Sustainable Postharvest Preservation of Berry Fruits

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Berries are highly perishable and susceptible to spoilage, resulting in significant food and economic losses. The use of chemicals in traditional postharvest protection techniques can harm both human health and the environment. Consequently, there is an increasing interest in creating environmentally friendly solutions for postharvest protection.

edible coatings essential oils postharvest preservation emerging technologies berries

1. Introduction

Berries are a diverse group of small size, sharp color (red, blue, or purple), soft texture and characteristic flavor, and highly perishable fruits that are cartilaginous endocarps full of seeds [1]. Commercial berries include strawberries, currants, gooseberries, blackberries, raspberries, blueberries, cranberries, grapes, and others less well-known such as boysenberries, bilberries, Jost berries, cloudberries, loganberries, and lingonberries. The berries' structures differ depending on whether they are formed from a single or several fused fertilized ovaries, being categorized as simple (e.g., blueberries, cranberries) and aggregate (e.g., strawberries, raspberries, blackberries) fruits, respectively [1][2]. The major producers of berries are China, the United States (US), Mexico, Poland, and Germany. The global production of berries in 2021 reached 89.10 million tons [3].

Fresh, frozen, or processed berries, such as those used to make jams, juices, purees, syrups, and wines, are all consumed. However, other procedures, such as the thermal and irradiation techniques used to produce fresh and processed berries, respectively, might cause nutritional losses. [4]. Additionally, fresh berries are quite perishable and highly susceptible to suffering contamination by pathogens and spoilage microorganisms, generating great economic losses and health problems such as food poisoning [5]. Over time, several physical and chemical techniques, such as the use of pesticides, have been employed to mitigate these losses [2][6]. Moreover, the high-value market of these fruits promotes the constant search by scientists and the industrial sector for green alternatives to prevent deterioration and extend the postharvest shelf life of berries, aiming to achieve the worldwide distribution of premium-quality berries. In line with this, nanotechnology and artificial intelligence (AI) have significant roles in the preservation of berries. Nanotechnology can be used to enhance food packaging, creating a protective layer that slows down the spoilage process and reduces moisture loss [7]. This is achieved by the incorporation of nanoparticles adding antioxidants and antimicrobial compounds into the packaging material; which helps to maintain the berries' quality and nutritional value [8][9]. Otherwise, AI algorithms can analyze the data from the environmental conditions used during the preservation process, such as temperature and humidity levels, to optimize the packaging used in the preservation procedure or predict the shelf life of the berries. AI also helps to automate the process, aiming to reduce the risk of human error while increasing the efficiency of the preservation processes [10][11]. The use of these technologies for berry preservation is an alternative to reduce waste and improve food safety concerns regarding these fruits.

2. Brief View of Traditional Methods of Microbial Growth Control: Fungicides

Fungicides are chemical substances used to control fungal diseases. Azoxystrobin and pyrimethanil are two of the most widely used fungicides in berries against *B. cinerea*, *Alternaria tenuissima*, and *Colletotrichum* spp. [12]. Azoxystrobin binds to cytochrome B, inhibiting electron transport between cytochromes B and C, suppressing mitochondrial respiration [13]. Instead, pyrimethanil inhibits methionine (an essential amino acid) biosynthesis by inhibiting cystathionine γ-synthase and cystathionine β-lyase. Furthermore, it inactivates extracellular enzymes such as cellulase and pectinase of *B. cinerea,* which produce fruit rotting [14]. Sulphur dioxide, a compound generally recognized as safe (GRAS), is employed as a gaseous disinfectant in berries to limit contamination by *B. cinerea* and prevent fruit browning by inhibiting enzyme reactions [1]. This substance is used in blueberries and grapes, and it is effective at concentrations ranging from 8 to 15%. Sulphur dioxide can be applied using tiny sachets inside the packing to delay fruit rotting by inhibiting enzyme-catalyzed reactions in spoilage microorganisms [15]. Even after remarkable results in fruit protection and quality, chemical treatments have serious consequences for the environment and human health [12]. For example, in neural cells, fungicides such as azoxystrobin quickly can constrain oxidative respiration and change the amount of lipids, producing neurotoxicity [16]. That is why there is an increase in the research into biological techniques for disease control [6].

3. Sustainable Alternatives for the Postharvest Protection of Berries

The postharvest protection of berries is important to preserve their quality, extend their shelf life, and reduce losses due to spoilage and diseases. Sustainable alternatives for the postharvest protection of berries are important to reduce the negative environmental and health impacts of traditional methods. Alternatives to preserve berries and increase their shelf life include biological control agents, natural plant extracts, modified atmosphere packing, cold storage, ultraviolet (UV) radiation, and tools based on molecular biology (**Figure 1, Table 1**) [1][17].

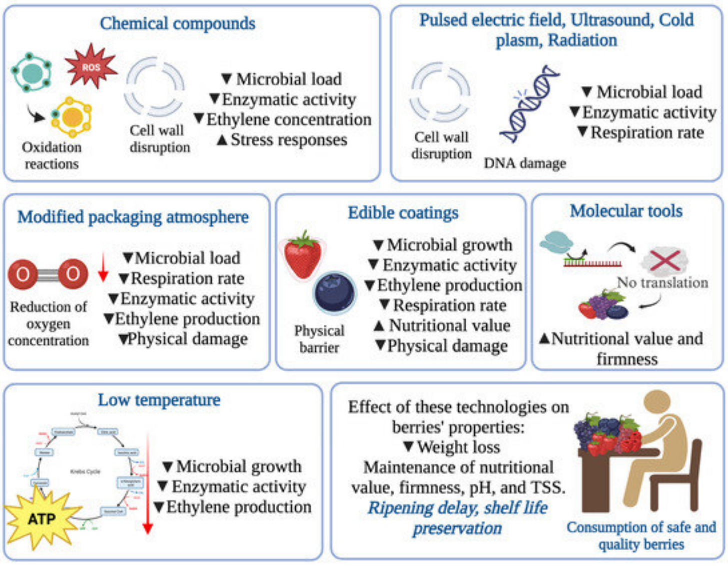

Figure 1. Action mechanisms and effects of different sustainable alternatives in berry preservation. The symbols ▲ and ▼ indicate increment and reduction, respectively.

Table 1. Pros and cons of the main sustainable alternatives applied for berry preservation.

Technique	Advantages	Disadvantages	Reference
Chemical compounds	• Inhibition of phytopathogenic fungi. Induction of stress responses. • Ethylene oxidation. • Inhibition of enzymatic activity. • Low cost of implementation at an industrial scale.	• High concentrations cause discoloration, texture changes, and chemical burns. • Reduction in anthocyanin content. • Modification of taste and aroma. • Activity affected by environmental conditions and by interaction with food components. • Cytotoxic effect at high concentrations in plant cells.	[18]
Modified atmosphere packaging	• Reduction in physical damage during transportation and storage due to the packaging. • Ethylene absorption. • Freshness preservation.	• Moisture condensation. • It does not eliminate the bacteria, and the growth of anaerobic microorganisms can be promoted.	[6]
Low temperature	• Decrease in microbial growth rate, reduction in respiration rate and water loss, delaying the ripening and senescence processes.	• Temperatures below freezing produce mushy fruits that lose their texture and flavor. • Reduction in vitamin C.	[19]
Ultraviolet (UV) irradiation	• Inhibition of microbial load. • Stimulation of the production of anthocyanins and flavonoids, improving the color, taste, and antioxidant properties of berries. • Fast and relatively low cost on a large scale.	• Excessive exposure to UV light can cause damage to the cellular components of the berries, reducing their quality and shelf life. • Poor penetration capacity. • High cost. • Low consumer acceptance.	[20]
Pulsed electric field	• Useful at the industrial scale. • Maintenance of nutritional value.	• High cost of implementation at the industrial scale. • Strong conditions can affect vegetable cells, causing softening.	[21]
Cold plasma	• Changes in the metabolism that extend the shelf life.	• Diminution of anthocyanins content. • Softening. • High cost.	[22]

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Ionized irradiation	• Induction of stress response in the berries, increasing the production of antioxidants and other protective compounds, extending their shelf life.	• Reduction in citric acid content in berries. • High cost, low consumer acceptance.	[23]
Ultrasound	• Low cost of implementation. Inhibition of enzymes.	• Softening	[24]
Edible coatings	• Low cost of implementation. • Generation of added value products. • Increment of the nutritional value. Fully consumed. • Enhancement of the organoleptic properties. • Carrier of antioxidant and antimicrobial properties. • Reduction in weight loss.	• Fermentation of the coated foods. • Optimization according to the requirements of each fruit. • Instability depends on storage conditions (polymers can absorb large amounts of water).	[25]

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3.1. Green Chemical Compounds

3.1.1. Ozone

Ozone is a powerful oxidant that can be used as a gas to control postharvest diseases and maintain the quality of berries, particularly blackberries, blueberries, and raspberries [22][26]. The action mechanisms of ozone in the postharvest stage of berries include direct damage to fungal spores and bacteria cells by modification of the membrane permeability through the phospholipids oxidation [27]. Ozonolysis refers to the breakdown of alkenes bonds in polyunsaturated chains; then, these compounds are cleaved into organic radicals, peroxides, and aldehydes [28]. Ozone treatment can effectively control postharvest diseases such as grey mold and anthracnose (**Table 2**). Additionally, this compound delays fruit senescence and ripening by reducing the enzymatic activity and oxidating ethylene leading to a longer shelf life and improved nutritional value and quality without compromising the flavor and texture of the fruit [2][22]. However, it is important to optimize the treatment conditions to minimize any potential negative effects, such as ozone-induced damage to the fruit surface [2]. Strawberries of the varieties Camino Real and San Andreas were treated with ozone (0.3 and 1 ppm) and stored at 10 °C for 12 days. The lower concentration showed a better effect on physicochemical (weight loss, firmness, color, pH, and total soluble solids—TSS) and microbiological (mesophilic aerobes, fungi, and yeasts) properties and improved total phenolic compound content in comparison with strawberries treated with 1 ppm. However, the concentration of 1 ppm affected the physicochemical properties of both varieties, mainly in San Andreas [47]. Hence, the response to a compound can vary between different cultivars, so the appropriate evaluation of each cultivar must be carried out to reduce the economic losses while maintaining the quality parameters.

3.1.2. Hydrogen Peroxide

Hydrogen peroxide (H_2O_2) can be used as a postharvest treatment for berries to protect them against decay and extend their shelf life. The action mechanism of H_2O_2 involves its ability to break down into reactive oxygen species (ROS) in the presence of enzymes such as catalase, peroxidase, and superoxide dismutase. ROS can oxidize lipids, proteins, and nucleic acids, leading to cellular damage and dysfunction [29]. H_2O_2 effects vary from minor oxidative stress to cell death depending on the concentration and exposure time of the H_2O_2. Moreover, at low concentrations, H_2O_2 acts as a signaling molecule, activating various pathways in the cell that regulate growth, development, and stress responses [30]. This means that the berries can protect themselves against environmental stressors and diseases that could lead to decay. In addition to this, H_2O_2 is shown to reduce ethylene production in berries, which helps to slow down the ripening process and extend the shelf life of the berries to maintain quality attributes such as color, texture, and flavor [29][30]. H_2O_2 was tested on fruits such as strawberries, red bell peppers, and watercress at higher concentrations (1 and 5%) for the assessment of the inhibition of *Listeria innocua*, coliforms, and mesophilic aerobes. H_2O_2 at 5% had a higher microbial reduction but produced color alterations, modified the sensorial properties, and decreased the anthocyanin content of strawberries [31]. There is not an established concentration for the use of H_2O_2 alone [32], but it is important to consider the effect of the high concentrations on the sensorial properties of the fruits.

3.1.3. Peracetic Acid (PAA)

PAA is a powerful oxidizing agent used as a sanitizer for fresh produce, including berries, during postharvest handling. When used properly, it can effectively reduce the population of microorganisms on the surface of the berries and helps extend their shelf life [33][34]. This reduction is achieved by the formation of radicals (•OH) that oxidate proteins, enzymes, and DNA. This process disrupts the structure and function of these components, eventually leading to cell death [35]. The action of PAA is concentration-dependent, and higher concentrations are more effective in killing microorganisms. The allowed concentration used by PAA to disinfect fruits and berries must not exceed 80 ppm in wash water [32]. However, like other disinfectants, it was tested in several ranges, which are slightly higher than the permissible limit. PAA at 24 and 85 ppm was tested to control *B. cinerea* and *Alternaria* spp. in blueberries stored between 0 and 1 °C for 4 weeks. As was expected, when using a higher concentration, the disease was reduced between 12 and 17% in comparison with untreated fruits without modifying their sensorial properties [33]. However, the use of PAA on berries must be carefully controlled, as excessive exposure or concentration can cause damage to the berries, including discoloration, texture changes, and even chemical residues [36]. In addition, the presence of peracetic acid on the berries may also affect the sensory characteristics of the fruit, including taste and aroma. In line with this, treatments with PAA at 80 ppm reduced the anthocyanins content in strawberries, whereas, at 20 and 40 ppm, it did not affect any quality parameter. Additionally, after 2 min of exposure, all the assessed concentrations were reduced by more than 4 Log_{10} CFU/g of *Listeria innocua* [34]. Therefore, it is important to use peracetic acid according to the manufacturer's instructions. Furthermore, more research related to the effect of PAA on the quality parameters of berries should be addressed. Because few studies have focused on the assessment of the effect of this compound on the sensorial properties, demonstrating that under the assessed conditions, the PAA does not modify the taste, firmness, and other sensorial properties of the fruit is essential [33].

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Table 2. Postharvest preservation of berries by green alternatives.

Berry	Preservation Technique	Storage Conditions	Main Result	Reference
Blueberries	Peracetic acid (PAA, 85 µL/L)	1 °C/4 weeks	Inhibition of *Botrytis cinerea* maintaining the quality parameters of the fruit during the storage.	[33]
Blackberries and grapes	Ozone (18 mg O_3/L for 10 min)	4 °C/ 20 days	Reduced fungal decay and loss of weight along with storage.	[26]
Strawberries, raspberries, and blueberries	Ozone (13 mg/m^3 for 16 h at 1 ± 0.5 °C) and MAP (10 kPa O_2 and 40 kPa CO_2)	4 °C/15 days	The treatment did not affect the quality parameters of the fruits. In the case of blueberries, it protected the total and individual content of anthocyanins.	[22]
Strawberries	γ-irradiation (2 kGy, at 0.5 kGy/min)	4 °C/15 days	The antioxidant activity increased in comparison with untreated fruits.	[23]
Strawberries	γ-irradiation (2 kGy)	4 °C/14 days	Decreased the proliferation of molds and yeasts; sensory and physicochemical scores were not affected in comparison to the non-treated.	[24]
Goji berry	γ-irradiation (10 kGy, at 2.6 kGy/h)	5 °C/50 days	Irradiation increased antioxidant activity by almost 30% in comparison with untreated fruits.	[37]
Blueberries	Cold plasma (4 kV/10 min)	25 °C/10 days	Reduced decay, maintaining the quality and anthocyanin content of the fruits during storage.	[38]
Blueberries	Cold plasma (45 kV/50 s), ultraviolet (UV-C, 2.76 kJ/m^2), or aqueous ozone (0.3 mg/L/5 min)	20 °C/8 days	Cold plasma was the most effective treatment in the maintenance of the quality parameters, inhibiting the fungal decay and the growth of the microflora.	[39]
Strawberries	Electron beam irradiation (2 kGy, 70 cm/min)	4 °C/14 days	Guaranteed microbial safety for up to 7 days and improved the physicochemical and sensorial properties of the coated fruits.	[40]
Strawberries, blackberries, and raspberries	Biodegradable packaging of gelatin-carboxymethylcellulose added with avocado peel extracts.	25–28 °C/6 days	Protected the fruit from fungal growth during storage.	[41]
Blueberries	Biodegradable packaging based on polyvinyl pyrrolidone and carboxymethyl cellulose added with bacterial cellulose and guar gum.	21 °C/15 days	Maintained the color and structure of the fruits after the storage period.	[42]
Blackberries and raspberries	Biodegradable packaging of poly (lactic acid) added with cyclodextrin and thymol.	4 °C/ 21 days	Prolonged shelf life by one more compared with commercial clamshell packaging, this means 21 days.	[43]

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3.1.4. Organic Acids

An organic acid is a compound that contains one or more carboxyl (-COOH) functional groups. Organic acids are commonly found in nature, in both plants and animals, and they play important roles in biological processes. Organic acids can be classified as either weak or strong, depending on their ability to donate hydrogen ions (H^+) in aqueous solutions [36][44]. As a result of this event, organic acids reduce the environmental and cellular pH of microorganisms, which eventually causes the cell to die. Some examples of organic acids used to preserve the quality of berries include citric, ascorbic, malic, acetic, and lactic acid [36][45]. These weak acids are naturally found in fruits and vegetables (except lactic acid, which is a mild acid produced during the fermentation of dairy goods and vegetables) and are widely used to prevent spoilage and reduce browning while enhancing the flavor and aroma of berry fruits [45]. The application of organic compounds in berry preservation enhances the natural taste of berries and promotes color retention by preventing enzymatic browning, which occurs due to the oxidation of polyphenols in berries. Hence, the use of organic acids in berries could make them more appealing to consumers [4][45]. However, few studies were focused on the study effect of organic acids on berries; therefore, further research is needed to evaluate the safety and effectiveness of these chemical compounds on a larger scale and in different contexts.

3.2. Bioactive Compounds

Bioactive compounds such as essential oils (EOs) and plant extracts were extensively studied due to their outstanding properties, including their antimicrobial, antioxidant, and nutritional properties [46]. Those advantageous characteristics are usefully employed in the development of novel protective coatings for perishable food products. In this manner, different bioactive compounds were extracted for their evaluation and further application, to describe the effect of their composition, concentration, and extraction techniques, among many other influential parameters.

3.3. Physical Methods

Physical methods play a key role in preserving the quality and safety of berries by reducing microbial contamination, preventing physical damage, and controlling ripening. These methods involve controlled atmosphere packaging, cooling, hot water treatment, or the use of edible coatings [1]. The use of physical methods in berry preservation can have several benefits, including (i) improving food safety by reducing microbial contamination and preventing the growth of pathogenic bacteria that can cause foodborne illness; (ii) extending shelf life by slowing down the ripening process, reducing physical damage, and preventing decay; (iii) improving nutritional and sensory quality by reducing oxidation, preserving texture, and maintaining color and flavor; and (iv) reducing the use of chemical preservatives that can be harmful to human health and the environment (**Table 1**) [1][36].

3.4. Biocontrol Agents (BCAs)

Biocontrol is an innovative alternative that has been widely used in recent years, consisting of the use of bacteria, yeasts, endophytic fungi, or their products to prevent, reduce, or eliminate the development of pathogenic and spoilage microorganisms, their applications being possible via coatings or sprays [6]. BCAs inhibit the growth of other organism competition for space and nutrients, biofilm development, and the production of secondary metabolites, such as volatile organic compounds (VOCs), lytic enzymes, peptides, antibiotics, and the activation of plant defenses [6][47]. The first action mechanism used for BCAs such as bacteria and yeast is competition for nutrients and space, which have a time generation ranging from 0.3 to 2 h for being able to use the carbon sources efficiently for their survival and multiplication, limiting the availability of essential nutrients for the growth of phytopathogenic fungi [48][49]. The production of antimicrobial compounds such as active peptides, antibiotics, hydrolytic enzymes, and VOCs is the second most important mechanism used by BCAs [6][49]. The production, assessment, and alternatives to apply VOCs are being widely studied; however, most of the studies do not report the application of these compounds on fruits, even when it is reported that VOCs such as 2,4-di-*tert*-butylphenol produced by *Bacillus siamensis* G-3 remain in ~10% of the diseases caused by *B. cinerea* and *R. stolonifer* in raspberries stored at 0 °C for 20 days [50]. However, it is well known that the presence of multiple action mechanisms in BCAs improves the probability of reaching a higher control of spoilage microorganisms; for this, biocontrol is considered to be a dynamic process affected by the interaction of antagonist–pathogen–fruit [51]. Contributing to the effectiveness of BCAs tends to be lower in vivo than in vitro conditions; however, most of the studies are focused only on the in vitro assessment without the performance of the in vivo test. In line with this, *Bacillus subtilis*, *Bacillus licheniformis*, and *Leifsonia aquatica* inhibit up to 40% of the soft rot caused by *R. stolonifer* in blackberries. This was possible due to the convergence of several action mechanisms present in the tested bacteria. *Bacillus* species synthesize surfactants such as surfactin, initurin A, and amicoumacin, and additionally, both genera produce siderophores, VOCs, and enzymes [49]. Although the activity of BCAs can vary depending on the environmental conditions, biocontrol is a beneficial alternative to increase the shelf life of berries because it is effective in the short, medium, and long terms and does not harm the environment or the health of people or

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animals [47][49]. Additionally, BCAs could help to maintain the natural defense mechanisms of the berries during the postharvest stage without leaving residues, as occurs with chemical compounds [6][52][53]. It is important to mention that BCAs provide better preservation of fruits when applied in the postharvest stage because of their sensitivity to environmental conditions such as ultraviolet light, water limitation, nutrient limitation, temperature variations, and so on [6]. To improve their stability at the preharvest stage and contribute to the replacement of chemical compounds protecting BCAs, alternatives such as spray drying can be explored.

3.5. Molecular Tools to Improve Berry Preservation

Biotechnological tools encompass a wide range of techniques and technologies that leverage biological systems or living organisms to develop innovative solutions and products based on genetic modification. These tools have applications in various fields, including agriculture and food preservation [54][55]. The ripening and softening of fruits are two key factors in their perishability. In these processes, numerous biochemical process-regulated by well-coordinated genes are involved; regulating the expression of these genes is an opportunity to extend the shelf life of the fruits [56][57]. In line with this, antisense technology is a molecular tool that involves the use of synthetic oligonucleotides that are complementary to a specific mRNA sequence to selectively inhibit or downregulate the expression of a target protein. For example, the inhibition of PL genes for preserving fruit quality using antisense technology was assessed. Transgenic strawberry plants were obtained with an antisense pectate lyase gene under the control of a 35S promoter to control fruit softening. Forty-one transgenic lines were identified, of which six were selected for their transformation with the *pGUSINT* plasmid. The produced fruits with the transformed lines were firmer than non-modified strawberries, owing to the gene expression of the six PL lines being reduced by 30%, and three of them were suppressed in three lines. Hence, the use of antisense technology to reduce the expression of PL genes emerges as a prime candidate for enhancing strawberry softening through biomolecular tools [54]. On the other hand, pectin methylesterase, which catalyzes the pectin de-esterification, is regulated by RNAi-silencing of the *FvPME38* and *FvPME39* genes. As a result, the firmness of the assessed fruits was improved in comparison with the control [55]. Instead, the edition of *FaPG1* gen involved in polygalacturonase synthesis in strawberry plants cultivar Chandler was knockout using the CRISPR/Cas9 system delivered via *Agrobacterium tumefaciens*. Physical analyses showed that seven of the eight lines analyzed produced firmer fruits (33 to 70%) than the control. Additionally, modified fruits showed less transpiration water loss and were less susceptible to the disease caused by *Botrytis cinerea*. Finally, minor changes were observed in color, soluble solids, titratable acidity, or anthocyanin content [56]. The use of molecular biology tools is a promising approach to extend the shelf life and improve the quality properties of fruits. However, their implementation should consider factors such as safety, regulatory compliance, consumer preferences, and environmental impact.

4. Role of Artificial Intelligence (AI) in the Postharvest Protection of Berries

One of the primary applications of AI in berry preservation is in the monitoring of environmental conditions. AI algorithms can be used to analyze data from sensors that measure temperature, humidity, and other factors that affect berry quality. By monitoring these conditions in real time, AI systems can identify any deviations from the ideal conditions and take corrective actions. For example, if the temperature rises above a certain threshold, the AI system could adjust the cooling system to bring the temperature back down [58]. The prediction of berry quality can be achieved with the use of AI by analyzing data on factors such as berry size, color, and sugar content; it is possible to estimate how long the berries will remain fresh and identify any potential quality issues [4]. The use of mathematical models based on image analyses and electronic devices coupled with instrumental equipment provides new opportunities to apply AI in fruits and vegetable preservation. Image-processing algorithms recently were examined for estimating the TSS and pH of strawberries. Multiple linear regression and support vector machine regression (SVM-R) models were developed using RGB, HSV, and HSL color-space channels as input variables.

AI helps distributors make better decisions about transporting berries, reducing waste, and improving profitability. However, one of the primary challenges is the need for high-quality data. AI algorithms rely on large amounts of data to learn and make accurate predictions. Therefore, it is important to ensure that the data collected from sensors and other sources are accurate and representative of the conditions in which the berries are being stored. In addition to this, developing and implementing AI systems can be time-consuming and costly and requires expertise in data science and computer programming. Furthermore, there may be regulatory and ethical considerations associated with the use of AI in food production and preservation [1]. However, AI is the most powerful tool for improving berry preservation by providing more precise and efficient methods for monitoring and controlling environmental conditions.

5. Nanotechnology Applied to Postharvest Protection of Berries

Nanotechnology has great potential in the postharvest protection of berries, which is an area of increasing concern due to substantial losses and deterioration in the quality of fruits during the handling and storage process [2]. Researchers have applied nanotechnology to the postharvest protection of berries in various innovative ways to extend berry shelf life (**Figure 2**). The coatings made or added with nanoparticles from natural sources, such as chitosan or cellulose nanocrystals, provide a protective barrier against moisture loss, gas exchange, and external pathogens, thus, improving the fruit's quality and extending its shelf life [3]. Nanomaterials made of chitosan ethyl cellulose, alginate, poly-ε-caprolactone, polylactic acid, poly-D, L-lactide-co-glycolide, and cellulose acetate phthalate, were used as antimicrobial agents to inhibit the growth of pathogenic microorganisms, including fungi, yeast, bacteria, and viruses, or to develop composite coatings to improve the shelf life of berries [5]. Furthermore, they provide multiple advantages to food coatings, such as the enhancement of mechanical properties and selectivity to gas permeability. Moreover, nanotechnology-based edible coatings have been successfully used for the preservation of berries by the nanoencapsulation of EOs [7].

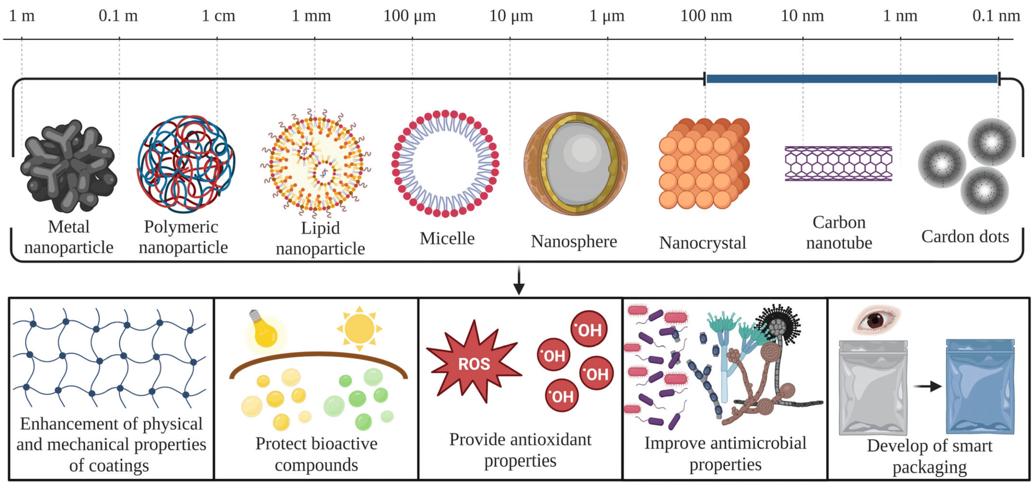

Figure 2. Main nanostructures used for berry preservation and their effect on coatings. The blue line indicates the range of the size of nanostructures.

Nanostructures are usually used with matrices of polysaccharides and proteins and are mainly used to modify the mechanical properties (tensile strength and elasticity), provide thermal stability and improve the permeability barrier towards water vapor and oxygen in food packaging [122]. The use of nanotechnology in the postharvest protection of berries provides a sustainable alternative to conventional methods, essential for meeting the growing demand for high-quality fruits and vegetables, reducing postharvest losses, and improving food security.

6. Current State and Challenges in the Implementation of Sustainable Alternatives at the Industrial Scale for Berry Protection

The rising concerns about synthetic fungicides and other chemical treatments' negative environmental and health impacts have led to an increased interest in developing alternative solutions that are natural-based, such as the use of nanotechnology-based coatings and antioxidant compounds derived from plant extracts. There is a growing awareness of the development of sustainable alternatives at an industrial scale for the postharvest protection of berries that can contribute to improving the quality and quantity of fruit production, reducing postharvest losses and enhancing food security [8]. However, there are also several challenges associated with the implementation of sustainable alternatives for berries protection on a large scale, including cost, safety, compatibility, scaling up, and regulatory policies (**Figure 3**). One of the significant challenges in developing sustainable alternatives is the high cost of production. While the use of synthetic fungicides and other chemical treatments is relatively cheap, some sustainable alternatives, such as nanomaterials, can be expensive, and this may lead to profitability reduction [9]. Moreover, the implementation of sustainable methods requires specific knowledge and skills, thereby limiting their widespread application.

Another concern is the efficacy of sustainable protection methods against the diverse pathogens that berries encounter during harvesting, storage, and transportation. Moreover, improper hygienic and manufacturing practices promote their contamination with pathogenic bacteria such as *E. coli* and *Salmonella*, requiring customized treatment approaches, making it a complex and time-consuming process [6,66]. Large-scale industrial applications require the development of efficient technologies that can detect and respond to these challenges in real-time. This issue is less relevant in using fungicides and disinfectants because, in most cases, they have activity against several microorganisms [9].

Sustainable alternatives must be safe for consumption to protect human health. It is essential to ensure that the use of nanomaterials and other alternative solutions does not pose any risks to human health. In addition to this, the selected technique should be compatible with the fruit's requirements during transportation and storage, such as temperature and humidity [10]. Currently, most of the alternatives reviewed in this paper were tested on a small scale. There is a need to scale up production to meet the demand for a large quantity of fruits. The challenge is to translate the laboratory concept of a sustainable alternative for the industrial scale. Finally, regulatory issues around the use of natural compounds and nano-based materials in the food industry remain a significant challenge. The implementation of sustainable alternatives at an industrial scale for berry protection is governed by several regulatory frameworks that ensure the use of safe and appropriate substances and technologies. Adherence to these regulations takes time and requires strict compliance, posing a challenge to the widespread adoption of sustainable protection methods.

Despite these points, an increase in research interest has led to the development of several sustainable alternative approaches to the postharvest protection of berries, including the use of nanotechnology-based coatings and natural-based solutions. The scientists' efforts are mainly focused on developing novel technologies and techniques in laboratory-based experiments. The gap between the research and industrial sectors should be reduced and aimed to promote a quick advance in the scale-up of the use of these technologies for berry preservation. Green alternatives for the postharvest protection of berries at an industrial scale are crucial for addressing food security challenges by preserving fruit quality and reducing postharvest losses, which are significant contributors to food waste.

Figure 3. The main challenge for the implementation of sustainable alternatives for the postharvest protection of berries.

7. Conclusions

Berry preservation is crucial for extending its shelf life and maintaining its quality. Traditional methods of preserving berries often involve the use of chemicals and other harmful techniques, which can have negative impacts on the environment and human health. However, several sustainable and eco-friendly postharvest protection strategies can be employed to preserve berries. These alternatives include the application of physical treatments, such as cold storage, modified environment packaging, natural coatings, and so on, as well as the use of natural substances, such as organic acids and essential oils. Additionally, advancements in nanotechnology have led to the development of nanocomposite coatings that can effectively protect berries from spoilage and extend their shelf life. Regarding this, the use of CDs is a promising alternative to developing smart coatings and packaging to enhance the shelf life of berries through agro-waste valorization. These strategies offer promising alternatives to traditional methods and can contribute to a more sustainable and environmentally friendly approach to berry preservation regarding the quality and safety of berries while minimizing our impact on the environment. The combination of two or more treatments can provide better results. However, it is important to consider that these technologies' effectiveness strongly depends on the conditions used during the treatment (temperature, concentration, exposure time, etc.). Otherwise, the use of tools based on molecular biology is a promising alternative, of which the main concern is the resistance of the population to consume genetically engineered foods. Further research should be addressed to have a comprehensive understanding of the interaction of these factors and their effect on the microbiological, physicochemical, and sensorial properties of berries. Meanwhile, the joint work of scientists, industry, and government is the most reliable way to overcome the challenge that implies the implementation of sustainable alternatives for berry preservation. Investing in sustainable postharvest preservation practices can provide a variety of long-term benefits beyond immediate protection. These benefits have far-reaching implications for the environment, the economy, food security, and the overall sustainability of the agricultural systems.