

Review on techniques and treatments toward the mitigation of the chilling injury of peaches

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Abstract

The peach is a stone fruit with a very juicy flesh, smooth skin, and a taste that satisfies the most demanding palate. The quality of this fruit is usually determined by texture, appearance, scent, flavor, and nutritional value. Peaches are very sensitive fruits, which deteriorate and ripen very quickly at environment temperature. Cold conservation is the usual method for delaying the product deterioration, but this process may cause chilling injury (CI). This damage is a physiological low temperature-driven disturbance, which affects the fruit quality, reducing its storage and shelf life and impairing its organoleptic characteristics. The characteristics of the main techniques and treatments to mitigate the CI such as: temperature-dependent, controlled and/or modified atmosphere, intermittent warming (IW), ethylene inhibitors, Glycine Betaine (GB), Methyl Jasmonate (MeJA) treatments, exposure to ultraviolet radiation (UV) and genetic determination are reviewed. Its consequences are evaluated and the ideal conservation air temperature and humidity are set to enhance organoleptic characteristics.

Practical applications

This paper provides a review of research studies assessing the CI in peaches. The consequences of this damage are evaluated and the ideal values of conservation air temperature and humidity to enhance the organoleptic characteristics are described. It aims to help producers and retailers to know in advance the quality of peaches stored in refrigeration chambers and decide the price based on this prediction.

1 | INTRODUCTION

The peach [*Prunus persica* (L.) Batsch] is a stone fruit, that although the scientific name *Prunus persica* is originated from Persia, it was first cultivated in China and was introduced in Europe at the beginning of the Roman Era, emerging in the United States of America (USA) during the 19th century. Between 1999 and 2001, the world production of this fruit was, approximately, 13.5 million tons, 40% of which is produced in Asia, 30% in Europe, and 10% in America (Aubert & Milhet, 2007). According to Food and Agriculture Organization [FAO] (2017), there was an increase in the world production of peach and

nectarine with values of approximately 22.8 million tons of which 66.1% were produced in Asia, 19.8% in Europe, and 9.9% in America. China is the world's main producer, representing 57.9% of the production and 51.1% of the area. Table 1 shows the five countries with the highest productivity levels, of which three are European, Spain, Italy, and Greece, followed by the USA.

Portugal is ranked 36th as a world producer, with annual production of approximately 42 thousand tons, distributed over 4.7 thousand hectares (FAO, 2017; Simões, 2016), with large capacity for expansion of peach production not only for good edaphic and climate conditions but, also because of deficitary balance of needs and production.

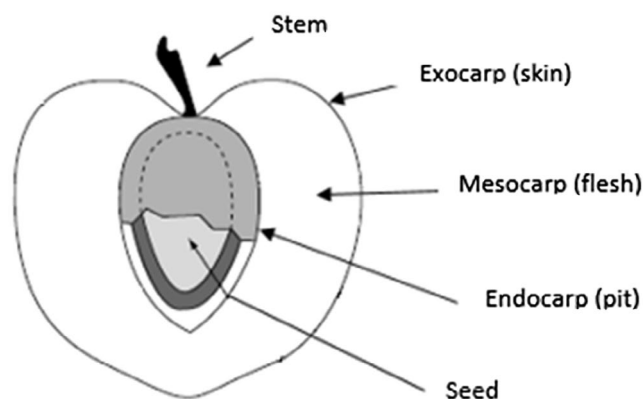
TABLE 1 Main countries producing peach and nectarine in 2019 (FAO, 2017; United States Department of Agriculture, 2019)

Country	Production		Area	
	Tonne (t)	%	Hectare (ha)	%
China	14,294,973	57.9	781,882	51.1
Spain	1,799,685	7.3	84,219	5.5
Italy	1,250,721	5.1	67,021	4.4
Greece	938,000	3.8	41,000	2.7
United States of America	775,189	3.1	45,304	3.0
...				
Portugal	41,646	0.2	4,722	0.3
...				
World	24,691,842	100%	1,530,362	100

The period of production extends from beginning of June to middle of September, but the commercial period can be extended through October if conservation methods allow it. Refrigeration is the most common method used over world to extend shelf life of fruits and vegetables aiming to conserve quality characteristic.

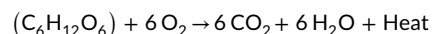
The fruits of the peach tree are also known as drupe, characterized by a thin exocarp, designated skin, a flesh and juicy mesocarp, called a pulp/flesh, and a hard and lignified endocarp, designated a pit, usually containing one or two seeds in its interior, as can be observed in Figure 1. The quality of the fruits is generally determined by its appearance, color, texture, aroma, flavor, nutritional value, and food safety. The peach are valued for its excellent flavor and taste (Zhao et al., 2019; Zhou, Sun, Li, Zhu, & Tu, 2019). In addition, it is widely recognized that the peach contribute to reduce risks of several degenerative human disease (Noratto, Porter, Byrne, & Cisneros-Zevallos, 2009; Sun, Angelidaki, Wu, Dong, & Zhang, 2019), due the high nutritional values, high levels of antioxidants and anticarcinogenic compounds, carotenoids, and phenolic (Durst & Weaver, 2012). An important characteristic of the peaches is that they deteriorate quickly at ambient temperature (Lurie & Crisosto, 2005) because they are climacteric fruits and have a short storage life period (Abidi et al., 2015; Liu, Cao, & Jiang, 2015), that cause substantial losses in the quality during maturation period, including strong loss of firmness (Abbasi, Ali, Hafiz, Alenazi, & Shafiq, 2019). To extend their commercial life the refrigeration method is over-spread (Liu et al., 2015; Zhou et al., 2019).

However, is consensual in the literature that most of refrigeration process compromises the quality of peach fruit, especially when the peach is maintained on low temperature storage range. The main cause identified is the chilling injury (CI) confirmed by the several studies (Abbasi et al., 2019; Liu, Jiang, Cao, & Li, 2019; Nilo-Poyanco et al., 2019; Zhao et al., 2019; Zhou et al., 2019), and it is described as a physiological disorder, that according Lurie and Crisosto (2005) is induced by low temperatures, but not negative (Crisosto, Mitchell, & Ju, 1999). These authors demarcated that the CI symptoms are develops when the storage conditions are between 2.2°C and 7.6°C

**FIGURE 1** Diagram of a typical peach (Aubert & Milhet, 2007; Simões, 2016)

(killing temperature zone) taunting floury pulp, a dry texture, and flavor loss.

The time and success of the conservation process depends on biological factors, such as, the fruit respiration, transpiration, and the action of ethylene. The fruit respiration is considered the most adequate index to express physiological activity, as well as the storage potential. It is a biological process under aerobic conditions by which organic compounds, especially carbohydrates, are degraded into simpler products (carbon dioxide and water) and heat.



This process involves the oxidative decomposition of the organic constituents of the fruit and loss of food reserves (sugars, organic acids, and starch). These losses will lead to a decrease in nutritional value (energetic and vitamin), reduction of quality characteristics, such as flavor, weight, and texture and, consequently, aging of the fruit, called senescence (de Souza e Silva et al., 2005; Pinto & Morais, 2000). During the fruit respiration process, there are gas exchanges with the environment, such as CO_2 production and O_2 consumption. The respiration rate is measured by CO_2 produced per kg_{fruit} per hour (Kader, 2002) and is related to their degradation, that is, the higher the rate of respiration, the greater the degradation of the products. The peach has a moderate respiratory rate (Kader, 2002; Pinto & Morais, 2000). It is, still, necessary to highlight the importance of the quantification of the heat released, essential for the estimation of refrigeration and ventilation needs. When the level of O_2 consumed is low, the combustion is incomplete and the formation of by-products that give an abnormal flavor to the fruits occurs (de Souza e Silva et al., 2005; Pinto & Morais, 2000). The respiration rate is expressed in mg of CO_2 per kg_{fruit} per hour. In general, all products have a low respiration rate when the temperature is at $0^\circ C$. Although the respiration rate varies in some cases, it tends to be more stable and lower when temperatures vary between $0^\circ C$ and $5^\circ C$. This temperature range is suitable for fruits that are stored for longer periods and promotes greater conservation of its organoleptic characteristics.

The transpiration, that correspond to the water loss, is influenced by external factors, such as temperature, relative humidity, air

circulation during storage and by the characteristics of the product, namely, surface/volume ratio, epidermis damage, and maturation status. The fruit transpiration consists, essentially, in the evaporation of water from the tissues.

Ethylene is a natural hormone produced by plants that affects physiological process in plants namely the senescence and abscission of plants organs (Kader, 2002). The interference on metabolic pathway of ethylene production is a method of retard fruit decay. 1-MCP (1-methylcyclopropene) is largely used to reduce de ethylene production and prevent the activation of senescence- and ripening- associated genes (Du et al., in press). The peach is known to be climacteric fruit, characterized by increase of respiration rate and ethylene production near ripening and are sensitive to ethylene concentration to accelerate ripening process (Kader, 2002; Lurie & Crisosto, 2005).

Thus, to increase storage period and maintenance of fruit quality, respiration, transpiration, and ethylene must be reduced, which is usually reached by low temperature, increase of CO₂ concentration, decrease of O₂ concentration as well as the use of inhibitors of ethylene production. The knowledge of the better combinations of different factors represents an advantage for postharvest handling and commercialization agents.

The length of conservation time varies according to the cultivar under study, since each one has different genetic backgrounds and also different varieties of peach present diverse responses to treatments to inhibit CI. Although there are several studies describing peaches' CI, it is still the major problem associated with peaches cold storage (Fruk, Cmelik, Jemric, Hribar, & Vidrih, 2014). Several treatments to reduce CI can be applied, individually or combined. Murray, Lucangeli, Polenta, and Budde (2007) observed that combined techniques for the cold conservation of peaches and nectarines reduce more the CI than the separately application of the treatments. Jin, Zheng, Tang, Rui, and Wang (2009) and Cao, Zheng, Wang, Jin, and Rui (2009) reached the same conclusion using prestorage (storage of harvested fruits at temperatures between 20°C and 30°C for 1 or 2 days before cold storage) and methyl jasmonate (MeJA), modified atmosphere, and salicylic acid treatments, respectively. Yang, Cao, Zheng, and Jiang (2012) and Bal (2013) concluded that the combined effects of ultrasound treatment with salicylic acid and putrescine, respectively, provided greater inhibition of CI in cold-stored peach fruit than each treatment alone. Gang et al. (2015) evaluated the

effects of calcium chloride, salicylic acid, and gibberellic acid, either alone or combined, on the peach quality and CI. The effects of the combined treatments were better than those of each individual treatment. The combination of the first two treatment was the most effective in alleviating CI, although the single application of calcium chloride treatment keeps the fruit firmness and retarded weight loss rate during cold and subsequent ambient temperature storage. Cao et al. (2018) used melatonin treatment during cold storage to alleviate chilling symptoms in postharvest peaches. Thus, it is verified that CI mainly develops during fruit ripening after cold storage. The CI symptoms such as internal browning and woolliness are noticed only the fruit reaches customers. This paper characterizes the main techniques and treatments to alleviate the CI, highlights their advantages and disadvantages and aims to serve as a practical guideline for both fruit producers, retailers, and consumers on evaluating in advance the quality of peaches in cold storage.

1.1 | Chilling injury

The CI is characterized as a physiological disturbance, induced by low temperatures, but not negative, that affect fruit quality (Meng, Han, Wang, & Tian, 2009) and harms lifetime at storage (Lurie & Crisosto, 2005; Martínez-García et al., 2012). The symptoms of CI were divided into mealiness (M) characterized by dry and sandy fruit mesocarp, flesh leatheriness (FL) when pulp turns corky, flesh browning (FB) visible only when cutted and flesh bleeding (FBL) when a red veins can be seen through the mesocarp (Martínez-García et al., 2012). The FB as well as M develops more rapidly between 1 and 2 weeks when fruits are stored at temperatures between the 2.2°C and 7.6°C (Lurie & Crisosto, 2005). In these conditions, and as can be seen in Figure 2, the peach will also present a floury pulp, a dry texture, lack of flavor and, in more advanced cases, the peach eventually undergoes a separation of the pulp and form cavities (Brecht & Kader, 1982; Fernández-Trujillo, Cano, & Artés, 1998). The development of CI symptoms has been associated with decreased total phenolic, flavonoid, and total antioxidant concentrations and reduced juiciness during storage (Abidi et al., 2015). In addition to the CI, the discoloration of the mesocarp is also due to the oxidation of the phenolic compounds. Thus, these compounds can have a double antagonist action, that is, its presence allows the peach to have a good antioxidant power, common



FIGURE 2 Chilling injury symptoms and evolution over time (Lurie & Crisosto, 2005)

feature in this fruit, and, related to its degradation when subjected to storage at high temperatures, causes the discoloration of the pulp (Crisosto, Garner, Andris, & Day, 2004; Lurie & Crisosto, 2005; Meng et al., 2009; Pan et al., 2016). However, the experiment conducted by Abidi et al. (2015) demonstrated that a positive interaction between antioxidant compounds and carbohydrates may alleviate CI symptoms on peach. Table 2 includes the most common CI symptoms on peach fruits according to the literature.

The CI is generically influenced by the combination of storage temperature and the period of storage (Lurie & Crisosto, 2005; Pan et al., 2016). For peach, cold storage is the most commonly used method, since it includes an effective technology (Zhang et al., 2011), has the ability to delay the deterioration of the product, both in terms of the consumers perception and of nutritional value (Tsantili, Shin, Nock, & Watkins, 2010), and, still, extends the shelf life of the peach (Zhang et al., 2011).

1.2 | Techniques and treatments to mitigate chilling injury

In the last years, and according to several studies, the CI has been considered the main problem for the peach industry (Shan et al., 2016). Several methods, techniques, and treatments to overcome or alleviate the development of this phenomena have been tested, always with the perspective to preserve the organoleptic peach characteristics. Thus, several preharvest and postharvest manipulations that can be used to delay the onset of the CI symptoms will be discussed below, according the literature reviewed.

1.3 | Temperature dependent

Refrigeration is the most common method to extend shelf life and preserve fruit quality (Abidi et al., 2015; Pan et al., 2018). At the refrigeration chamber, the ideal storage temperature depends on the total refrigeration capacity of the equipment and the air velocity that passes through the evaporator and reaches the product. In most refrigeration chambers, the air circulation is moderate, so

the water loss is smaller and the storage time longer (de Souza e Silva et al., 2005). Thus, the fruit should be quickly refrigerated after harvesting so that at an early phase, a rapid decrease in temperature occurs and, then the temperature stabilizes. In order to remove heat from the fruit quickly and efficiently, precooling methods are used.

1.3.1 | Precooling

The precooling methods depend on the thermal properties of the fruit (specific heat, thermal conductivity, and heat transfer resistance of the fruit surface), its nature, initial and final temperature, temperature, and properties of the cooling medium. The main precooling methods are briefly enumerated (de Souza e Silva et al., 2005; Pinto & Morais, 2000):

1. **Forced air cooling:** consists of cold air flow directly on the fruit. This method is quite versatile and can be incorporated into the existing refrigeration chambers. It does not require highly sophisticated technology and can be used on a vast range of products. However, to prevent water loss, and consequently the weight loss of the fruit, the environment must contain a high relative humidity (about 95%).
2. **Water cooling:** consists of the use of cold water in immersion processes and sprinkling on the fruit. This method is faster than the forced air cooling, in this case, the dehydration of the fruit does not occur. Thus, it is necessary that the water reaches the largest possible fruit surface and its temperature be as cold as possible, without damaging the fruit, to ensure the effectiveness of this method.
3. **Ice cooling:** consists of rapid refrigeration, compared to the previous methods, however it is only effective in products that tolerate direct contact with water and ice. In this case, packaging should be water tolerant and present small holes for the process of draining water. The main disadvantage of this method is the costs associated with the manufacture of specific packaging.
4. **Vacuum cooling:** consists of placing the packaged product inside of an airtight chamber, in order to evacuate the air from the package.

Chilling injury symptoms	Authors
<ul style="list-style-type: none"> • Brown color of the peach mesocarp (pulp) • A floury pulp, a dry texture, lack of flavor • Separation of the pulp and form cavities • Flesh bleeding • Internal browning, wooliness or leatheriness and failure to ripen 	Crisosto et al. (1999) Lurie and Crisosto (2005) Martínez-García et al. (2012)
<ul style="list-style-type: none"> • Decreased total phenolic, flavonoid and total antioxidant concentrations and reduced juiciness • Internal browning and lignification of flesh • Mealiness (dry, sandy fruit mesocarp) 	Abidi et al. (2015) Zhao et al. (2019) Crisosto et al. (1999), Obenland and Carroll (2000), Nilo-Poyanco et al. (2019)

TABLE 2 The most common chilling injury symptoms on peach fruits according to the literature

This is the most efficient and fastest method, because when the product undergoes this type of cooling will occur a decrease in pressure and the boiling point of the water. Consequently, the water on the fruit surface evaporates. The main advantage of this method is the speed at which precooling takes place. However, this method is recommended only for products that have a good area/volume ratio. Since the equipment required presents high costs, their use is limited to a specific scale of products.

Table 3 provides a general comparison of precooling methods, taking into account the time required to cool the product, the weight loss, the main consequences, and the energy consumption.

1.3.2 | Cold storage

The storage life is limited by loss quality owing to development of CI under continuous low temperature (Pan et al., 2018; Zhang et al., 2011). For example, the peach fruit is highly vulnerable to CI during the cold storage, especially at the temperature below 8°C for more than 20 days (Wang et al., 2019). However, Liu et al. (2019) conclude that the chilling-temperature treatments was more severe when peaches are exposed to higher temperature (4–6°C). In these conditions increased pulp browning (PB) symptom and significant discoloration on 10 days.

Other investigation, conducted by Abidi et al. (2015) that evaluated, during 2 years (2010–2011), the CI symptoms after storage at an air temperature of 5°C and relative humidity (RH) of 95% for 2 and 4 weeks and then ripening at environmental temperature for 2–3 days, allow to conclude: the major CI symptom observed after 4 weeks of storage was FB. However, a continuous distribution of symptoms was observed for leatheriness, browning, bleeding, and off-flavor, suggesting a polygenic control, and also the longer duration of storage (2 or 4 weeks at 5°C) increases the severity of CI symptoms. Instead, recently (Zhao et al., 2019) concluded that near-freezing temperatures, between 0°C and 5°C, may be a promising strategy for enhancing chilling tolerance of nectarine fruit during long-term cold storage.

It is common associate different variables on some experiment, for example, testing the cold storage combined with the temperature fluctuation. The experiment of Pan et al. (2018) in refrigeration chambers with temperature fluctuation had a negative effect on peach quality and allows to conclude then 0°C could delay ripening

and improve the peach quality. Similar conclusions are obtained by the experiment of Obenland and Carroll (2000). These results determine that the intermittent warming (IW) during storage was far less effective in preventing M when heat treatment was superimposed upon cold storage.

1.4 | Controlled atmosphere

The controlled atmosphere (CA) has been a widely analyzed technique. Usually CA storage are used to supplement low temperature storage to delay ripening, reduce physiological disorders, and suppress decay in many fresh fruit products (Pan et al., 2018).

According (Lurie & Crisosto, 2005), a CA with 17% of CO₂ and 6% of O₂ at 0°C, is ideal for storage peaches, delaying deterioration and prolonging its shelf life. In order to the storage process to be efficient, the ideal will be to increase the CO₂ concentration and decrease the O₂ concentration. These conditions allow the peach to have a longer storage life and prevent the appearance of the brown color of the mesocarp, the floury pulp, the lack of flavor, and the formation of cavities. However, the most important concentration that delays the appearance of CI and all its symptoms is the CO₂ concentration. Study with nectarines *Fantasia*, *Flavortop*, and *Flamekist*, demonstrates that a CA with 10% of CO₂ and 10% of O₂, at 0°C, for 6 weeks, allows to prevent the appearance of the typical symptoms of CI and, provides, a distinct flavor and juiciness to the fruit. In addition, storage at CA, along with a treatment based on AVG (aminoethoxyvinylglycine). The application of about 150 ppm of AVG in the fruits, 7 days prior to harvest, followed by storage at 0°C, in 90% ± 5%, during 8 weeks under CA with 17% of CO₂ and 6% of O₂, guaranteeing the efficiency of this technique at the commercial level reference. Thus, a decrease in acidity is confirmed, increased soluble solids, lower ethylene production, greater firmness, as well as, a delay in peach maturation and coloring, ensuring its quality and characteristics (Çetinbaş, Butar, Onursal, & Koyuncu, 2012).

In Pan et al. (2018) study, an experiment were conducted under steady-state-CA of 10% O₂ and temperature fluctuation conditions (storage conditions were set four temperature fluctuation values, 1 ± 0°C, 1 ± 0.5°C, 1 ± 1°C, and 1 ± 2°C). This study put in evidence that the negative effect obtained in quality and sensory maintenance of peach.

TABLE 3 Precooling methods (de Souza e Silva et al., 2005)

Variable	Precooling methods			
	Forced air	With water	With ice	In vacuo
Time	2 to 8 hr	20 to 40 min	2.5 hr	20 to 40 min
Weight loss	Small	No	Moderate	Small
Consequences	No	Disease propagation	Freezing the product	Freezing the product
Energy consumption	High	High	Moderate	High

1.5 | Intermittent warming

Over the last years, IW techniques or ripening controlled that allow to reach the ideal point of maturation have been analyzed as ideal conservation methods, achieved by controlling the temperature and specific storage periods (Lurie & Crisosto, 2005). The effectiveness of this technique consists in storing the fruit, after harvesting, at 0°C and, then, every 10 to 14 days subject the fruit to a higher temperature (around 20°C to 24°C) during 1 day. In these conditions, there is an improvement and preservation of the peach characteristics such as flavor, texture, aroma, succulence, and hardness, organoleptic characteristics highly appreciated by the consumer's according the results obtained by Shinya, Contador, Frett, & Infante, 2014). The peach shelf life increases and a delay in CI and deterioration of the fruit as also observed by (Lurie & Crisosto, 2005). In addition to these advantages, IW technique allows the increase of ethylene production which, according to, can contribute to a good conservation of the peach during cold storage (Lurie & Crisosto, 2005; Zhou et al., 2000) and increase the formation of esters, improving the flavor and aroma quality of the peach (Xi et al., 2012). This strategy is reported as an environmental friendly approach and has also been reported to be practical in preventing CI in peach (Liu, Jiang, Cao, & Ma, 2018). However, Liu et al. (2018) identified some limitations of IW since it might limit the peach shelf-life storage and indicate the need to neutralize the negative response of IW with a commercial ethylene inhibitor, suggesting the 1-MCP.

1.6 | Ethylene and ethylene inhibitors

Ethylene and ethylene inhibitors are used to delay the symptoms of CI (Dong, Zhou, Sonogo, Lers, & Lurie, 2001; Fan, Argenta, & Mattheis, 2002; Hayama, Tatsuki, & Nakamura, 2008; Jin et al., 2011; Liu et al., 2015). However, ethylene during the storage can be detrimental, because it has the ability to trigger a rapid maturation process and deterioration of the fruit (Lurie & Crisosto, 2005; Pinto & Morais, 2000). Nevertheless, according to these authors, the presence of ethylene during cold storage may contribute to good conservation. In the treatment of *Fairlane* and *Flamekist* nectarines with ethylene at 0°C, it was not verified color change, nor a rapid maturation process (Brecht & Kader, 1982). Thus, it is possible to conclude that a storage with ethylene production and a temperature of 0°C, contributes to the normal maturation and prevents the appearance of a floury pulp (Lurie & Crisosto, 2005; Zhou et al., 2001). According to Lurie and Crisosto (2005), the use of ethylene inhibitors, such as 1-MCP in peaches, also prevents normal ripening in cold storage.

The control of ethylene production and action is an important component in peach postharvest (Liu et al., 2015). These authors suggest when it is applied at the correct time increasing their postharvest life. The most common ethylene inhibitor identified in the literature is the 1-MCP treatment, that promote the lower ethylene production and respiratory rates.

Recently, CI index was evaluated by Liu et al. (2018) according three different treatments that combine 1-MCP and IW techniques during 45 days and then located at 20°C for 3 days as shelf time. The main results related about the control peach fruit exhibited CI, manifested as PB, after storage at 2°C for 30 days. However, no internal browning symptoms were detected in the treatment with 1-MCO, IW, or 1-MCP + IW in the 30th day. According the results, by the end of the 45-days at 2°C the CI index of control peach fruit was 45%, and concluded that the development of CI was more evident after shelf life period, specifically after 3 days, with 76% of peaches with CI symptoms. Generally, this experiment that combine 1-MCP and IW cannot reduce CI, but also counteract the side effect of IW.

1.7 | Glycine betaine treatment

Glycine Betaine (GB) treatment demonstrates promising results in control or reducing CI in several types of fruits (Jin et al., 2015; Rodríguez-Zapata et al., 2015). GB is a neutral compound that plays an important role in maintaining the osmotic pressure of cells, protection of proteins or enzyme function and in regulating plant stress (Mansour, 1998; Shan et al., 2016). This compound has been found to be effective in controlling or reducing of CI in cold storage, on bananas (Rodríguez-Zapata et al., 2015) and in loquats (Jin et al., 2015) and peach (Shan et al., 2016; Wang et al., 2019). Shan et al. (2016) inserted peaches in a GB solution, with a concentration of 10 mM, during 10 min. Afterwards, the peaches were air-dried during 30 min and stored at 0°C for 5 weeks. It was considered a very promising treatment in peaches, both in terms of increasing energy content and decreasing membrane damage, as well as in the increase in the amount of γ -aminobutyric acid (GABA) (Shan et al., 2016). This compound is partially responsible for the reduction of CI (Cao, Cai, Yang, & Zheng, 2012), by the increased activity of antioxidant enzymes and by preserving a high energy state (Yang, Cao, Yang, Cai, & Zheng, 2011). Recently, Wang et al. (2019) indicate that GB treatment in peach fruit during cold storage enhanced chilling tolerance. This result was obtained by their capacity to regulating phenolic and sugar metabolisms what is important to maintaining nutrient quality.

1.8 | Methyl jasmonate treatment

The treatment based on MeJA reduces the symptoms caused by the CI, maintaining the fruit hardness and postharvest quality during the storage period (González-Aguilar, Buta, & Wang, 2001; González-Aguilar, Buta, & Wang, 2003; Gonzalez-Aguilar, Wang, & Buta, 2004; Yao & Tian, 2005) refers also that MeJA treatment might prevents the FL development and maintains fruit quality during refrigerated storage.

In the research conducted by Meng et al. (2009), peaches were stored for 3 weeks at 5°C, and at intervals of 3 days at a temperature

TABLE 4 Summary of techniques and treatments that retard/prevent chilling injury

Treatment/ Technique	Conditions	Storage time	Temperature	Relative humidity	Results	Advantages	References
Refrigeration chamber	Stored at chilling temperatures	10, 20, 30, 40, 50 days	0, 2, 4, 6°C	85%–90%	All chilling-temperature treatments promoted pulp browning (PB) of peach fruits The PB was more severe in peaches exposed to higher temperatures (4 and 6°C) than lower temperatures (0 and 2°C) At 30 days, the browning index of peaches reached to 72.5% (4°C) and 78.8% (6°C)	The fruits there were stored at 0°C and 2°C, there were no PB symptoms until 20 days and the discoloration were mild until 40 days	Liu et al. (2019)
Controlled atmosphere (CA)	Controlled atmosphere (17% CO ₂ + 6% O ₂) Controlled atmosphere (10% O ₂ + 20 L) + IW	42 days 15 days	0°C 1 ± 0°C 1 ± 0.5°C 1 ± 1°C, and 1 ± 2°C	–	Prevents the appearance of typical symptoms of chilling injury The temperature fluctuation has a negative effect on quality and sensory maintenance of Peach	Delays the deterioration of the fruit. Extends the useful life of the fruit Storage temperature without any fluctuation could delay ripening and improve the postharvest edible quality of peach	Lurie and Crisosto (2005) Pan et al. (2018)
Intermittent warming	Intermittent warming	21 days	0°C after harvest and 20°C to 24°C for 1 day	–	Improvement and preservation of characteristics at the level of taste, texture, aroma, succulence and hardness of the peach	Increased fruit shelf life Delay of fruit decay Increased production of ethylene	Zhou et al. (2000); Lurie and Crisosto (2005); Xi et al. (2012).
Ethylene inhibitors	Ethylene inhibitors (1-MCP) and intermittent warming Ethylene inhibitors (1-MCP) and intermittent warming	12–14 days 48 days	0°C in storage and 20°C in intermittent warming 0.5°C in storage and 20°C 1 day at environmental conditions	– 85%–90%	Delay the chilling injury Extends the useful life of the peach 1-MCP treatment can offset the ineffectiveness of IW and the combined treatment (1-MCP plus IW) was most effective in alleviating chilling injury and maintaining fruit quality, phenolic compounds as well as antioxidant activity	Good conservation Better quality of the taste and aroma of the peach The application of 1-MCP plus IW could be a favorable practice for preventing chilling injury and maintaining fruit quality	Zhou et al. (2001); Lurie and Crisosto (2005) Liu et al. (2018)
Glycine betaine treatment (GB)	Glycine betaine solution (10 mM) 10 mmol/L GB solution for 10 min	35 days 35 days	0°C 0°C	– 85%–90%	Increased amount of GABA. Reduction of chilling injury Maintenance of high levels of total phenolic, flavonoid and sucrose content	Increase in energy content. Decrease of membrane damage Decrease of chilling injury Enhance chilling tolerance	Shan et al. (2016) Wang et al. (2019)

(Continues)

TABLE 4 (Continued)

Treatment/ Technique	Conditions	Storage time	Temperature	Relative humidity	Results	Advantages	References
Treatment with methyl jasmonate (MeJA)	MeJA	21 days	5°C at intervals of 3 days at 20°C	–	Decrease in chilling injury index Lower content of phenolic compounds	Better fruit quality. Reduction of injury caused by chilling injury	Meng et al. (2009)
	10 mmol/L MeJA and hot air treatment	4 days	37°C for 3 days 5°C for 24 hr	–	High sucrose content Increased tolerance to chilling injury	Increased shelf life	Yu et al. (2016)
	1, 10, 100 or 500 µmol/L MeJA (Aldrich Chemical Company, Milwaukee, WI, USA)	8 days	MeJA vapor at 20°C for 24 hr before stored at 25°C for 8 days 25°C	80%–90%	Treatment with low concentrations of MeJA (1–100 µmol/L) significantly inhibited fruit decay and 1 µmol/L MeJA was the most effective, while high concentration MeJA (500 µmol/L) promoted fruit decay	Low concentrations of MeJA treatment may application for commercial use to reduce fruit decay and maintain fruit quality in peaches during postharvest distribution at ambient temperature	Jin et al. (2006)
Exposure to ultraviolet radiation (UV)	Ultraviolet radiation with a wavelength of 254 nm	8 days	20°C	90% ± 2%	It delays the senescence of the peach Decreases chilling injury	Increases peach shelf life Decreases the peach deterioration	Yang et al. (2014)
	Hot Air at 40°C for 4 hr or irradiated with UV-C lamp (1.5 kJ/m)	35 + 3 days	1°C (35 days) 20°C (3 days)	90%–95%	Maintain quality in peach fruit, exhibiting higher flesh firmness respiration rate during the late storage, as well as lower electrolyte results indicated that HA and UV-C treatments could inhibit the losses of sensory quality	Maintain higher flesh firmness Suppressed chilling injury significantly Lower internal browning index	Zhou et al. (2019)

of 20°C. A decrease of the CI index was observed, the fruit quality was maintained and the integrity of the cell membrane, as well as the activity of the antioxidant system increased (Cao et al., 2009; Meng et al., 2009) and therefore it was considered a very effective treatment.

The effect of a postharvest application of MeJA on peach fruit decay and quality was also investigated by Jin et al. (2006), referring a period of 8 days at 25°C. The main results allow to conclude that a low concentrations of MeJA (1–100 µmol/L) significantly inhibited fruit decay and 1 µmol/L MeJA was the most effective and the quality was maintained, while high concentration of MeJA (500 µmol/L) promoted fruit decay. These results suggest that it is possible to preserve peaches at ambient temperature during 8 days.

1.9 | Ultraviolet radiation (UV)

Ultraviolet radiation (UV) allows to control CI and delay senescence in different fruits (Erkan, Wang, & Wang, 2008; González-Aguilar et al., 2001; Gonzalez-Aguilar et al., 2004; Yang, Cao, Su, & Jiang, 2014). Fruit senescence is associated with an increased in the oxidative damage of proteins, lipids, and nucleic acids, by reactive oxygen species (ROS) and, therefore, its production and removal should be strictly controlled (Mittler, 2002). Mitochondria are the main sites of ROS formation. The accumulation of these species can damage the integrity of the mitochondria membrane, resulting in irreversible mitochondrial dysfunction (Møller, 2001), being one of the main causes of senescence in several fruits (Wu et al., 2016). In the study performed by Yang et al. (2014), the storage of peach subjected to UV radiation with a wavelength of 254 nm, at 20°C, relative humidity of 90% ± 2%, for 8 days, are the ideal conditions to guarantee the efficacy of the treatment (Yang et al., 2014). It was concluded that UV treatment delayed senescence of the peach, through inhibition of the respiration rate (Yang et al., 2014). In the study of Zhou et al. (2019) the UV combine with hot air (HA) treatment were conducted. This experiment was outlined with HA at 40°C for 4 hr and irradiated with UV-C lamp (1.5 kJ/m²), and store at 1°C for 35 days plus 3 days of shelf life at 20°C. The results obtained exhibit a relative improve peach quality parameters comparing with other experiments. This study showed that HA and UV-C suppressed CI significantly, exhibiting lower internal browning index.

1.10 | Genetic determination

Although technical production management as nitrogen fertilization and irrigation, as harvest date can also influence CI, the different susceptibility of free stone-Melting peaches and non-melting peaches to CI soon suggested that CI was genetically controlled (Crisosto & Costa, 2008). Recent studies (Abidi et al., 2015; Martínez-García et al., 2012) try to understand the genetic determination by analyze the segregated progenies of different crosses to identify the associated gene and contribute to breeding programs.

However, CI is associated with the presence and metabolic pathway of phenolic compounds (Wu, An, Yu, Ma, & Yu, 2018). The correlations observed between CI and phenolic contents highlight their potential influence on susceptibility to internal browning. This relationship should be considered in the current breeding programs to select cultivars with high bioactive compound contents that can contribute to low the incidence of CI as well to enhance the health-related compounds. Principal Component Analysis statistical analysis suggested that genotypes with high antioxidant capacity (high levels of total phenolic and flavonoid and high RAC), high sugar content (Soluble Solid Content and total sugars) and high fruit weight presented low bleeding after 2 and 4 weeks of storage, but there was different inheritance patterns for different symptoms of CI of the progeny considered. However, off-flavor show the higher proportion of phenotypic variance attributed to year and storage duration. These results reveal the complexity of factors evolved on CI and point out for a genetic approach to CI mitigation by the genetic breeding.

Table 4 summarizes the studies described above. This analysis intends to compare temperature ranges, humidity, storage time, the applied technique, assessment of CI and, consequently, the main results and the technique advantages.

2 | CONCLUSIONS

Chilling injury is the main limitation of cold storage over a long period of time. This type of storage is the most used, in the conservation of fruit, because it has the capacity to delay the deterioration of the product, both in terms of perception toward the consumer and in terms of nutritional value. The symptoms of CI impair visual quality and nutritional quality, limiting, therefore, its commercialization. Thus, it is possible to conclude that the appearance of these symptoms in cultivars depends so much on biological/genetic factors, such as respiration, transpiration, and ethylene action, and essentially from external factors, such as temperature, relative humidity, and circulation of air, and still by product characteristics, as morphological characteristics, surface/volume ratio, damage to the epidermis and state of maturity.

In order to maintain fruit quality during the marketing period it is necessary to implement techniques or treatments that delay the symptoms of CI, resulting in high quality fruit on the market. Thus, it is necessary to inform producers, transporters, receivers, and consumers on short-term solution techniques to reduce the development of symptoms caused by cold damage. In conclusion, the research of new and better techniques to delay the development of the CI is relevant for the postharvest activity of peach production.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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