Reducing post-harvest losses and improving quality in sweet corn (Zea mays L.): challenges and solutions for less food waste and improved food security

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Abstract
Demand for fresh-cut fruit and vegetables is increasing, in the face of global population growth and new interest in plant-based diets. At the same time, year-round supply across the world of popular vegetables means that post-harvest losses, which can be significant, need to be minimized in the face of complex global supply chains and markets. Sweet corn (Zea mays L.) is harvested before physiological maturity when the kernel has high water and sugar concentrations making it a very perishable fresh produce and effective post-harvest handling essential to reduce losses and ensure quality. Taste, aroma and colour are the main customer-appreciated characteristics, hence the most important to preserve. Among the sweet corn post-harvest disorders, loss of sweetness, dehydration, fungal growth and post-cooking browning are the biggest issues impacting sweet corn quality, leading to post-harvest losses. The critical factor driving these losses in sweet corn is temperature. Sweet corn is not a chilling sensitive product and has high sugar content. For this reason, temperatures as close as 0°C and the appropriate use of packaging films to create an altered gas composition with high CO2 and low O2 concentrations can significantly prevent post-harvest decay. The use of low temperatures and effective choice of appropriate packaging films can control sweet corn respiration rates and prevent microorganism growth, subsequently delaying quality loss. This comprehensive review assembles a description of the most customer-appreciated sweet corn characteristics. And it describes the major sweet corn post-harvest challenges and provides a summary of four approaches to improve post-harvest quality in this popular fresh-cut vegetable.

KEYWORDS
food security, fresh-cut, post-harvest, sweet corn
1 CHARACTERIZING POST-HARVEST QUALITY IN SWEET CORN

1.1 Sweet corn (Zea mays L.)—A food crop with growing global demand

The demand for fruit and vegetables is increasing due to world population growth and higher awareness of the health benefits and sustainability associated with plant-based diets (Tilman & Clark, 2014). Growers, suppliers and supermarkets face the challenge of meeting this increased demand while at the same time maintaining high-quality produce, often year-round. Agricultural losses in fruits and vegetables during post-harvest operations, storage, transport, processing and packaging are a major contributor to food losses and waste. This is generally tackled by the selection of elite varieties, crop management and the appropriate application of pre- and post-harvest technologies, but despite this, post-harvest losses remain a major cause of wasted food for fresh produce (Gustavsson et al., 2011). In Europe and North America, highest losses are caused at the consumer level, while in Africa, South America and East Asia they occur at the processing stage (Gustavsson et al., 2011). The overall reduction in the post-harvest losses at the early and late stages of the supply chain would contribute to preserving the challenging global issue of food security.

Sweet corn is widely consumed as fresh, frozen or processed produce (Siddiq & Pascali, 2018). The USA is the top producer nation of sweet corn with 2237 million pounds in 2018, with California the top producer state for the fresh market (31,749 acres) and Minnesota in the frozen and processed market (104,508 acres) (ers.usda.gov). Japan is the most significant importer country with 19%, followed by the UK with 12% of all global imports (oec.world).

Sweet corn (Zea mays L.) is a sweeter variety of field corn, with several available varieties produced by a number of contrasting mutations in the sugar to starch conversion metabolism. Sweet corn also differs from field corn in the maturity stage at harvesting, being harvested when the grain has high moisture and soluble sugar content. These two factors make sweet corn a very perishable product, highly susceptible to post-harvest decay (Kader, 2002).

Post-harvest management of sweet corn is essential to reduce the amount of product wasted and to help maintain the quality of the product throughout the supply chain. Due to the high perishability of fresh-cut produce, from the very first moment after harvest, the correct handling of the product is essential to reduce losses and ensure a long and high-quality shelf life. Cooling, handling, packaging and shipment are some of the main action points to work with, when optimizing the supply chain (Watkins, 2016). Fruits and vegetables sensitivity to storage conditions varies widely between commodities (Kader, 2002). Hence, the knowledge of the post-harvest biology of each product and the optimization of all the variables affecting the product throughout the supply chain is required to reduce losses and ensure quality at all the stages of the agricultural chain, from the farmer to the customer.

1.2 Sweet corn post-harvest characteristics

Alongside the increased demand for fresh-cut produce comes a higher customer expectation for freshness and quality. Because of long shipping times and perishability of fruit and vegetables, post-harvest handling can jeopardize the quality of the produce, compromising flavours and aroma. Sweet corn sweetness, odour, colour and tenderness are the principal qualities perceived by the consumer and therefore, the most important characteristics to preserve (Azanza et al., 1994; Carey et al., 1984; Flora & Wiley, 1974). Within flavour, sweetness is the main attribute of sweet corn, and as a counterpart starchiness when the former is lost. There are three principal sweet corn mutations (su, se, sh2) involved in kernel sugar metabolism either: increasing the mono- and di-saccharide concentration (sweetness), and/or reducing the amount of starch accumulated in the grain (texture; Ferguson et al., 1978; Laughnan, 1953; Lertrat & Pulam, 2007). Sucrose is the main soluble sugar accounting for approximately 94, 88 and 85% of the soluble sugars in the genotypes sh2, se

| Genotype | Day | Sucrose | Glucose | Fructose | Maltose | Total |
|----------|-----|---------|---------|----------|---------|-------|
| sh2      | 0   | 10.36 ± 0.04 | 0.44 ± 0.00 | 0.23 ± 0.01 | 0.10 ± 0.00 | 11.01 ± 0.05 |
|          | 5   | 9.63 ± 0.13  | 0.3 ± 0.01  | 0.2 ± 0.01  | 0.09 ± 0.01 | 10.18 ± 0.14 |
| Su       | 0   | 3.04 ± 0.04  | 0.23 ± 0.01 | 0.14 ± 0.00 | 0.15 ± 0.00 | 3.58 ± 0.05  |
|          | 5   | 2.68 ± 0.04  | 0.22 ± 0.01 | 0.11 ± 0.01 | 0.39 ± 0.01 | 3.39 ± 0.06  |
| Se       | 0   | 7.13 ± 0.09  | 0.41 ± 0.00 | 0.41 ± 0.00 | 0.18 ± 0.00 | 8.13 ± 0.10  |
|          | 5   | 5.17 ± 0.01  | 0.3 ± 0.01  | 0.26 ± 0.00 | 0.31 ± 0.00 | 6.05 ± 0.03  |

Modified from: (Zhu, Mount & Collins., 1992).
and su, respectively (Table 1). When assessing sweetness, it is important to consider all sugars as they can have different flavour intensities (Schwieterman et al., 2014). Among the physical features (texture), juiciness, tenderness and crispiness are the properties highly appreciated, with juiciness the most important texture for the consumer. Aroma is a second of the organoleptic characteristics much appreciated, but also its counterpart, off-odour development (alcohol, sour, water-soaked) as decay signs (Azanza et al., 1996; Deák et al., 1987; Shao & Li, 2011).

1.3 | Other sweet corn characteristics

Colour is a fruit and veg characteristic highly appreciated by customers, since colour is an indicator of ripeness and freshness. Hence, its preservation during post-harvest is essential to safeguard the quality of the product. Colour parameters measured in sweet corn are lightness, chroma and hue angle (Calvo-Brenes & O’Hare, 2020; Kachhadiya et al., 2018). Yellow and white sweet corn are the most popular varieties, but other colours are marketed especially in Central and South America countries. Sweet corn colour is determined by the pigments in the kernel, ranging from white to dark purple, with carotenoids (carotenes and xanthophylls) and anthocyanins (cyanidin) the main pigments determining colour, with carotenoids responsible for yellow kernels and anthocyanins for red-blue kernels (Hu & Xu, 2011; Ryu et al., 2013). Research on detrimental sweet corn colour changes during post-harvest has focused on colour change after blanching (Kachhadiya et al., 2018) or freezing (Calvo-Brenes & O’Hare, 2020). The former found that blanching produced an increase in sweet corn brownness proportional to blanching times (Kachhadiya et al., 2018) and the latter finding no changes in sweet corn colour measured during 15 days of storage at 4°C.

Tenderness and crispiness are textural characteristics largely determined by the kernel pericarp. During post-harvest, the kernel texture such as pericarp softening or loss of juiciness can severely devalue sweet corn quality. Pericarp thickness studies suggested a relation with the kernel endosperm type. When evaluating the three main sweet corn mutants (su, se and sh2), su was tougher and less accepted than se or sh2. Moreover, higher cob maturity was also found to be a reason for a tougher pericarp (Hale et al., 2004). Hale et al. (2004) suggested penetrometer measurements of 0.15 and 0.11 g−1 cm−2 as indicators of a though pericarp and tender pericarp, respectively.

Along with colour and flavour, sweet corn aroma informs the customer about product freshness. Although sweet corn lacks strong aromas, development of off-odours in packed sweet corn can compromise customer acceptability. The aroma of cooked fresh sweet corn has been described as grassy, ethanolic and fruity (Azanza et al., 1994; Flora & Wiley, 1974). Between the volatiles thought to be responsible for this aroma, sulphur compounds seem to be responsible, including dimethyl sulphide, which is found at high levels in affected corn. Besides sulphur compounds, ethanol and acetaldehyde were also detected and may contribute to the ethanolic aromas (Buttery et al., 1994). While aroma is important in cooked sweet corn, sweetness and texture have higher importance in customer perception (Flora & Wiley, 1974), although prevention of off-odour development in packed sweet corn might have a greater relevance ensuring quality and reducing losses.

1.4 | Taste panels

Taste panels are important to evaluate quality and ensure products have consumer acceptability. Moreover, taste panels on many occasions can determine the length of shelf life for a product through the assessment of product characteristic under different post-harvest conditions. Panellist training and compliance of the ISO standard significantly improves the reliability and consistency of the results (Losó et al., 2012). Table 2 represents a summary of the most common characteristics evaluated in sweet corn panels. Some taste panel scores have been based on descriptors but most of them consist of a rating scale with anchors such as ‘none’ to ‘very intense’ or ‘lacks sweetness’ to ‘sweet acceptable’ (Azanza et al., 1996; Hale et al., 2005; Shao & Li, 2011).

| Characteristic                  | Positive descriptors                  | Negative descriptors                           |
|--------------------------------|---------------------------------------|-----------------------------------------------|
| General appearance             | Bright, shiny, turgid,                | Water-soaked, discolouring, gelatinous, dull, denting, translucent |
| Flavour                        | Sweetness, fresh                      | Starchiness, dough, bland,                    |
| Texture (Tenderness, Crispiness, Juiciness) | Turgid, creamy, crunchy, juicy, moisture | Soft, mushiness, dough                        |
| Aroma                          | Fresh grassy odour, no smell          | Rotten smell, alcoholic, sour                  |
| Husk                           | Dark green, turgid appearance, flexible, fresh, | Yellowing, dryness, water-soaked leaves,      |
| Silk                           | Light, fresh, turgid                  | Browning, dryness, limp texture, water decay  |
The feature assessed in most taste panels is sweetness, although other flavours and characteristic such as salty taste and aftertaste have been added to taste panels (Losó et al., 2012). Sucrose solutions 0, 5 and 10% can be useful for panellist training and during taste panels as sweetness references (Azanza et al., 1996). In a sweetness comparison of three sweet corn mutants su, se and sh2 (scale from 0 to 15), sh2 showed the highest panel scores (10.1/10.9) and su the lowest (3.7–6.8). Moreover, this perception of sweetness score differed by 3.1, 1.4 and 0.8 for su, se and sh2, respectively, between early and late maturity harvested cobs, indicating that maturity level can have an impact in sweetness perception and post-harvest quality (Hale et al., 2005).

Pericarp tenderness is one of the texture qualities most customer-appreciated describing the chewiness of the sample. When assessed on a 15 cm linear scale with anchor words, su mutants were the least tender kernels and se as the most (Hale et al., 2004). Other texture characteristics are crispiness in reference to the first bite texture and juiciness as the mouth-feel succulence (Azanza et al., 1996).

The most difficult characteristic to describe in sweet corn taste panels are cooked odour and odour intensity (Losó et al., 2012). Cooked sweet corn aroma is a very popular trait of the product, but off-odours developed during the post-harvest life of the product have been little researched and might have a more important role in the product acceptability at the retail stage. Some authors have suggested a relation between the occurrence of off-odours (ethanolic and acetaldehyde) and fermentation under low oxygen environments (Rodov et al., 2000).

Since sweet corn is harvested at an immature physiological status, choosing the right time for harvest is crucial to ensuring a high-quality product. Sweet corn harvest occurs 18–22 days after pollination (Azanza et al., 1996; Espinoza & Ross, 2003) at a maturity stage where kernels have reached their final size but before the sugar to starch conversion and dehydration is initiated. The right growing practices and harvesting time can yield a crop with high homogeneity and an enhanced post-harvest life (Kwabiah, 2004).

Pests are also a preharvest factor causing major post-harvest losses. Fungal infections such as corn smut (Ustilago maydis) and ear rot (Fusarium verticilloides) lead to losses due to altered morphology or the accumulation of mycotoxins (Thompson & Raizada, 2018). Caterpillars of corn earworm (Helicoverpa zea) and European corn borer (Ostrinia nubilalis) are two of the main pests feeding from the corn cob and increasing post-harvest losses (Shelton et al., 2013; Sobek & Munkvold, 1999). In addition to direct feeding on the produce, these insects can act as vectors for the previously mentioned fungal infections (Sobek & Munkvold, 1999). The disorders and damage from pests and pathogens can significantly reduce the produce quality and safety during the post-harvest shelf life due to mechanical damage, or microbial growth (Figure 1b).

Kernel splitting or cracking can be caused by a low carbohydrate content of the endosperm that under changing post-harvest conditions can damage the pericarp, and another cause of kernel cracking can be irregular irrigation leading to quicker growth of the endosperm than the pericarp. This damage can increase the exposure to pathogens and moisture loss limiting or reducing the product shelf life (Hallauer, 2001; Han et al., 1996).

Sweet corn is commonly harvested at kernel moisture around 75–80% (Calvo-Brenes & O’Hare, 2020; Szymanek et al., 2015), and dehydration is a post-harvest issue that can be caused by pre- and post-harvest factors. Within the preharvest factors, over-maturity is the main cause of kernel dehydration. During post-harvest life, dehydration can be caused by low moisture environments. A loss of 2% kernel moisture can lead to significant kernel denting compromising the freshness appearance (ASHRAE, 2010). Among the post-harvest handling, vacuum cooling can also reduce the kernel moisture content and lead to significant loss of quality (ASHRAE, 2010). During shelf life, cobs stored with husks have been shown to keep a moisture content similar to those packed with polyethylene films suggesting the positive influence of wrapping on kernel moisture (Oluwalana et al., 2017).

Non-physiological disorders can be caused by post-harvest factors such as handling, processing or ripening. Although sweet corn shelf life benefits from storage temperatures close to 0 °C and is not chilling sensitive, freezing injuries can arise from these conditions. Sweet corn
storage with husk leaves is more prone to freezing injury, developing water-soaked leaves and silks. This injury leads to discoloration and development of off-odours. Moreover, freezing injury is also possible in kernels stored at temperatures lower than 2.5°C (Shao & Li, 2011). Thawed kernels show discoloration, gelatinous texture and a slimy surface, and rapid development of off-odours (alcoholic and sour) characteristics (Shao & Li, 2011).

Browning is a phenomenon that has been described in a wide range of fresh-cut vegetables such as lettuce or avocado (Rensburg & Engelbrecht, 1986; Saltveit, 2004) and processed vegetables and fruits such as sliced onion or apple juice (Bernaś & Jaworska, 2015; Cao et al., 2018). This process causes deterioration of food during storage and commercial or domestic processing. In contrast with the browning commonly observed in other fresh-cut products such as bananas, apples or mushrooms, browning in sweet corn happens after cooking. The main cause of after cooking browning is the complex Maillard reaction first described by Louis-Camille Maillard (Nursten, 2005). This reaction generally happens between a reducing sugar and amino group yielding a glycosylamine, which can react in multiple ways to produce different compounds determining the flavour and colour of the post-cooked product (Nursten, 2005). Additionally, these brown products can occur from alternatives routes depending on the reaction environment (pH, temperature, moisture, among others; Nursten, 2005).

Moreover, it can happen from degradation of relatively small molecules such as ascorbic acid or sugar monomers or from the degradation of bigger molecules such as sugar polymers or lipids (Claus et al., 2008; Hidalgo & Zamora, 2000).

Riad et al. (2003) and Blanchard et al. (1996) described post-cooking browning in sweet corn and onion, respectively. Both studies suggest the positive effect of a low oxygen modified atmosphere to reduce the browning, and how this browning does not follow the Maillard reaction browning characteristics. The fresh market and the canned sweet corn industry are the ones concerned about the browning issues. Sweet corn browning happens in multiple varieties, inconsistently along the ear’s rows, and throughout the season. In the canned industry, sweet corn is harvested and taken to facilities for processing (kernel cutting and boiling). In fresh sweet corn, post-cooking browning occurs at the customer level, causing customer dissatisfaction with the product. Browning most commonly happens at the cut-ends of the cob although single kernels along the cob rows also occasionally brown (Figure 1c). Within browned kernels, different types or browning have been observed. On some occasions the browning only happens in the kernel pericarp, while the endosperm remains yellow. On other occasions, the whole kernel turns brown.

In the first instance, this kind of browning does not seem to be caused by the Maillard reaction. Although temperature has
an essential role in this reaction, this browning is restricted to certain kernels and it does not always happen. Moreover, microwaving as a cooking method does not lead to browning by the Maillard reaction (Meda et al., 2016), suggesting that other mechanisms are at play. Further support for this contention is found in the study by Riad (Riad et al., 2003), where 5-hydroxymethylfurfural (HMF), a characteristic intermediate of the Maillard reaction could not be found. CA packaging appears to have a positive effect leading to reduced browning, through the inhibition of polyphenol biosynthesis (Blanchard et al., 1996). Hence, this kind of browning might be more like the browning that happens as a consequence of the accumulation of polyphenols and the interaction of these with other compounds such as proteins or iron rather than being due to the Maillard reaction (Blanchard et al., 1996; Riad et al., 2003).

3 | SWEETCORN POST-HARVEST TREATMENTS FOR IMPROVED QUALITY: THE SOLUTIONS

3.1 | Defining effective cooling to extend sweet corn shelf life

Storage conditions have a critical role in ensuring a longer shelf life for sweet corn (Lum et al., 2016), with refrigeration the principal method to limit the product’s metabolism, pathogen development and extended shelf life. Higher temperatures result in higher respiration rates, synthesis of undesired products, ripeness and loss of freshness. Lower temperatures generally reduce enzymatic activity and therefore decay and post-harvest disorders; however, very low temperatures can have a counter effect due to freezing injury, development of ice crystals and reducing membrane fluidity what can produce damage and shorten shelf life (Chisari et al., 2007; Nguyen et al., 2003). For fresh sweet corn, the optimum storage temperature is as close to 0°C as possible, but avoiding freezing (Liplap et al., 2013; Shao & Li, 2011; Xie et al., 2017). Sweet corn harvests commonly take place during the summer and beginning of the fall. At this time of the year, elevated ambient temperatures do not favour an extended post-harvest life. To minimize this problem, farmers often begin harvesting at night through to early morning before the ear is warmed by the sun. Co-incidently, for other crops such as leafy green and aromatic herbs, this night-time harvesting has a negative effect on shelf life since it has been shown that leaves are at their most vulnerable due to reduced sugar content following dark hours depletion (Clarkson et al., 2005). Immediately after harvesting, cobs are cooled down as quickly as possible, a practice that reduces the temperature resulting from the environment and the heat produced by cob respiration. Vegetables with high respiration rates such as sweet corn, peas and broccoli can produce heat to melt the equivalent of 125 kg of ice per tonne of vegetables (ASHRAE, 2010). The conversion of sugars to starch happens as long as the kernel metabolism is active and is responsible for the loss of sweetness (Carey et al., 1984). Therefore immediately after harvesting, the ear must be cooled down to 0°C to preserve quality (Vigneault et al., 2007; Xie et al., 2016) and after first temperature depletion, crushed ice and/or cold air systems are used for storage and shipment.

A common system to cool down sweet corn is hydrocooling, but some producers are still using chambers of cold airflow which can take up to 180 min to cool from 28.2°C to 3°C (Xie et al., 2016), which is probably too slow to have maximum positive impact. Hydrocooling consists of a steady flow of cold water (0°C) at a rate of approximately 2 litres per kilogram and per hour for sweetcorn (Sousa et al., 2015; Iribe-Salazar et al., 2015). Sweet corn is loaded into containers, and then, a steady flow of 0°C cold water is continuously running from 30 min to 1 h. This drenching is very effective to rapidly remove field heat. If the cooling is made in crated cobs, perpendicular orientation to the water flow has been shown to significantly reduce the half time for cooling (Vigneault et al., 2007). The circulating water in hydrocooling systems is usually cooled down with the addition of crushed ice as required to maintain the temperature. Other water-cooling systems such as spray flow are not as effective as water flow (Vigneault et al., 2007).

Vacuum cooling is also becoming popular to cool down fresh-cut produce, although it requires higher infrastructure and associated costs. This technique was first implemented to cool down bakery products but is currently applied to many fresh-cut fruit and vegetables and cut flowers (Brosnan & Sun, 2003; Siddiq & Ubersax, 2018). This method has a shorter cooling time when compared to room cooling (Liu et al., 2012). When vacuum cooling is used for sweet corn, pre-wetting the cob is highly recommended to reduce moisture loss (ASHRAE, 2010; Brosnan & Sun, 2003).

3.2 | Understanding how temperature and oxygen determine sweet corn respiration rates to ensure extended shelf life

Due to the high sugar and moisture content, sweet corn has one of the highest respiration rates among all fresh-cut vegetables (Kader, 2002), with respiration rates variable between genotypes, environments and post-harvest conditions. Morales-Castro et al., (1994) showed that respiration rates in fresh-cut produce increased over time, although other authors (Riad, 2004) have suggested that the microorganism flora may contribute to higher respiration rates in late shelf-life scenarios. Respiration rate varies from 15 ml CO₂ kg⁻¹ h⁻¹ at −1°C to 480.3 ml CO₂ kg⁻¹ h⁻¹ at 30°C (Table 3). Temperature is the
factor with the highest impact on the respiration rate, showing that for every 10°C rise, the respiration rates are doubled (Morales-Castro et al., 1994). Oxygen is the factor limiting respiration in most situations and thus can be exploited to extend post-harvest shelf life, since respiration rates are also affected by the oxygen available in the atmosphere. Increase in the respiration rates at 5 and 21% oxygen are of 10 and 30 ml−1 O2−1 kg−1 h at 2°C and 20 and 60 ml−1 O2−1 kg−1 h at 10°C, showing a threefold increase at 21% relative to 5% oxygen (Morales-Castro et al., 1994). The combination of a low temperature and low oxygen atmosphere can be very effective in reducing respiration rates to prevent sugar loss and post-harvest decay.

Summary: The optimum temperature for sweet corn storage is 0°C, which helps to reduce microorganism development and sweet corn respiration rates. Hydrocooling has been shown to be more efficient than air cooling in reducing sweet corn temperature after harvesting. Moreover, vacuum cooling reduces the cooling times, but infrastructure and costs can be limiting.

### 3.3 | Modified (MA) and Controlled Atmosphere (CA) packaging for sweet corn

The regulation of the gas composition in a passive MA or active CA during storage has been vital in enabling the extension of post-harvest life for a wide range of fresh-cut produce. Since fresh-cut fruit and vegetables are living tissues, available concentrations of CO2 and O2 can impact on their metabolism. Moreover, the gas composition can also modify the microbiome of the produce (Kader, 2002).

Given that sweet corn has a high respiration rate, most fresh-cut producers rely on the ability of the produce to create its own passive atmosphere after packaging (MA). This change is essential in perishable products with high sugar content such as sweet corn or peas, as it preserves the product sweetness (Tewfik & Scott, 1954). However, due to differences between varieties and post-harvest temperatures, respiration rates can vary between post-harvest conditions, making the design of the right atmosphere and film challenging and highly depending on the variety, post-harvest conditions and harvesting with an absolute requirement for specific trials on specific genotypes (Morales-Castro et al., 1994; Smyrniotaki et al., 2010).

One of the benefits of a MA is the reduction in respiration and therefore the loss of sugars, and following this, a limit on aerobic plant pathogens and reduction in ethylene production. Although sweet corn is not ethylene sensitive, when packed with husk leaves, ethylene production can cause leaf yellowing (Deák et al., 1987; Liplap et al., 2013). On the other hand, too low oxygen or too high CO2 content can cause injuries and development of anaerobic microorganisms and consequently, off-odour and off-flavour (Rodov et al., 2000). The implementation of an effective modified or controlled atmosphere regime relies heavily on commodity, cold chain and packed volume. When sweet corn is stored at 10°C, two cob packs can take up to 5–7 days to reach a stable gas balance (Riad, 2004).

Previous experiments have shown contradictory results of CA or MA treatments. Very initial work with some of the earliest sweet corn varieties by Spalding et al. (1978) suggested that controlled atmospheres had no effect on appearance or flavour. But since then, several studies have shown a positive effect on preventing sweet corn decay by the use of modified atmospheres (Meng et al., 2013; Morales-Castro et al., 1994; Oluwalana et al., 2017; Riad & Brecht, 2003; Rodov et al., 2000; Smyrniotaki et al., 2010), showing that CA or MA can reduce the high respiration rates of sweet corn and consequently preserve sweetness and flavour loss.

Riad and Brecht (2003) tested multiple combinations of MA with 2% and 21% O2 and 0.3%, 15%, and 25% CO2 at 5°C. Their results showed that sweet corn stored in all modified atmospheres had a higher sugar content and better appearance than the control treatment (21% O2 and 0.3% CO2). The treatment with low oxygen concentrations (2%) and high CO2 (25%) triggered a quick rise of the respiration rate, probably caused by the anaerobic respiration of sugars. On the other hand, treatments with 21% O2 and high CO2 (15 and 25%) showed the lowest respiration rates. The treatment

| Temperature | ml CO2−1 kg−1 h | Reference |
|-------------|----------------|-----------|
| 0 | 40.7–49.57 | Tewfik and Scott (1954) and Xie et al. (2017) |
| 5 | 62.34–63 | Gross et al. (2016) and Xie et al. (2017) |
| 10 | 105.0–150.34 | Gross et al. (2016) and Xie et al. (2017) |
| 15 | 159.0–234.67 | Gross et al. (2016) and Xie et al. (2017) |
| 20 | 261.0–290.51 | Gross et al. (2016) and Xie et al. (2017) |
| 22 | 266.9 | Tewfik and Scott (1954) |
| 25 | 359.0–380.65 | Gross et al. (2016) and Xie et al. (2017) |
| 30 | 480.34 | Xie et al. (2017) |

TABLE 3 The range of respiration rates of sweet corn cobs reported by several authors.
with 2% O\textsubscript{2} and 15% of CO\textsubscript{2} did not show low respiration rates, but it showed the best organoleptic parameters (sugar content, aroma and appearance). Similar results were found by Smyrniotaki (2011) who observed that sweet corn cobs stored in 8% of O\textsubscript{2} and 12% of CO\textsubscript{2} at 3\textdegree C maintained the sugar content and sweetness for 24 days. Thus, in summary, this works shows that the optimal conditions for extending sweetcorn shelf life are in the range of 5–10% of O\textsubscript{2} and 10–15% CO\textsubscript{2} to be optimized for each post-harvest scenario.

Anaerobic respiration of sugars and development of anaerobic organisms can significantly damage sweet corn quality. While low oxygen can prevent loss of sweetness and development of microorganisms, low oxygen atmospheres coupled with high temperatures can rapidly cause the development of off-odours and off-flavours. When the product is exposed to high temperatures (>15 \textdegree C), oxygen levels are recommended to be kept high as fermentation can happen with oxygen levels as high as 8% (Rodov et al., 2000).

Due to the rapid change in respiration rates with temperature (Table 3), sweet corn can rapidly develop an undesired anoxic atmosphere. To solve this problem, nested liners are used during shipping to reduce O\textsubscript{2} flow and maintain the desired atmosphere when the temperatures are low such as during shipping. For the shelf-life period when the packages are exposed to higher temperatures, outer liners are removed and high perforation films that allow more oxygen into the package are used (Rodov et al., 2000). Canned sweet corn is subjected to boiling and sterilization processing reducing the perishability of the produce. Moreover, atmospheres with 3% of O\textsubscript{2} and 15% of CO\textsubscript{2} can enhance the nutritional value (higher ferulic acid) when compared to those stored in an air atmosphere (Chudhangkura et al., 2018).

In addition to oxygen and carbon dioxide, other compounds have been used to improve product preservation and shelf life. Nitrogen is a substitute for oxygen and carbon dioxide in modified atmosphere packages. It is used to balance, or to increase the package volume when the O\textsubscript{2} and CO\textsubscript{2} are fixed (Church & Parsons, 1995; Jamie & Saltveit, 2002). Inert gases (such as argon and helium) enriched atmospheres have been applied to the preservation of fresh-cut products as they have different diffusion rates of oxygen, carbon dioxide and nitrogen (Burg & Burg, 1965). Little is known about the effect of these gases, but research has suggested that they are suitable to reduce the alterations in the phenolic and antioxidant content (Char et al., 2017; Pinela et al., 2018), while in contrast, other research has shown a comparable effect to nitrogen (Baldassarre et al., 2015; Jamie & Saltveit, 2002).

**Summary:** When low temperatures can be assured, low O\textsubscript{2} (<10%) and high CO\textsubscript{2} (>15%) can prevent microorganism development and the maintenance of quality. When temperatures higher than 8\textdegree C are unavoidable, high CO\textsubscript{2} (>15%) can prevent microorganism development, but levels of O\textsubscript{2} must remain high (>8%) to prevent anaerobiosis.

### 3.4 The right choice of packaging film

Packaging films in the food industry have four major functions: containment, protection, convenience and communication recently reviewed by Kim and Seo (2018). Containment and protection are the functions intending to enhance the produce shelf life. Packaging films have an essential role in the development of the favourable modified atmosphere (MA) previously mentioned. Table 4 shows some example of films currently commercially available, with their oxygen and carbon dioxide transmission rates used for sweet corn packaging. Alternatively, when films have a low or no permeability impeding gas exchange, micro-perforations from 3770 \textmu m\textsuperscript{2} to 0.12 mm\textsuperscript{2} can be used to achieve modified atmospheres (Gonzalez-Buesa et al., 2013).

Cuquel et al. (2012) found that wrapping with stretchable PVC films enhanced shelf life at room and refrigerated temperatures when compared to unpacked cobs. Similarly, other

| Table 4  | Example of films used in sweet corn packaging and their oxygen and carbon dioxide transmission rates |
|---------|-----------------------------------------------------|
| **Film** | **O_{2}** | **CO_{2}** | **Reference** |
| Cryovac E bags\textsuperscript{®} | 0.4 mL 100 cm\textsuperscript{2} 24 h\textsuperscript{-1} | - | Deák et al. (1987) |
| Cryovac carrier bag\textsuperscript{®} | 0.003–0.004 ml cm\textsuperscript{2} 24 h\textsuperscript{-1} | - | Deák et al. (1987) |
| SM–250–1 SM–570 Cryovac | 300 ml cm\textsuperscript{2} h\textsuperscript{-1} | 465 ml cm\textsuperscript{2} h\textsuperscript{-1} | Morales-Castro et al. (1994) |
| Polyolefin AM Suntec\textsuperscript{®} | 1.8 ml cm\textsuperscript{2} 24 h\textsuperscript{-1} | 8.0 ml cm\textsuperscript{2} 24 h\textsuperscript{-1} | Aharoni et al. (1996) |
| Polyolefin K–400 T Asahi Chemical\textsuperscript{®} | 1.2 ml cm\textsuperscript{2} 24 h\textsuperscript{-1} | 5.0 ml cm\textsuperscript{2} 24 h\textsuperscript{-1} | Aharoni et al. (1996) |
| Polyvinyl chloride (PVC) | 1.9 ml cm\textsuperscript{2} 24 h\textsuperscript{-1} | 14.0 ml cm\textsuperscript{2} 24 h\textsuperscript{-1} | Aharoni et al. (1996) |
| SM60 M Cryovac | 0.16\% perforated area | - | Rodov et al. (2000) |
| Polyvinyl chloride (PVC) | 1.91 ml cm\textsuperscript{2} 24 h\textsuperscript{-1} | 14.1 ml cm\textsuperscript{2} 24 h\textsuperscript{-1} | Rodov et al. (2000) |
| Copolymer film Cryovac | 51.2 ml cm\textsuperscript{2} 24 h\textsuperscript{-1} | 51.2 ml cm\textsuperscript{2} 24 h\textsuperscript{-1} | Risse and McDonald (1990) |
| Polyvinyl chloride (PVC) | 1.2 ml cm\textsuperscript{2} 24 h\textsuperscript{-1} | 5.0 ml cm\textsuperscript{2} 24 h\textsuperscript{-1} | Risse and McDonald, 1990 |

* 0.001% of perforation.
authors have observed that cobs packed with PVC film had a positive effect due to the creation of a moisture saturated atmosphere, that prevented weight loss (Sousa et al., 2015; Xie et al., 2016). This prevention of moisture loss is essential as a loss of 2% of moisture can result in kernel denting, gravely compromising appearance (ASHRAE, 2010).

Temperature fluctuations during storage and shelf-life can lead to condensation on the inner surface of the film. These water droplets can lead to higher microbial spoilage (Caleb et al., 2013; Rodov et al., 2000), and thus, constant temperature must be maintained. Films with low permeability can be particularly susceptible to high condensation due to reduced gas transmission. If temperatures are difficult to control, antimist treated films can help to reduce this problem dispersing the droplets creating an invisible layer (Gross et al., 2016).

When temperatures during the cold storage can be ensured but not the retail temperatures, Rodov (2000) suggested the use of plastic liners. Liners with low OTR (Xtend® Table 4) can be used to ensure a CO₂ level of 10 kPa during shipping but for retail temperatures, and these liners have to be removed to avoid fermentation. In addition to these liners, packaging with high perforations can be used during retail shelf life to ensure enough oxygen inside of the package (Rodov et al., 2000).

Breakages in the cold chain causing higher temperatures cause a rapid change in the product respiration but small variations in the film permeability. To tackle this issue, new films capable of changing its permeability in a wider range are being developed. One example of this is the membrane patented by Clarke and Derringer (2004), which uses a membrane formed by a porous substrate coated by a side chain crystalline (SCC) polymer. The SSC polymer can be designed to melt at a determined temperature allowing the transmission of O₂ and CO₂ into the pack preventing the development of anaerobic atmospheres (Clarke, 2011).

Moreover, the use of low perforation films (AM Suntec® and K-400 T Asahi Chemical ®) showed a lower decay incidence of the cut-ends compared with those cobs packed with PVC film. This higher decay in PVC films could be caused by the higher proliferation of microorganisms due to a higher oxygen availability compared with lower perforation ones (Aharoni et al., 2008). Differently, other authors have reported that although films had a beneficial effect maintaining freshness, they can accelerate microbial growth in the presence of damaged husks or kernels (Riad & Brecht, 2003; Risse & McDonald, 1990).

New films meeting the customer demand of a more environmentally friendly packaging are coming up. Polylactic acid polymers are one of the alternatives to polyvinyl chloride and polypropylene films, that have successfully shown to be suitable for developing and maintain a modified atmosphere for fresh-cut produce (Mistriotis et al., 2016). Furthermore, new technologies are being applied to the packaging of fresh produce industry, such as freshness sensors that indicate spoilage and ripeness (Kuswandi, 2017) and ethylene scavengers that delay ripening (Gaikwad et al., 2020).

**Summary:** Films for sweet corn packaging provide two benefits; first the containment of the produce moisture and secondly the development of an atmosphere that prevents decay and loss of quality. Film permeabilities must be carefully selected for each for each shelf-life scenario, choosing higher perforation for ambient temperatures and lower perforation for chilled produce.

### 3.5 How the sweet corn microbiome impacts shelf life

Supply chains and post-harvest handling are complex processes that may put at risk the safety of the product. The microbiome of a produce is firstly established during the product development in the field being soil, rain and animal sources of colonizing microorganisms. Evidence suggests that the microbiome during crop growth can be dynamic (Compant et al., 2019). Furthermore, other factors such as moisture and temperature can have importance determining the final community (Müller et al., 2016). Fungi are the main cause of post-harvest losses in maize and other cereals (Lane et al., 2018), particularly from the genus *Fusarium* and *Aspergillus*. These present the biggest concern due to the production of mycotoxins and their capacity to infect and spread through the maize plant (Munkvold et al., 1997). Additionally, post-harvest handling in the packing house and during distribution is intricate practices that can alter the microbial load. Zoellner et al. (2018) modelled and identified parameters and processes including chlorinated wash, cross-contamination and time after packaging as some of the most influential in the determination of the microbial loads in tomato post-harvest procedures from Mexico to the USA.

The microbiota is one of the problems that has potential to reduce the shelf life of sweet corn. Levels lower than 2 colony forming units (CFU⁻¹ g) need to be guaranteed for the safety of the produce. Poor hygienic conditions in post-harvest handling of freshly shelled kernels can lead to high counts of aerobic microorganisms (8 CFU⁻¹ g), yeasts and mould (7 CFU⁻¹ g) and possible coliforms (4 CFU⁻¹ g) on sweet corn kernels (Kumar et al., 2015). In an early study on irradiated sweet corn by Deak et al. (1987), 89 strains of bacteria were identified with the most frequent genera including *Pseudomonas, Flavobacterium, Xanthomonas, Enterobacter* and *Serratia*. Also, 65 strains of yeasts and 12 of moulds were present. Among which, the most abundant genera were *Rodotorula, Candida, Penicillium* and *Aspergillus*. These genera differed between temperatures dominated by pseudomonas and basidiomycetes yeasts at 10°C and fermentative yeasts and enterobacteria at 20°C.
Listeria monocytogenes is one of the major pathogens in food-borne diseases that is prevalent in fresh-cut produce, leading to significant numbers of food-borne disease outbreaks (Qadri et al., 2015). An evaluation of salads with and without sweet corn inoculated with L. monocytogenes found that the presence of sweet corn resulted in increased pathogen development (Nguyen-The et al., 1996). A different study of sweet corn inoculated with a concentration of 4 log CFU\(^{-1}\) g of L. monocytogenes, the contamination surpassed 8 log CFU\(^{-1}\) g after 8 days at 10°C (Carlin et al., 2001). This suggest that the inclusion of sweet corn in mixed raw salad bags can lead to increased development of this human pathogen to dangerous concentrations. This emphasizes the importance of the prevention and inhibition of food-borne diseases during sweet corn post harvest handling. Multiple studies concur that de-husked and cut end cobs have higher spoilage due to microorganism development (Deák et al., 1987; Oluwalana et al., 2017; Riad & Brecht, 2003; Risse & McDonald, 1990). The use of MA has also proven to be beneficial in controlling the development of mycelial growth & spoilage due to microorganism development (Deák et al., 1987; Oluwalana et al., 2017; Riad & Brecht, 2003; Risse & McDonald, 1990). The use of MA has also proven to be beneficial in controlling the development of mycelial growth due to the fungistatic effect of high concentrations of CO\(_2\) (10–20%), and the reduced development of bacteria in low O\(_2\) (2–5%) atmospheres (Riad et al., 2003; Sebők & Baár, 2009).

To prevent contamination, sanitation techniques are used across all the production processes. Solutions of antimicrobial compounds are the most used technique to sanitise surfaces, reduce microbial loads and prevent cross-contaminations. Among the most popular antimicrobials are sodium hypochlorite (25–200 mg l\(^{-1}\)), peroxyacetic acid (60–80 ppm), hydrogen peroxide (only for surfaces) and citric acid (0.1–0.5 M; Artés et al., 2009; Gil et al., 2009). For sweet corn kernels, Kumar and Gautam (2016) suggested a chlorination process based on the use of 200 ppm of sodium hypochlorite for 5 min, which achieved a shelf life of kernels at 4°C for up to 30 days.

A new trend in the sweet corn market is high-temperature sterilised or blanched sweet corn cobs being commercialized in Asian countries and already available in some European countries, where sweet corn kernels are exposed to high temperatures (>80°C) for 15 min or 20 min at 95 - 98°C in the case of hot water blanched cobs (Meng et al., 2013; Sebők & Baár, 2009). The high-temperature sterilization procedure can reduce the microbial load from 5.5 log CFU\(^{-1}\) g in fresh corn to 1.5 log CFU\(^{-1}\) g, ensuring the safety of packed corn for 90 days (Meng, 2013).

Summary: Fresh-cut sweet corn exposes sugars and water to the environment and is an ideal media for microorganism development. Prevention of microorganism development is essential to reduce produce spoilage and ensure food safety; thus, high hygiene standards must be kept, and cleanliness of cutting blades and surfaces ensured at all times.

**4 | CONCLUSIONS**

Effective post-harvest management of sweet corn can help reduce food waste and financial losses and support the growing demand for fresh, high-quality fruit and vegetables. Maintaining sweet corn post-harvest quality and shelf life is challenging because of the high sugar and water content in the cobs. On the other hand, these characteristics give sweet corn its sweetness, texture and customer appeal. In this review, we found that post-harvest shelf life and quality can be best preserved and enhanced by (a) keeping temperatures as close as possible to 0°C throughout the post-harvest process, which is the most important factor to extend sweet corn shelf life, (b) reducing field and respiration heat in sweet corn by rapid hydrocooling. In addition to low temperatures, (c) the use of films to create a modified or controlled atmosphere is proven to preserve sweet corn quality and lessen the effect of higher storage temperature. Film properties and perforation rates should be considered for each shelf-life scenario (d) A modified atmosphere of 10% O\(_2\) and 15% CO\(_2\) is optimal for fresh-cut sweet corn stored at low temperatures (0–5°C).

Further research on sweet corn post-harvest is needed to characterize the whole post-harvest chain and the interactions between treatment at various stages of the process. Moreover, the application of new post-harvest technologies including packaging and treatments, and breeding of elite varieties are some of the upcoming trends to meet future demands and ensure high quality in the fresh-cut produce market.

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