used in the food industry (O'Sullivan et al. 2019; Karaynir et al. 2022). They are ubiquitous, self-replicated, easy to isolate, and produce inexpensive low intrinsic toxicity (Alves et al. 2019) resistant to stress factors. They are effective against multidrug-resistant bacteria and have no side effects (Alomari et al. 2021).

The literature reported that due to the lack of precision, using natural phages has low effectiveness and applicability in abundant production compared to the conventional biocontrol approaches. However, with the progress in genetic engineering, synthetic biology proposed innovative tools to construct engineered phages (Huss & Raman 2020). Phage therapy will be considered valuable for extending the shelf life of fresh produce (Table 9) (Vonasek et al. 2018). Bacteriophage showed promising results against three leading foodborne pathogens: *Listeria monocytogenes*, *Salmonella* spp., and *Escherichia coli* O157:H7. The study that examined the efficiency of the bacteriophage Listex P100 to control the growth of *Listeria monocytogenes* on pear, melon, and apple products (slices and juices) stored at 100 °C informed that the phage treatment was more competent on melon than pear and had no effect on apple products due to high pH during storage (Oliveira et al. 2014). The limitation of bacteriophages includes a narrow host range due to the high specificity for a single type of bacteria, poorly stable under temperatures > 50 °C, low pH < 3.5, ultraviolet light, and sunlight, and a variable survival time depending on the host bacteria (Alomari et al. 2021).

Table 7. Edible films and coatings in fruit preservation

Preserved fruits	Edible films and coatings	References
pears	papaya	Rodríguez et al. 2020
mango	guar gum supplemented with the ethanolic extract of *Spirulina platensis*	Ebrahimi & Rastegar 2020
strawberries	sodium alginate and chitosan	Du et al. 2021
strawberries	chitosan assimilated with apple peel polyphenols	Riaz et al. 2021
plums	pectin	Panahirad et al. 2020a
plums	carboxymethyl cellulose and pectin in combination or separately	Panahirad et al. 2020b
Chinese cherry, frozen grapes	chitosan coating	Xin et al. 2017
blueberry	chitosan and *Aloe vera* coating	Vieira et al. 2016

Table 8. Bacteriocins in fruits preservation

Preserved fruits	Bacteriocins	References
blackberry	bacteriocin produced by *Bacillus methylotrophicus* BM47	Tumbarski et al. 2020
strawberry	bacteriocin produced by *Lactobacillus*	Zhou et al. 2013
apples, tomatoes	bacteriocins produced by *Bacillus pumilus*, and *Bacillus safensis*	Babich et al. 2019
strawberries	bacteriocin produced by *Bacillus methylotrophicus* BM47	Tumbarski et al. 2019

Table 9. Bacteriophages in fruits preservation

Preserved fruits	Bacteriophages	References
strawberries	whey protein concentrate-loaded phages	Sezer et al. 2022
cherry tomatoes, sliced apple	whey protein coated with T7 bacteriophages	Vonasek et al. 2018

CONCLUSIONS

Fruits are nutrient-rich foods that can reduce the chance of persistent diseases through regular consumption. Food preservation aims to maintain freshness, color, and unique texture to extend the shelf life of these fruits. This review has presented emerging trends and advancements in the biopreservation of fruits, such as lactic acid bacteria, EOs, herbal extracts, nanoparticles, microencapsulation, edible films and coatings, bacteriocins, and bacteriophages. These biopreservation techniques are easy, inexpensive, eco-friendly, and GRAS by the WHO, which provides natural and "green" factors for the preservation of fruits because the chemical preservation methods can result in the loss of nutrients by adding unwanted chemicals. These biopreservation techniques can reduce postharvest crop loss and fruit-borne illnesses but have certain limitations, so it is necessary to consider them before implementation. Research is continued on these methods, including increasing their efficiency. Mainly, not enough results were obtained for microencapsulation and bacteriophages. Technologies for complementary use of the above ideas are also necessary.

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