# *Prunus* spp. Fruit Quality and Postharvest: Today's Challenges and Future Perspectives

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# Abstract

Prunus is a genus of trees and shrubs that date to the Eocene. Some species are known for their health benefits and for their exceptional role in international trade. Several Prunus species are widely cultivated all over the world, such as sweet cherry (Prunus avium L.), sour cherry (Prunus cerasus L.), plums (Prunus salicina L.), prunes (Prunus domestica L.), peaches (Prunus persica L.) or almonds (Prunus amygdalus, syn. Prunus dulcis). In this work, we review the most important quality parameters and sensory attributes for the abovementioned main Prunus species. Moreover, we focus on the postharvest challenges that are posed today to producers and retailers, as well as on consumer preferences. Finally, we discuss some new commercialization perspectives considering that the final aim agronomic activity is to produce fruits of good nutritional and sensory quality, with the least environmental impact possible and in a sustainable manner, according to the Sustainable Development Goals (SDGs) of 2030 Agenda of the United Nations.

## Keywords

- stone fruits
- quality
- shelf-life
- consumers
- trade

## Author Information

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# 1. Introduction

Peaches (*Prunus persica* L.), Japanese plums (*Prunus salicina* Lindl), prunes (*Prunus domestica* L.), apricots (*Prunus armeniaca* L.), sweet (*Prunus avium* L.) and sour (*Prunus cerasus* L.) cherry fruits, and even some well-known varieties such as flat peach (*Prunus persica* var. platycarpa, also called var. compressa) and nectarines (*Prunus persica* var. nucipersica or var. nectarina Batsch), are fleshy fruits from the *Prunus* genus, whose culture is widespread, and these fruits are broadly consumed and appreciated all over the world. Within this genus, almonds (*Prunus amygdalus* Batsch) are an exception because they are a dry fruit, whose production and consumption have great expression.

Drupes can be of two types, namely dry or fleshy and succulent fruits. Drupes or stone fruits usually have one seed per carpel [1]. Fleshy or succulent fruits have a fleshy and thick pericarp, with three layers, an exterior protective epicarp, a fleshy and edible mesocarp and woody inner stony endocarp, which adhere to the seed [1]. On the other hand, dry fruits have an entire pericarp with enclosed seeds, which is dry stony at full maturity [1].



# 2. Respiratory pattern and maturity

The fruits continue metabolic processes such as respiration, transpiration, ethylene biosynthesis, carbohydrate metabolism, among others, even after being harvested and end up rotting naturally. The detachment from the mother plant speeds up all those processes. In the fruit respiration processes, oxygen is absorbed, and carbon dioxide is released using the accumulated carbohydrates (starch and sugars). The ultimate goal of this reaction is energy production. Respiration is a continuous process that takes place in fruits both in the field and after harvesting [1]. When the fruit is separated from the mother plant, it cannot replace carbohydrates and water. Therefore, respirations stops when the reserves of carbohydrates and water are depleted, followed by fruit senescence.

Considering the physiological behaviour of fruits during ripening, and from the practical point of view, fruits have been classified into two groups: climacteric and non-climacteric [2, 3].

Climacteric fruits are characterised by a marked increase in respiration and ethylene production at the beginning of ripening, while non-climacteric fruits do not exhibit such respiratory behaviour [4, 5]. It has been known for a long time that climacteric fruits have in common the presence of ethylene to regulate maturation in [1]. Moreover, the production of ethylene in climacteric fruits is autocatalytic, and the application of exogenous ethylene is able to ripe climacteric fruits [6]. On the contrary, the absence of ethylene can effectively stop their ripening. Already in 1934, Franklin Kidd [7] explained the climacteric ripening process of fruits and the existence of a climacteric peak.

Therefore, the non-climacteric fruits must be ripe at harvest. Non-climacteric fruits have a quite different ripening behaviour, without a peak of respiration or of ethylene production [5]. The behaviour and key regulators for non-climacteric fruits are poorly understood until today. Abscisic acid (ABA) has been suggested as one of the potential key regulators in ripening process of non-climacteric fruits [5]. In short, climacteric fruits can ripen after harvest, where non-climacteric fruits cannot do that.

This classification, although oversimplified, is very useful for practical reasons. Nevertheless, analyses of ripening and related changes in $CO_2$ and ethylene levels, at different fruit growth and maturation stages, have challenged this basic classification [4].

According to Cambridge dictionary, ripeness is the quality of being ready to be collected or eaten [8]. This is the popular concept that does not reflect the physiological knowledge of fruit ripening.

The knowledge of respiration and ripening pattern of each fruit is determinant to choose optimum harvest date, proper management strategies and storage practices, to achieve good nutritional and sensory quality, as well as decrease loss and waste [1].

Storage strategies involve temperature control, to decrease respiration rates and humidity control, to avoid transpiration, and eventually to control gases such as $CO_2$ and $O_2$ and eliminate ethylene in the atmosphere of the storage chambers [9].

Non-climacteric fruits should be kept away from any ethylene source to avoid the possible adverse effects on their ripening and/or quality, until more detailed information on the role of ethylene in these fruits is available. Moreover, the coexistence of ethylene-dependent and ethylene-independent pathways in climacteric and non-climacteric fruits has been described [4].

The mechanical or physiological damage, during harvest or storage, will cause an increase in respiration and consequently shorten shelf-life. Inappropriate temperatures (high temperatures and freezing) and lack of humidity may also cause physiological damages or disorders and an undesirable boosting of ripening [10].

Finally, it has been clearly demonstrated that many regulators of fruit ripening are common to both climacteric and non-climacteric fruits; namely, low $O_2$ and high $CO_2$ in the fruit microenvironment can delay the increase in ethylene and respiration, and consequently fruit ripening [5].

# 2.1 Ripening of Prunus species

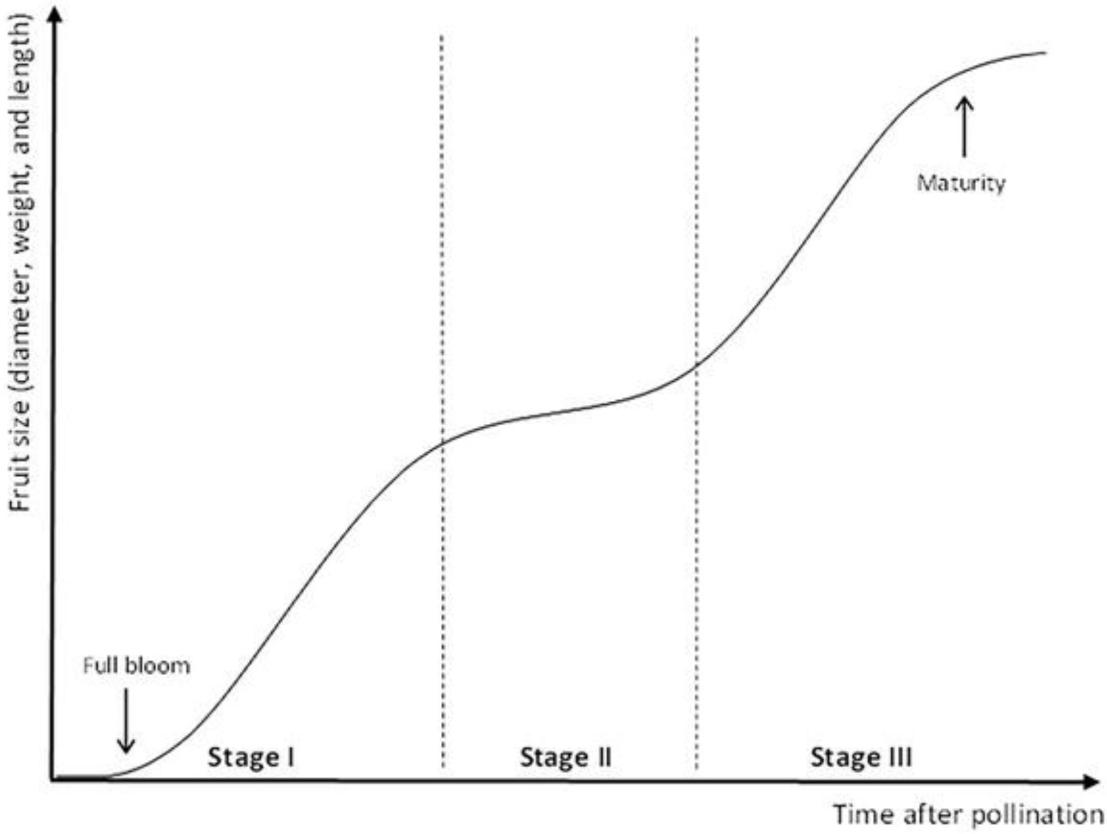
Considering the wide and diversified range of fruits included in the genus *Prunus*, apricot, peach, plum, nectarine and durian are climacteric, whereas sweet and sour cherry are non-climacteric fruits. However, it is far too simplistic [4].

Plums are generally classified as climacteric fruits, but some cultivars vary markedly in there ripening behaviour. Some cultivars are known for their rapid softening, while others remain firm enough for commercial purposes, exhibiting a longer shelf-life. Actually, there are two distinct patterns of ripening, with some cultivars behave typically as climacteric fruits and others showing a suppressed-climacteric behaviour due to their reduced capacity of converting 1-aminocyclopropane-1-carboxylic acid (ACC) to ethylene [11, 12]. El-Sharkawy and colleagues [6, 13, 14, 15] studied cultivars of Japanese plums that show different patterns: 'Early Golden' behaves as a climacteric fruit, and 'Shiro' presents a suppressed climacteric pattern. These differences can be caused by a wide range of factors such as different ethylene receptors [15], in the ACC-synthase genes [13], and in the role of auxins in mediating gene expression for ethylene-responsive transcriptional factors (ERFs) [6, 14].

Peaches are clearly classified as climacteric fruits, so the ripening process is controlled by ethylene. Moreover, an increase in auxins production in the fruits leads to the induce expression of the ACC-synthase [16, 17]. Additionally, Trainotti and co-workers [18] used a genomic approach and reported that there is a cross-talk between auxins and ethylene; that is, auxin genes are regulated by ethylene and vice versa, which confirm the role of auxins in regulating the ripening of peaches was confirmed.

# 2.2 Development, ripening and quality of Prunus spp.

Since the work of Chalmers et al. [19], it is assumed that a double sigmoid curve characterises the development and growth of some fruits, such as *Prunus* drupes (Figure 1).




# Figure 1.

Generalisation of the double-sigmoid growth curve typical of fruits of the genus Prunus.

Stage I is an initial exponential phase, from the fecundation of ovary throughout the morphological changes that occur until the formation of the fruit. During the first half of stage I, an increase in the number of cells is observed, while in the last part of that stage there is an increase in cell size. In cherries, the cuticle reaches its full thickness. Stage II corresponds to a plateau, characterised by no cell division and by a slight tangential elongation of cells, cell wall thickening and endocarp lignification. Stage III corresponds to the second exponential growth phase, when cells start to enlarge to the final fruit size, and it ends with the complete and mature fruit. Finally, stage IV corresponds to the physiological ripening of drupes, so that fruits achieve a high nutritional and organoleptic value, and are appropriate for human consumption, reflected in their economic valorisation.

During ripening, the morphological and physiological changes occur at different levels, the more evident being changes in colour, texture and biochemical composition [20]. Colour changes due to the degradation of chlorophylls, reflected in the loss of green colour, and the increase in anthocyanins and carotenoids, non-photosynthetic pigments, which confer a reddish and/or orange pigmentation to the fruits [21]. The decrease in fruit firmness that occurs throughout the ripening is a very complex process, which involves the breakdown of complex carbohydrates into sugars, and the activity of cell wall-modifying enzymes, causing reduction in intercellular adhesion, depolymerization and solubilisation of pectins, depolymerization of hemicelluloses, and loss of pectic galactose side chains [20]. All the aforementioned factors are responsible for the loss of firmness and the consequent increase in succulence of ripe fruits [22, 23, 24]. Changes in taste are very important for consumers' acceptance, and generally correspond to an increase in perceived sweetness, caused by a decrease in acidity and increase in sugar content. Moreover, in many fruits, the aroma becomes exquisite due to the release of volatile compounds, very appealing to the consumer. Carbohydrates, amino acids and fatty acids are the major fruit flavour precursors. The biosynthesis of volatile compounds is related to metabolic changes that occur during fruit ripening and have different profiles in the different ripening stages, and in different cultivars. Mihaylova and colleagues [25] studied the volatile compounds of eight peach varieties (*Prunus persica* L.) and identified 65 volatile compounds (aldehydes, esters and fatty acids), in different relative quantities depending on the variety.

The adequate ripening refers to fruits that present the best sensory and nutritional characteristics for consumers, and simultaneously allow the proper harvest management, storage and transport minimising loss and waste.

This concept of ripening, and consequently quality, although seemingly simple is, in fact, very complex and variable, depending among others, on consumer profile, agronomical practices, and the available facilities, and obviously on the fruit species.

The health-promoting properties of stone fruits also contribute to their quality and are due to the presence of vitamins, namely A, C, E, and folates, dietary fibres, and phenolic compounds, mostly flavonoids [26]. Phenolics display antimicrobial properties that are important in the preservation of fresh fruits [26]. Moreover, flavonoids may protect against chronic diseases and play a preventive role in neurological disorders [27, 28].

All fleshy fruits of the genus *Prunus* share their short shelf-life. The use of cold storage is undoubtedly mandatory. There are many variations of cold storage and many methods that can be applied to maintain quality and increase shelf-life in a sustainable way. It should be remembered that fruits are complex and dynamic biological systems, whose thermophysical properties vary with numerous factors, such as temperature, moisture content, species and even cultivar. These data are essential for the study and optimization of postharvest handling processes, such as pre-cooling and cold storage, predicting practical situations, namely cooling rate, cooling time, cooling uniformity and cooling energy utilisation, and allowing the monitoring of temperature-induced changes in fruit quality [28].



# 3. Some facts about the international trade of stone fruits

According to a recent report published by the United States Department of Agriculture (USDA), the production of peach and nectarine in 2022/23 will increase by 1 million tonnes, reaching 23.7 million tonnes [29]. This forecast is justified by the expected increase in production in China, the European Union and Turkey, which are the largest producers in the world.

China's peach production is expected to rise to 16.8 million due to higher yields despite area declines, because growers are switching to currently more profitable crops, such as cherries.

Russia lifted restrictions in February 2022, so exports are expected to increase. Remarkable is the investment of the China government in new smart farm tools, namely online selling. However, the political instability that is being witnessed at the moment, due to the invasion of Ukraine, leads to fears of some unexpected embargoes with unpredictable consequences on the international market. EU production is expected to improve to 3.1 million tonnes, with a significant recovery in French and Greek production. However, Spain has suffered a cold spring this year, reducing production, and this will have a negative effect. As most EU exports come from Spain, EU shipments are also expected to decrease.

Turkey is the world's third largest producer of peaches and nectarines. The investment of government programs in these commodities is remarkable. Turkey's production is expected to reach a record 940,000 tonnes, with nectarine supply increasing steadily. Exports decreased slightly due to the reduction of shipments to Russia.

According to the 2021 statistical data of the Food and Agriculture Organisation of the United Nations (FAO) [30], the world production of peaches and nectarines was of 1504682.00 ha of harvested area, with a yield of 166110.00 hg $ha^{-1}$, corresponding to 24994352.05 tonnes, whereas the harvested area for the European Union is 194050.00 ha, with a yield of 157908.00 hg $ha^{-1}$, corresponding to 3064200.00 tonnes.

Plums are one of the most important commodities in *Prunus* genus, occupying the second place and evidencing rapid worldwide growth in popularity [31]. According to FAO, the world's plum production reached 12 million tons in 2021, and the leading producer being China (5 million tons per year), followed by Romania and USA [30].

Sweet cherry (*Prunus avium* L.) is a highly valued fruit, with a large international market. In 2021, the top exporters of fresh cherries were Chile, Hong Kong, USA, Turkey and Spain [30].

Almonds are in high demand around the world and their long shelf-life makes them easy to store and transport. Increasingly health-conscious consumers are driving the rise in demand for almonds. According to the FAO 2021 statistical data, there is an harvested area of 2,283,414 ha for almonds that correspond to a yield of 17,491 hg $ha^{-1}$ [30]. The top three producer are the United States, Spain and Australia [30]. The United States is undoubtedly largest producer and marketer of almonds, with a current production figure of 2 M million tonnes that remain stable since 2019 [32]. For the first time in more than a quarter century in California almond area has declined in 2022, due to a faster rhythm of orchard removals than new planting grow, with a drop of 1.2% relative to 2021. There appears to be a declining trend in the area under almond cultivation in California [32]. A 10% decrease is expected for the 2022/2023 season, around 1.5 million tonnes, without the shell. Even so, the USA is by far the largest producer with 79% of the world production, followed far behind by Australia, with 7% and Spain with 4% of the world production. Iran, Morocco, Syria and Turkey are traditional producers of almond. The large increase of areas cultivated with almonds in Turkey and Portugal is remarkable. The consumption is increasing all over the world, with a special reference to the new Asian markets.



# 4. Quality and postharvest of selected stone fruits

## 4.1 Peaches (*Prunus persica* L.)

Peaches or *Prunus persica* L. are stone fruits rich in ascorbic acid (vitamin C), carotenoids (provitamin A), minerals, fibre and antioxidant compounds, namely phenolics [33].

Distinct peach varieties were developed and are cultivated in different countries to meet different demands, namely higher yield, disease resistance and higher postharvest quality, among others [34]. This is possible, because of the high metabolic diversity of peaches, which is responsible for the variability in fruit size, texture, flavour, sweetness/acidity ratios and/or skin and flesh colour [33].

Begheldo and co-workers [35] have classified peach cultivars into three different categories according to their fruit texture and firmness, namely: (1) melting flesh, showing soft and juicy fruit when fully ripe; (2) non-melting flesh; and (3) stony hard fruits, which remain firm after harvest.

Peach is a climacteric fruit, meaning that it can ripen fully upon harvest, its ripening being regulated by the production of ethylene. This influences the postharvest strategy of peaches, which must combine maturity with storage conditions [36].

The following ripening parameters are usually considered in peaches: firmness (measured in Newton, as the maximum force needed to penetrate the fruit), skin colour, soluble solids content (SSC), (measured in °Brix), titratable acidity (TA) (measured in %) and the ratio SSC/TA, which is sometimes used as a maturity index [36, 37]. The criteria used for quality evaluation of peaches take into account the satisfaction of consumers. Therefore, the postharvest quality criteria include appearance, firmness and flavour, as well as safety and nutritional value.

Additionally, phenolic compounds can be used to evaluate the postharvest quality of peaches, due to different reasons [26]: (a) they are the main source of antioxidants in peaches [38]; (b) they contribute to the browning of peaches [39]; and (3) they contribute to taste and may be responsible for astringency in peaches [40].

Peaches, as other stone fruits, have a short shelf-life, and thus, both consumers and producers have long been interested in identifying effective measures that can extend peach storage life [41].

Ripening at harvest, storage temperature and postharvest treatment are factors that influence postharvest quality of peaches and their attractiveness to consumers [36].

Cold storage is the most common method employed to delay ripening and increase the postharvest life of peaches [42]. Peaches are ideally kept at around 0°C, but a range of −1 to 1°C is acceptable for up to 2 to 3 weeks [37, 43]. However, prolonged storage at low temperatures may change the ripening processes and result in lack of juice and woolly texture [42].

Chilling injury is a physiological disorder caused by prolonged exposure to the low storage temperatures, triggered at room temperature [43]. It may reduce the ethylene release, and lead to abnormal ripening, causing changes in aroma volatiles (flavour loss), colour changes (flesh browning and flesh bleeding), and changes in texture, namely flesh mealiness, and leatheriness [44].

A recent study evaluated the transcriptomic profile of peaches upon postharvest cold storage [37]. Expression levels of ethylene related genes are correlated with genes involved in cell wall modification, membrane composition, pathogen and stress response, which are all involved in the development of chilling injury [37]. Moreover, early transcriptomic responses to chilling are detectable well before the onset of chilling injury symptoms. Genes that are activated early upon cold storage may provide markers for detecting chilling injury before it can be perceived visually [37].

Several innovative techniques are used to improve the quality of peaches for a long period of time, namely controlled atmosphere storage, modified atmosphere packaging, heat treatment, and use of nanocomposite packaging material and edible coatings [45, 46, 47, 48, 49].

It should also be noted that peaches are very susceptible to phytopathogenic fungi, such as *Monilinia laxa*, *Monilinia fructicola* and *Rhizopus stolonifer* [50]. These moulds are the main cause of high postharvest losses in fully mature and ripe peaches [50].

# 4.2 Plums (Prunus domestica L. and *P. salicina* Lindl.)

There are thousands of plums cultivars, and the most commercially important species of plums are generally classified into two groups: European (*Prunus domestica* L.) and Japanese (*Prunus salicina* Lindl.) plums [1, 45]. Plums can be cultivated in a wide range of climatic conditions if cold-hour requirements are suppressed. The Japanese plum has cold-hour requirements in the range of 550 to 800 h, while the requirements in the European plum are higher than 800 h [45].

Plums present an huge diversity of flavour, aroma, texture, colour, form and size [46]. Producers should be encouraged to harvest the fruit at the partial to full ripe stage because the consumers appreciate attributes such as colour, flavour and aroma [47].

The plums maturation leads to an increase in weight, soluble solids content (SSC), sugars and anthocyanins, as well as a decrease in firmness and a darkening of colour. Establishing the ideal ripeness stage at harvest is of extreme importance as it ensures good fruit quality, for both purposes of consumption, fresh or processed. Considering the high variability among plum cultivars, it is necessary to define maturity parameters for each cultivar [47].

The assessment of the correct stage and time-to-harvest plums is based on physical and chemical, methods, physiological evaluation or combinations of them, which allows monitoring the maturation advance by producers [47]. The most common maturation parameters used in plums are fruit exterior colour, pulp firmness, SSC, titratable acidity (TA) and the ratio between the last two [1, 47, 48].

Skin colour is one of the criteria commonly used to determine the ripeness of the plum; however, it should not be used exclusively, as many cultivars develop a misleading pigmentation, while the fruit is still developing [47]. Regarding firmness, an important quality parameter closely related to fruit ripeness is frequently a good indicator of shelf-life potential [47].

Fruit softening is a natural occurrence during storage and radically compromises the market potential, with large volumes of these fruits often being rejected from the market because the firmness values are below acceptable retail standards [47, 49].

In the last years, several works have been developed in plums, employing NIR technology for the rapid evaluation of quality parameters, among them the detection of *Monilia*contamination and prediction of quality parameters (SSC, TA, ratio SSC/TA and firmness) [50, 51].

Plums' quality is rapidly lost after harvest. The high respiratory rates that occur during the transport and marketing process are the main reason why plums do not reach the consumer with the required characteristics [52].

The ideal storage conditions for plums are 0 to 5°C of temperature and 90–95% of relative humidity [53, 54]. However, plums are very sensitive to low temperatures, which cause severe chilling injury, internal browning, translucence of the flesh, loss of flavour and bleeding after being subjected to room temperature [49, 54]. Several research studies have been conducted to improve the postharvest shelf-life. Technologies such as modified atmosphere packaging (MAP), fumigation with ethylene antagonists such as 1-MCP and salicylic acid treatment have been tested in plums [49]. Applications related to prediction and monitoring of temperature induced fruit quality changes. According to Martínez-Romero and colleagues [55], forced air could be a good solution to prevent mechanical damage in plums, and extend shelf-life, specifically if pre-cooling plums immediately after harvest and before moving on to usual handling processes. More recently, new methodologies have emerged. The application of edible coatings of natural origin, such as proteins and polysaccharides, or the use of biodegradable materials, such as starch, has proven to be effective in improving the plum postharvest characteristics [49, 52, 56, 57]. These coating materials are safe and without implications for human health or negative influence on the environment, allowing the preservation of fruit with good quality characteristics for a longer storage period, reduce food waste and offer consumers high-quality plums with a longer shelf-life.

Japanese plums cultivars are used for fresh consumption because they have lower SSC values than European plums [45]. In contrast, most cultivars of European plums are typically used for drying due to high soluble solid content and are usually classified in four groups: Prunes, Reine Claude, Yellow Egg and Lombard with the most commercially important group being Prunes. According to Bahrin et al. [31], 'All prunes are plums, but not all plums are prunes'. The term 'prunes' is commonly used when the plum is dried without removing the stone, while if the stone is removed before product drying is called dried plum [31]. The term 'plums' include every variety and can be considered for fresh consumption, but also for canning, freezing and making jams and jellies [1].

Japanese plums are available on the market in the summer and autumn months, while the European plums are usually processed into dried fruit and can be consumed throughout the year [58].

Plums have a high nutritive value, being rich in vitamins A, B1, riboflavin and are a good source in diet of sugars, proteins, carbohydrates and minerals, such as calcium, phosphorus and iron. It has multiple benefits for human health, presenting anti-inflammatory, antioxidant properties, and may be related to the control of jaundice and can reduce the risk of cardiovascular diseases or cancer [31, 58, 59].

# 4.3 Sweet cherries (*Prunus avium* L.)

At first glance, consumers look for cherries with a good calibre, attached green stems, shiny, with unblemished skin, and a typical colour [60]. The cherry colour depends on the chosen cultivar: from dark red to mahogany for dark-sweet cherries and in opposition some cherry cultivar should have a yellow background with a slight to full red blush [60]. The firmness is another important quality attribute for cherries. It is desirable that fruits are firm to the touch. At last, when eating cherries consumers valorise flavour, sugar acidity rate and firm flesh with smooth skin. Zoffoli [61] resumed the quality of sweet cherry by referring large fruit size, bright colour, fruit skin without signs of pitting and cracking, firm texture, and high total soluble solids.

The market requires fruits resistant to cracking and diseases, and with an extended ripening season that allows cherries to be available to the consumer for a long period of time. As a particular case of cherry commercialised without stalk, there are 'Picotas', which present lower labour costs in harvesting, less loss of appearance, namely due to dehydration and blackening of the stalk, and less aggression on adjacent fruits, avoiding perforation damage. These varieties of cherry are native to the Valley of Jerte, in northern Extremadura, in Spain where they are highly praised by consumers since the XVII century.

Cherry is a non-climacteric fruit, so it is necessary to harvest the fruit as nearly ripe as possible, because they will not ripe after harvest. Harvest operation generally is spread over 2 weeks and is manually made. After harvest, cherries present a moderate-to-high respiratory activity, and some physical changes occur due to transpiration [62]. Empirically cherries were always harvested according to their external colour. That's why there are so many quality standards for cherry colour, which can vary from light red to black depending on the ripeness stage and variety. But the texture is also considered to define fruit quality and determine storability, taking into account that mechanical resistance of the skin decreases with ripening. A high soluble solid content with minimum softening are the capital conditions used to define perfect time for harvest, considering fruit storage life, fruit quality and acceptability when reaching consumers final fruit value [61].

The respiratory rate is determinant to the longevity of cherry and depends mainly on genetic factors, such as cultivar. Alique et al. [63] evaluated the respiratory rate of 'Ambrunes' and 'Burlat' and found values of 20 to 25 mg $CO_2$ $kg^{-1}$ $h^{-1}$ and 45 to 50 mg $CO_2kg^{-1}$ $h^{-1}$, respectively.

Toivonen and Hampson [64] found that at 0°C there were no differences in the postharvest respiration rate among cultivars, but at higher temperature the cultivars presented different behaviour.

While respiration and transpiration cause loss of quality, the enzymatic changes cause the firmness reducing and so increase the possibility of the invasion of fungus and bacterial diseases. But unfortunately, it is known that more mature fruit is more susceptible to these fungal and bacterial rots.

Generally, sweet cherry presents a short shelf-life, due to severe weight loss, browning, and drying of stems, changes in external colour, pitting, and also softening, with dramatic consequences for stakeholders and consumers. To extend the storage period, the main factor is low temperature, which in cherry should be around 0°C, reducing the physiological activity of the fruit tissues and the growth of microorganisms [65]. The high relative humidity avoids weight loss due to reduced transpiration and maintain turgidity [66]. A period of 15 days is generally considered as the best time to store cherries [67], which limits the commercial aspects and encourages the search for different storage methodologies that can increase this period of time. However, recent technologies used during postharvest period may optimise fruit quality for 45 days at 0°C.

Zoffoli [61] recommend the use of Near Freezing Temperatures (NFT) to store sweet cherries with the goal of maximise storage time. This researcher states that comparing with storage at 0°C, senescence was slowed by reducing the rate of respiration, softening and malondialdehyde accumulation, and so the rate of decay was decreased. Considering that there are a relationship between soluble solids and the freezing temperature, for example cherries with SSC around 22.5% present the freezing temperature at −2.5°C, and those with values of SSC near 16.7% have the freezing point at −1.8°C [68, 69]. For harvesting and handling, the recommended temperature is between 10 and 20°C. A rapid decrease of temperature during the operations is important to slow down fruit respiration rate and stem dehydration and maintain fruit firmness that minimises impact damages [70].

González-Gómez and co-workers [71] tested different postharvest storage conditions in order to find the most appropriate to preserve the overall quality of 'Sweetheart' cherries, harvested in the south of Portugal and Spain. Modified atmosphere (MAP) at 1°C, 95% RH using micro-perforated bags of polypropylene (PPlus® Sidlaw Packaging, Bristol, UK) bags, allows the most appropriate conditions to maintain and the amount of the predominant bioactive compounds such as phenolic compounds doubled their concentration comparing with the amount after harvest.

Nowadays, the use of plastic obtained for petroleum is recognised as an enormous and urgent environmental problem. Therefore, the search for friendly materials for packaging fruits is an update issue. Koutsimanis et al. [72] tested a biomaterial, polylactic acid (PLA) and clamshell containers with a microperforated film, with cherries at 1°C. They found that cherries store in those biodegradable packages, when compared with control with perforated bag, increase their storability up to 27 days, and exhibit less weight loss and higher acceptability.

The use of edible coating is another possible approach to increase shelf-life of fruits mainly cherries. Several studies using Aloe Vera gel to enhance the quality and the shelf-life of cherries demonstrated promising results in reducing respiration rate and decreasing weight loss of coated fruits [73, 74, 75].

To take profit of the microbial effect of some natural composts is another line of study to enhance better shelf-life. Afonso et al. [76] found that the use of extracts of *Satureja montana* L. and *Thymus vulgaris* L. could preserve sweet cherry physical and chemical characteristics during 14 days of postharvest storage at 2 ± 1°C and 95% relative humidity in the darkness. Before this, Maghenzani et al. [77] demonstrated that the vapour phase of those essential oils have the ability of controlling some postharvest pathogens.

Tragacanth gum and Eremurus extract were used to made edible coating treatments and being used in cherry 'Takdaneh Mashhad'. The trial was conducted until the 45th days of storage and it was found that the quality was improved allowing larger marketability. One of the treatments (12.5 g $L^{-1}$of tragacanth and eremurus) shows the ability of maintaining fruit firmness and less colour change, and SSC increase and maintain acidity, and simultaneously decrease weight loss [78].

The advances observed in last times in the technologies to avoid decay an enlarge shelf-life are important do reduce waste, and to benefit all, from producers to consumers, and improve a better environmental situation.

## 4.4 Almonds (*Prunus dulcis* (mill.) D. A. Webb), *Prunus amygdalus* batch, or *Amygdalus communis* L.

Almond trees require a warm climate, such as the one in the Mediterranean region, but also large quantities of water. Water scarcity, a major environmental problem nowadays, could be a limitation for the new intensive almond orchards. Another big environmental problem is the amount of residues produced during the process of peeling almonds [79].

Increasingly health-conscious consumers are driving the rise in demand for almonds [80]. The long shelf-life of the almond itself, with or without shell, along with the various processed products, such as smooth drinks, snacks and toasted almonds, makes its trade reach very important values. Almonds are in high demand around the world and their long shelf-life makes them easy to store and transport.

The almond (*Amygdalus communis* L.) is a drupe, composed by the exocarp, commonly called skin, an outer layer covering its thick, leathery and grey-green coloured mesocarp, called the hull [80]. In the interior of the hull is the endocarp, hoody and reticulated, whose hard shell is called pyrena. Finally, the shell contains the edible part, and the seed, usually called nut. The ripening process can be identified by the natural separation of the hull from the shell when fruits can fall from the tree due to the formation of an abscission layer between the stem and the fruit.

The specific quality parameters for dry fruits, almonds included, are size, colour, texture, flavour (be attentive to the development of stiffness and rancidity), moisture content, and incidence of damaging fungi and insects.

To reach good levels of quality, some storage factors should be considered: controlled moisture content, relative humidity and temperature, oxygen concentration and insect control [81].

The control of water content is essential for the proper storage of dry fruits. For the storage of almonds, the moisture content at harvest based on fresh weight is usually between 5 and 15%. The drying methods used to decrease the value of water activity are sun drying, ambient air drying, two stage drying (first heated-air drying to about 12% moisture and second ambient-air drying to 5–6% moisture), and heated-air drying.

Storage occurs usually at temperatures between 0 and 10°C and low RH, depending on the humidity of the almond, which has normally a low water content. Various potential damages can occur during storage. Loss of quality can be due to darkening of nuts and absorption of off flavours. Wu et al. [82] reported moisture changes during storage, and Kazantzis et al. [83] described that the moisture loss on almonds during 6 months of storage at 20 and 5°C was responsible for their weight loss. The same researchers also reported that storage temperature and relative humidity are determinant for moisture changes during storage [83]. Weight loss was higher at 20°C and 60% RH than at 5 and 80%. Wu et al. [82] affirm that shelled almonds can be stored with good quality at 0°C for 1 year, or at higher temperatures (17.8°C) with a relative humidity between 60 and 75%.

Pleasance et al. [84] found that almonds stored in polypropylene bags had and extended shelf-life, and García-Pascual et al. [81] also showed that the use of plastic bags during storage limits moisture changes. Wu et al. [82] tested roasted and raw almonds for 2 years and observed stabilisation of the measured values (moisture content, firmness and sensory characteristics) with the use of PE film packaging and RH above 50% and temperature above 25°C.

One major problem is rancidification. The controlled atmosphere with $O_2$ concentrations below 1% delays rancidification and other deterioration symptoms. Hard-shelled varieties are less susceptible to rancidity than soft-shelled varieties [81].

Raise et al. [85] studied the effect of modified atmosphere packaging under vacuum and $CO_2$ and found that those conditions can allow a shelf-life of at least 10 months for the tested almond kernels, regardless of storage temperature and physical shape of the almonds. To study the oxidation progress, peroxide value (PV) and conjugated trienes (K268) were measured, and sensory evaluation was also performed considering odour and flavour.

Empirical observation has shown that nuts in shell are easier to storage than shelled nuts because shell acts as a protective layer and shelled almonds can absorb odours during storage period. Moreover, according to some producers, whole kernels and halves are easier to storage than broken pieces (F. Galvão, personal communication).

Despite their long shelf-life as a dry fruit, it is important to systematise the available information on the storage of almonds, since there is only limited accessible literature on the topic.



# 5. Mycotoxins in Prunus fruits: a serious health risk

Fungi are the microorganisms that cause the greatest postharvest losses in *Prunus* spp. *Penicillium*, *Botrytis*, *Rhizopus*, *Mucor*, *Alternaria*, *Cladosporium* and *Monilia* are among the most hazardous genera. Additionally, some undesirable bacteria, such as *Erwinia* and *Pseudomonas*, are also responsible for postharvest losses in stone fruits.

Another noteworthy problem is the presence of mycotoxins. Mycotoxins are secondary metabolites produced by filamentous fungi, mainly *Aspergillus*, *Fusarium*, *Penicillium* and *Alternaria* gender [86, 87, 88], and may be present in a large number of substrates, such as nuts, cereals, vegetables, fruits, milk and oilseeds [89, 90].

According to Liu et al. [91], approximately 500 mycotoxins have been identified, and among these, aflatoxins, ochratoxins, fumonisins, patulin, trichothecenes and zearalenone are the more frequent in agricultural goods and those with more adverse health effects on humans [92, 93, 94]. Excluding trichothecenes, all abovementioned mycotoxins are carcinogenic [89]. Other adverse health effects of mycotoxin include their teratogenicity, liver and kidney toxicity, neural-tube defects, genotoxicity, immunotoxicity, immunosuppression and cytotoxicity [95, 96, 97, 98, 99, 100, 101]. These effects depend on the extent of exposure, amount ingested and sensitivity of the consumer [96]. Nazhand et al. [102] reported that around the world, 4.8 billion people are exposed to mycotoxins at levels that significantly increase morbidity and mortality. Ingestion, inhalation and cutaneous contact can all lead to mycotoxin exposure [89].

Some technics, most of them using thermal mechanisms, have been developed to reduce mycotoxins from food [87]; however, in general, mycotoxins are stable including at temperatures of thermal operations (80–121°C). More recently, non-thermal techniques (cold plasma, pulsed light, pulsed electric fields, high pressure processing, electron beam irradiation) have being studied [87, 93, 94, 103, 104, 105, 106, 107, 108].

Among stone fruits, almond has been mostly associated with the presence of mycotoxins [109, 110]. Rodrigues et al. [111] informed about the presence of aflatoxins in almonds, Hidalgo-Ruiz et al. [112] found aflatoxins and zearalenone in almonds, and Ünüsan [113] reported the presence of aflatoxin B1 in almonds. Sadok et al. [110] made reference to the presence of patulin in stone fruits. Suman [87] reported the presence of putalin on olives, and Azaiez et al. [114] the presence of diacetoxyscirpenol in prune samples, while Iqbal et al. [115] showed the presence of ochratoxin A in apricots and plum, and Ünüsan [113] mentioned the presence of patulin in peaches, and the presence of ochratoxins in apricots. Additionally, Vidal et al. [86] mentioned the presence of patulin in apricots, peaches and peach juice, and Sadok et al. [110] reported the presence of patulin in cherries, peaches and plums.

Considering the long-term presence of mycotoxins in foods, also after the elimination of the fungi, an effective control of production, transport and storage conditions is required, as well as the monitorization of the presence of those substances in foods, mainly in fruits and vegetables, which should be both legally enforced and controlled.



# 6. Conclusions

*Prunus* is a huge genus of trees and shrubs that comprises the production of different types of stone fleshy fruits, drupes, such as peaches, plums, cherries, among others, and dry fruits as almonds. Some of these drupes are climacteric, while others are non-climacteric fruits. This knowledge is of vital importance for defining the ideal stage of ripeness for harvesting and to take the best decisions about postharvest storage.

*Prunus* fruits have great relevance in world trade markets. An overall analysis of world production and trade highlights the general increase in *prunus* production, with emphasis on the increase in areas and the upgrading of production techniques for fleshy fruits observed in China and Turkey, while the USA remains a key player in almond production, despite some decline.

The consumers are fond of good quality, which they evaluate looking at fruit size, form, skin and flesh colour, texture, taste, aroma, sweetness, acidity and sometimes easy peeling.

A huge number of new varieties that appear on the market are often very well received by consumers, which justifies the dynamism of this market.

In general, these fleshy fruits present a short shelf-life, and some of them suffer from chilling injury, or other physiological disorders. The emphasis is therefore put on developing new storage technologies that can extend the selling period and increase the distribution distance of the products. The morphological and physiological diversity of fleshy fruits of the *Prunus* genus and the distinct trade requirements have led to the development and implementation of various methods for improving the shelf-life of different species, which cannot be generalised. Ensuring effective storage methods to extend fruit shelf-life, without compromising consumers health and the environment, remains a vital area for future research.



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# Conflict of interest

The authors declare no conflict of interest.

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