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## Characterising the sweet corn postharvest supply chain: travel from Senegal to the UK

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**Abstract:** Sweet corn (*Zea mays* L.) is a grain harvested before maturity and consumed as a vegetable. An optimal supply chain, to preserve sugars and antioxidant (AO) capacity is essential to maintain quality of sweet corn. The choice of packaging film plays an essential role, especially in products with a high respiration rate such as sweet corn. Sweet corn grown on a commercial farm in Senegal was sampled at the harvest day, at the UK arrival date following 12–14 d of shipping (packaging date), at the best before date (BBD) and 5 days after the best before date. The results showed that high quality preservation of sweet corn is possible along a complex supply chain from harvest in Senegal through transport to the UK. Results suggested that lower perforation films have a beneficial role in preserving antioxidant capacity. Furthermore, damaged kernels in the cut-ends of the cobs were shown to be the main factor reducing the overall quality of the product.

**Keywords:** sweet corn; maize; postharvest; shelf life; packaging; films; sugars; starch; antioxidant; peroxidase; POD; polyphenol oxidase; PPO; damage; Senegal; UK.

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**Biographical notes:** Felipe Becerra-Sanchez is working to optimise from pre to post-harvest the quality of the products. Aiming to reduce the food loss and waste along the fresh vegetables supply chain. His PhD investigates how pre and post-harvest variables have an effect on different sweet corn varieties cultivated in diverse environmental conditions.

Gail Taylor has been employed by and based at The University of California, Davis, where she is Professor and Chair of the Department of Plant Sciences. During her 20-year tenure at Southampton, she held several position in the University including Director of Research for Biological Sciences (2012–2015). She is currently the Chair of the Department of Plant Sciences, UC Davis. She was a Full Professor of Plant and Environmental Biology at

University of Southampton (2004–2017), a Senior Lecturer and Reader at Plant and Environmental Biology, University of Southampton (1999–2004) and Lecturer and Senior Lecturer at Plant Biology, University of Sussex (1990–1999).

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## 1 Introduction

Food loss and waste during postharvest handling, distribution and consumption are an important, but often over-looked component of global food security (Gustavsson et al., 2011). In recognition of this, the FAO 2030 Agenda for Sustainable Development includes a target to; “By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including postharvest losses” (FAO, 2015). Thus, reducing postharvest food losses remains important at a global scale.

Sweet corn (*Zea mays* L.) is harvested at an immature stage and consumed as a vegetable. Sweet corn imports in the UK market have been continuously increasing totalling 61.5 thousand tonnes in 2018 (Horticulture, statistics <http://www.gov.uk> accessed: 05/04/20). Sweetness, odour, colour and tenderness are the principal qualities considered important by the consumer and therefore, the most important to preserve (Carey et al., 1984; Flora and Wiley, 1974). The high amounts of water, sugars and high respiration rates make sweet corn a very perishable commodity prone to fast degradation, with a shelf-life that may be as little as 2 days at room temperature (Riad et al., 2002). Sweet corn is a warm climate crop originating from the tropics, but the consumer markets rely on an adequate supply chain throughout the year, meaning production must move around the globe to satisfy this demand. Characterising the supply chain is therefore essential when handling highly perishable commodities. Handling, temperature and atmosphere are the main parameters to consider when optimising any produce supply chain. Although sweet corn can be stored at 0 °C or even lower temperatures, the cost and feasibility of these conditions over a long supply chain are often impractical and thus, modified atmospheres are used to counteract the effect of higher, sub-optimal temperatures during shipping and shelf-life (Aharoni et al., 1996; Rodov et al., 2000; Xie et al., 2016).

The atmosphere within the package is determined by the permeability of the film and the respiratory rates of the produce. When sweet corn is packed or stored in sealed containers, the atmosphere within the container changes rapidly, oxygen is depleted and carbon dioxide rises, creating a modified atmosphere (MA), that can have benefits if the permeability of the film or the container aeration favours an adequate exchange of gases. Previous studies have shown that atmospheres with less than 2% O<sub>2</sub> or more than 20% CO<sub>2</sub> can lead to accelerated product degradation (Manleitner et al., 2003). Riad, (2004) observed that the best atmosphere to store sweet corn was 2% O<sub>2</sub> and 15% CO<sub>2</sub>, maintaining the marketable quality for 10 days at 5°C. Similarly, Smyrniotaki (2011) found that sweet corn can be stored in 8% O<sub>2</sub> and 12% CO<sub>2</sub> at 3°C maintaining the sweet corn quality for 24 days. Thus, MA packaging can significantly improve shelf life and retain quality of harvested sweet corn.

Sweet corn varieties have been bred where the conversion of soluble sugars into starch is significantly limited (Lertrat and Pulam, 2007). A wide range of super sweet

corn cultivars that retain sweetness are now available, but the maintenance and enhancement of shelf-life remains a significant challenge. In some varieties, the soluble sugars can constitute up to 30% and the total carbohydrate concentration (sugars and starch) over 50% of the dry matter (Creech, 1968). This high concentration of soluble sugars contributes to sweet corn having one of highest respiration rates amongst other vegetables ( $30 \text{ mL CO}_2 \text{ kg}^{-1} \text{ hr}^{-1}$  at  $5^\circ\text{C}$ ) (Siddiq and Uebersax, 2018), that not only reduces the amount of sugar but also can lead to a faster loss of freshness. When inappropriately stored the decay of the product is accelerated, inducing softening, development of off-flavours and off-odours (Inglett and Gardner, 1971; Lee and Hammes, 2006; Liu et al., 2012; Rodriguez-Saona et al., 1995).

Another concern with a sub-optimal supply chain is the loss of nutritional value. Sweet corn is a rich source of phytochemicals with associated health benefits (Adom and Liu, 2002). Although corn vitamin C is one of the most abundant compounds extracted from maize, sweet corn has several other bioactive compounds such as carotenoids (lutein), phenolic compounds (ferulic acid), and fatty acids (linoleic acid) (Adom and Liu, 2002; Das and Singh, 2016; Sanjeev et al., 2014; Sitthitrai et al., 2016; Yang et al., 2019). Within all the phytochemicals, antioxidant compounds such as vitamin A, C and E, and polyphenolic compounds have been widely reported to have a positive effect on cardiovascular diseases and cancer (Kris-Etherton et al., 2002), making of them a valuable characteristic to preserve in the fresh-cut produce.

Several studies have been published on how cooking affects the antioxidant capacity of sweet corn (Harakotr et al., 2014; Kachhadiya et al., 2018; Lopez-Martinez et al., 2011; Sitthitrai et al., 2016) but only a few of these studies have assessed changes during the supply chain and shelf-life. Where antioxidants have been assessed, the emphasis has been on single groups of compounds such as phenolics, carotenes or ascorbic acid to assess the antioxidant capacity, with very limited data on total antioxidant potential. Although phenolics are thought to be one of the most important antioxidant compounds in sweet corn due to the high amounts of ferulic acid present, especially in the kernel pericarp (Chudhangkura et al., 2018; Dowd, 1994; Zhang et al., 2018), other compounds are also likely to contribute to overall antioxidant potential and thus most measurements underestimate the whole sum of compounds contributing to antioxidant activity.

In addition to health benefits, antioxidants play an important role in the postharvest life of fruits and vegetables. The identification and use of compounds that alleviate oxidative damage are becoming an important tool to extend the shelf-life of fresh-cut fruit and vegetables (Cao et al., 2018; Hu et al., 2014; Zhang et al., 2019). Moreover, physical treatments such as blanching (Lee and Hammes, 2006; Liu et al., 2012) and chemical ones like melatonin or hydrogen sulphide (Cao et al., 2018; Hu et al., 2014) have been shown to have a positive effect, modulating reactive oxygen species (ROS) and enhancing the antioxidant systems. ROS are oxygen radicals such as hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) or the anion superoxide ( $\text{O}_2^-$ ) produced during metabolism in response to abiotic or biotic stressors, which can cause oxidative damage deteriorating cellular components (Gill and Tuteja, 2010; Suzuki et al., 2012).

One of the main antioxidants in maize are polyphenols due to the high content of ferulic acid (Rouau et al., 2003). But also other phenolic compounds such as maysin, chlorogenic acid, phlobaphenes and ferulic acid polymers have been identified, which are involved in plant pest and pathogen resistance (Guo et al., 2010; Rouau et al., 2003). For

this reason, peroxidases and especially polyphenol oxidases have been studied in the corn tassel and silk rather than in kernels (Guven et al., 2016; Šukalović et al., 2010).

Plant peroxidases (POD) are a multigenic family of proteins involved in many physiological processes (Passardi et al., 2005). Due to its double catalytic cycle (peroxidative and hydroxylic), they can participate in the regulation of hydrogen peroxide ( $H_2O_2$ ) concentration within plant cells (Passardi et al., 2004). Along with POD, polyphenol oxidases (PPO) intervene in the oxidation of polyphenols into quinones, playing a role in plant defence and wounding (Passardi et al., 2005; Taranto et al., 2017). Both enzymes have been characterised to play a role in pathogen resistance in the maize silk (Šukalović et al., 2010). Due to its involvement in the regulation of ROS and oxidation of polyphenols, the inactivation of these enzymes has been suggested by several authors to improve sweet corn quality during storage and shelf-life (Lee and Hammes, 2006; Liu et al., 2012; Rodriguez-Saona et al., 1995).

Prevention of physical damage is one of the most important and most effective mechanisms to reduce postharvest losses, across many types of fresh produce. In some fruits, such as avocados, bruising can cause internal browning (Gamble et al., 2010) and in others, wounding can increase the internalisation of pathogens into the fresh product (Bartz et al., 2015). When cutting is unavoidable such as in the fresh-cut produce industry, very high hygiene standards, chlorination, sterilisation of equipment and blades, and precise cuts are the first approaches to reduce losses (Artés et al., 2009). Rodov et al., (2000) determined that the cob cut-ends can be the main cause of spoilage, having a higher fungal growth especially when very high diffusion rate films were used.

The aim of this research was to characterise the sweet corn supply chain from Senegal to the UK, enabling improved postharvest quality, through targeted management of the whole chain from harvest to sale. Senegal-supplied sweet corn is important, supplying the UK market for 7-8 months of the year. Generally sweet corn is harvested and hydro-cooled on-farm and shipped in refrigerated containers to the UK, where it is further processed and packed for the fresh-cut market. Sweet corn was analysed from harvest until 5 days after the best before date (BBD), quantifying sugars, antioxidant capacity, peroxidase and polyphenol oxidase activity as an indicator of produce decay. At the same time, both damaged and undamaged kernels were analysed to assess the importance of damage for sweet corn shelf life.

## **2 Materials and methods**

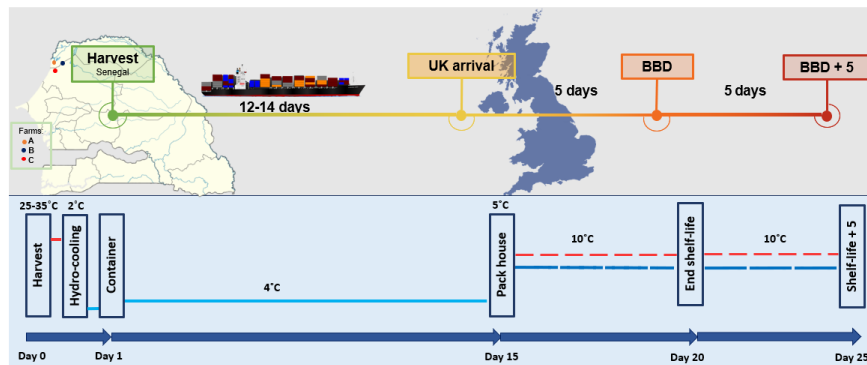
### *2.1 Location*

Commercial sweet corn was produced by the Société de Cultures Légumières (SCL) in Senegal. Sweet corn cobs were collected at four different times throughout the supply chain; harvest, UK arrival, best before date (BBD) and five days after the best before date (BBD+5).

Sweet corn ears were harvested from farms in three locations in northern Senegal within 10 miles of Saint Louis (lat: 16.02, long: -16.49) (Figure 1). In each location, sampling was completed on the same day as the commercial harvest. Samples at harvest point were taken following farmer criteria of maturity on the 9 May 2018. The moisture content of all the samples was between 75–85%, suggesting a similar maturity level among the samples, quantified as fresh to dry weight in 5 g of sweet corn kernels.

Moreover, qualified and experienced personnel were in charge of recognising harvest maturity, assessing parameters such as tip filling, milk line, yellowness, sweetness, and silk colour and all harvesting was undertaken at commercial scale using these criteria. Samples were collected randomly along multiple rows, avoiding the ten first plants on the field edges, to minimise edge effects. Unpollinated or damaged ears were discarded. For each site, six ears were sampled (3 sites  $\times$   $n = 6$ ).

**Figure 1** Image of the sweet corn supply chain from Senegal to the UK, with sampling points shown as harvest, UK arrival, BBD and BBD+5 (see online version for colours)



Note: Red and blue dashed lines represent two different packaging films.

## 2.2. Sampling

At the harvest site, cobs were pulled away from the plants and husked, until the desired number of cobs without disorders ( $n = 6$ ) was achieved. Then they were snapped approximately into two halves and kernels were pulled out of the cob and immediately snap-frozen in a tube filled with liquid nitrogen. Samples were transported in a cryoshipper to the University of Southampton where 5 g of kernels were freeze-dried for 72 h ( $n = 6$ ). The remaining kernels (20–30g) were ground in liquid nitrogen using a pestle and mortar and stored in a  $-80^{\circ}\text{C}$  freezer until assayed.

The remaining cobs were treated as a commercial crop and hydro-cooled to  $2^{\circ}\text{C}$  and shipped in refrigerated containers ( $8^{\circ}\text{C}$ ) to the UK packhouse. Upon arrival, the same number of unprocessed cobs ( $n = 6$ ) from each of the three containers were sampled as previously described. In addition, finished products (sweet corn twin packs) were taken to the University of Southampton, where they were refrigerated at  $10 \pm 1^{\circ}\text{C}$  for shelf life experiments. The cobs were packed using two polypropylene films differing in their laser perforation, film 2 having a higher degree of perforation than film 1. Packages were sampled on day 5 and 9 after processing as previously described. In addition, the wounded kernels from the cut edges of the commercial product were cut with a scalpel and snap-frozen. Six replicates were taken from each farm, packaging film and time, totalling 108 undamaged samples and 72 damaged samples.

## 2.3 Sugars

Soluble sugars and starch were quantified as described by Leyva et al. (2008) with minor modifications. 30 mg of freeze-dried ground tissue were weighed into centrifuge tubes,

and 1 ml of buffer (sodium acetate 0.2 mol/L pH 5.5) was added. Samples were thoroughly mixed and incubated on a thermomixer at 70°C for 15 min. Tubes were then centrifuged at 15,000 rpm for 10 min, and 30 µl of the supernatant was diluted in 1 ml of water and used for soluble sugar quantification. The remaining pellet was re-dissolved and incubated for 10 min at 100°C. Enzymatic digestion was carried out by adding 100 µl of amyloglucosidase (70 units/ml) and 100 µl of  $\alpha$ -amylase (7 units/ml) and incubating for 4 h at 37°C. Centrifugation was repeated, and 30 µl of supernatant was diluted in 1 ml of ultrapure water for starch quantification. 50 µl of sugars and starch dilutions were added to a 96-well flat-bottom plate. 150 µl of anthrone in sulphuric acid (0.1% v/w) was added to each well, incubated for 20 min at 100°C and then at room temperature for 10 min. Absorbance measurements were made with a ThermoScientific Multiskan spectrophotometer at 620 nm.

#### 2.4 Antioxidant capacity

A ferric reducing antioxidant power (FRAP) assay was carried out according to Benzie and Strain's (Benzie and Strain, 1996) method with some modifications (Payne et al., 2013). Due to its low cost, high reproducibility and high throughput, the ferric reducing antioxidant power of plasma (FRAP) is a common assay used to evaluate the total antioxidant activity in plant tissues based on the reduction of the complex  $\text{Fe}^{3+}$ -TPTZ to  $\text{Fe}^{2+}$ -TPTZ by antioxidants present in the sample.

Previous snap-frozen kernels were ground with a pestle and mortar in liquid nitrogen. This material was transferred to a QIAshredder tissue homogeniser tube (QIAGEN), weighed and centrifuged at 13,000 rpm for 5 min at 4°C. Serial dilutions of iron sulphate heptahydrate were used to create iron standards ranging from 0.25–8 mmol. Reagent mix was prepared with acetate buffer (300mmol/L), TPTZ /HCl (10 mmol/L) and ferric chloride hexahydrate (20 mmol/L). Flat-bottom 96-well plates were randomly filled with 5 µl of sweet corn sap from each sample, in triplicate, and the standards. The reagent mix was added to each well and absorbance was read at 584 nm on a Spectrostar Nano (BMG LABTECH).

#### 2.5 Enzyme activity

Peroxidase (POD) and polyphenol oxidase (PPO) activity of extracted sap were assessed as validated by Siguemoto and Gut (2017) with minor modifications.

To calculate the peroxidase activity, a potassium buffer of pH 6 was prepared with potassium phosphate monobasic (59 mmol/L) and sodium phosphate heptahydrate (15 mmol/L). The plates were incubated prior to loading at 25°C for 5 min then 125 µl of buffer and 10 µl of the sample were added to each well and incubated at 25°C for 1 min with stirring. The enzyme substrate 25 µl of 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulphonic acid) (ABTS) 1.16 mmol/L and 25 µl of hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) 0.1 mol/L were added to the reaction. In this case, the plate was read at 405 nm and 734 nm every 30 s for 30 min on a Spectrostar Nano (BMG LABTECH).

For the polyphenol oxidase assay, the buffer had a pH of 9 (53.5 mmol/L sodium phosphate heptahydrate and 0.04 mmol/L potassium monobasic). As the peroxidase substrate, a 0.1 mol/L pyrocatechin solution was prepared. Before loading the mix, the plate was incubated at 35°C for 5 min, then 100 µl of buffer and 30 µl of the sample were added to the plate and incubated at 35°C for another 5 min. 70 µl of pyrocatechin solution

was added to each well, and the plate was loaded into the Spectrostar Nano. The absorbance was read at 420 nm every 5 min for 21 cycles. In both cases, the enzyme activity (U) was calculated as a 0.001 increase in the absorbance per minute.

## 2.6 Statistical analysis

Data distribution was tested for normality and homogeneity of variances. One-way ANOVA ( $P < 0.05$ ) was performed to examine the effect of time, followed by a post-hoc HSD Tukey test to identify differences between groups for the response variables; sugar, starch, antioxidant capacity, peroxidase, polyphenol oxidase, and pH. Two (time and film) and Three-way ANOVA (time, film and damage) were used with a significance level of  $P < 0.05$  to identify differences. Sources of variation were time, treatments, and undamaged/damaged kernels. When differences were observed, Tukey's test was performed to identify differences between group means. Statistical analysis was performed using IBM SPSS Statistics software version 25 (Armonk, NY, USA).

## 3 Results

### 3.1 Effect of time (shipping and shelf-life)

#### 3.1.1 Carbohydrates

Total carbohydrates accounted for over 50% of the kernel dry weight [Figure 2(a)]. The results of the carbohydrate assay showed that soluble sugars decreased by 14% during the shipping and shelf-life period, from  $427.5 \pm 9.1$  mg/g dry weight (DW) at harvest day to  $369.0 \pm 14.6$  mg.g<sup>-1</sup> DW, 5 days after the best before date and the differences among the timepoints were significant [Figure 2(a); ANOVA  $F_{3,87} = 4.61$   $P < 0.001$ ). This loss of sugars postharvest, was only significantly different between the time points (Harvest and UK arrival) and 5 days after the end of the commercial shelf life (BBD+5, 10 days at 10°C). Total soluble sugars were not affected by shipping (Harvest to UK arrival), nor during the shelf-life period (harvest to BBD). In parallel, starch content increased from  $154.8 \pm 7.8$  mg/g DW at harvest to  $194.0 \pm 8.6$  mg/g DW, 5 days after the best before date and this was significantly different among timepoints [Figure 2(a); ANOVA  $F_{3,86} = 3.58$   $P = 0.005$ ). This represented an increase in the starches of 15.2% at the end of the shelf-life (BBD) and 24.2% 5 days later (BBD+5), compared to harvesting date.

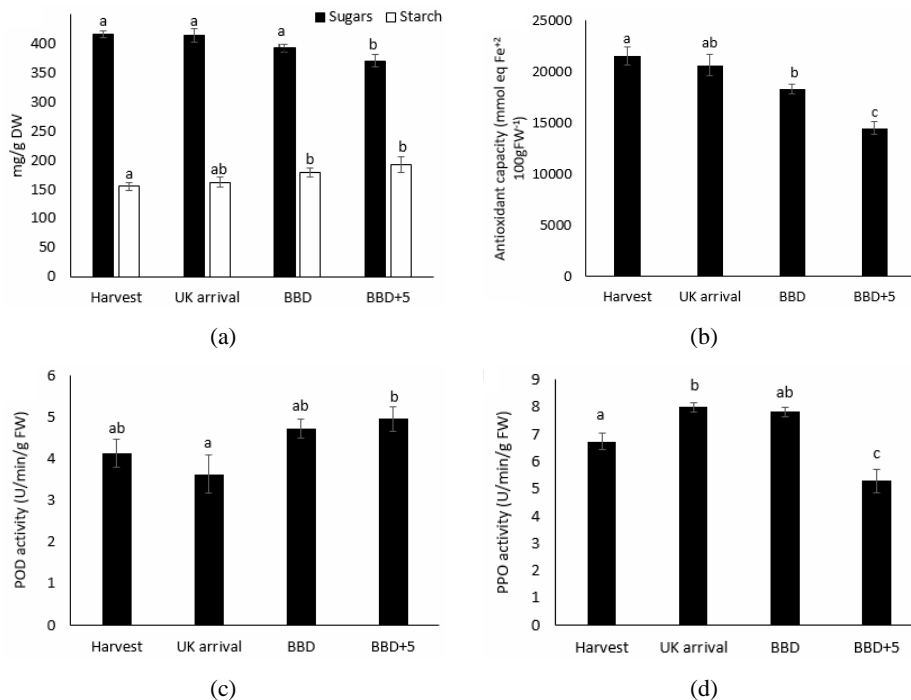
#### 3.1.2 Antioxidant capacity

Antioxidant capacity declined across the entire process showing significant differences among the timepoints (ANOVA  $F_{3,97} = 20.59$   $P < 0.0001$ ). However, there was no significant loss during shipping, whereas during the shelf-life period when the temperature was raised to 10°C, a 15% decrease in the antioxidant capacity of the undamaged samples was observed between harvest and BBD [Figure 2(b)], which was further increased at the BBD+5 to 33% of the original antioxidant capacity at the harvesting date.

### 3.1.3 Enzymatic activity

Peroxidase activity increased during the shelf-life period. No significant differences were observed from harvest to UK arrival, but a significant increase in POD activity was observed from UK arrival to BBD+5 [Figure 2(C), ANOVA  $F_{3,96} = 3.40$   $P = 0.021$ ]. Polyphenol oxidase activity showed a significant initial increase followed by a significant decrease after the BBD (ANOVA  $F_{3,96} = 18.588$   $P = 0.0001$ ). The PPO activity significantly increased from harvest to UK arrival, it remained constant during the first five days of shelf-life and it was significantly reduced at the BBD+5 [Figure 2(d)].

**Figure 2** Analysis of changes throughout the supply chain and shelf-life period for undamaged sweet corn kernels independently of the packaging film used, (a) sugar and starch concentrations (b) antioxidant capacity. (C) peroxidase activity (D) polyphenol oxidase activity



Notes: Bars represent the mean  $\pm$  SE. Harvest and UK arrival,  $n = 18$ , BBD and BBD+5,  $n = 36$ . Letters are significantly different groups of Tukey test  $p$ -value  $\leq 0.05$  for each test. One-way ANOVA (Table 1), BBD – best before date and BBD+5 – best before date plus 5 days.

## 3.2 Effect of film and damage

### 3.2.1 Carbohydrates

When comparing sugar content between the films used and between the BBD and BBD+5 time points no significant differences were observed (time  $F_{1,56} = 3.20$   $P = 0.079$ , film  $F_{1,56} = 0.78$   $P = 0.383$ ). The results showed that the film type had no impact on the amount of soluble sugars in the kernels. Similarly, starch did not show significant



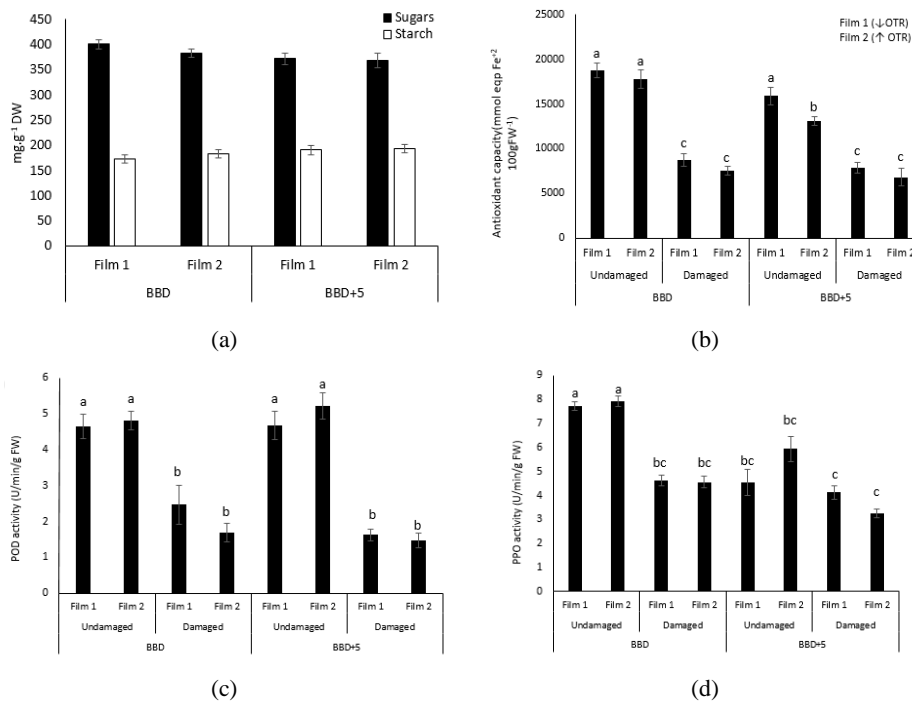
differences between the two packaging films (time  $F_{1,56} = 2.09$   $P = 0.154$ , film  $F_{1,56} = 0.87$   $P = 0.356$ ) [Figure 3(a)].

The overall loss of soluble sugars from harvest ( $427.5 \pm 9.1$  mg/g DW) to the BBD was of 6.2% for film 1 ( $401.00 \pm 9.85$  mg/g DW) and 10.4% for film 2 ( $383.10 \pm 8.48$  mg/g DW), and the increase in starch from harvest ( $154.84 \pm 7.77$  mg/g DW) was of 11.8% for film 1 ( $173.05 \pm 9.10$  mg/g DW) and 18.5% for film 2 ( $183.50 \pm 7.44$  mg/g DW).

### 3.2.2 Antioxidant capacity (FRAP)

Sweet corn packed in the film with the higher oxygen transmission rate (film 2) had a significantly greater loss of antioxidants [Figure 3(b)] (film  $F_{1,125} = 8.15$   $P = 0.005$ ). The difference between films was 4.4% at the BBD and raised to 12.5% at BBD+5, however the interaction of time and treatment was not significant (Table 1).

**Figure 3** Comparison of changes during the shelf-life period between films and undamaged and damage kernels, (a) sugar and starch concentrations (b) antioxidant capacity (c) peroxidase activity (d) polyphenol oxidase activity



Notes: Bars represent the mean  $\pm$  SE (n = 18). No significant differences were observed between treatments for the sugar and starch assay (two-way ANOVA). Three-way ANOVA was carried out for antioxidant capacity, POD and PPO activity. Letters are significantly different groups of Tukey test p-value  $\leq 0.05$ . BBD (best before date) and BBD+5 (best before date plus 5 days).

The damage produced at the cut-ends of the cobs resulted in the greatest difference in antioxidant content. The antioxidant capacity in the damaged kernels was significantly reduced to 50% of the antioxidant capacity in the undamaged ones (damage  $F_{1,125} = 267.38$   $P < 0.0001$ ). The packaging film did not have an effect on the antioxidant capacity in the damaged kernels [Figure 3(b)].

### 3.2.3 Peroxidase and Polyphenol oxidase

When assessing the POD activity between packaging films no differences were observed in damaged or undamaged kernels (films  $F_{1,112} = 0.50$   $P = 0.818$ ). On the other hand, damage was the factor that caused a significant decrease in the POD activity (damage  $F_{1,112} = 138.28$   $P < 0.0001$ ) [Figure 3(c)].

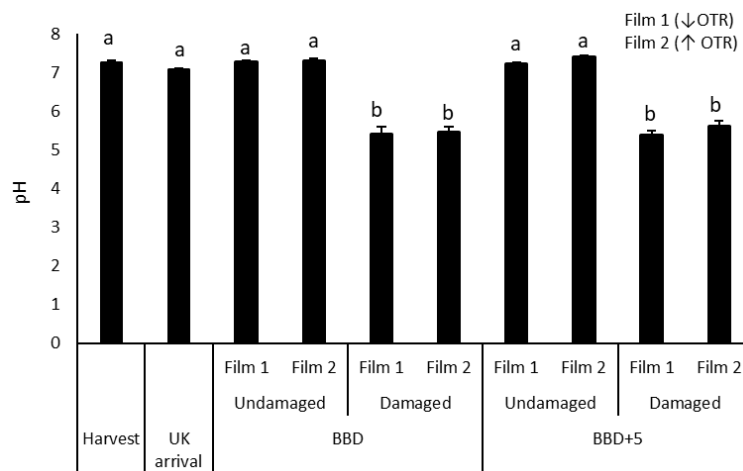
The polyphenol oxidase activity did not show differences between the treatments (films  $F_{1,112} = 0.35$   $P = 0.556$ ), as for POD the activity was significantly reduced by the effect of the damage produced at the cut-ends at the BBD (damage  $F_{1,112} = 85.66$   $P < 0.001$ ).

The variation in antioxidant capacity and enzymatic activities correspondent to undamaged kernels showed in Figure 2, are of a smaller relevance when compared to the effect produced on these variables by damage.

### 3.2.4 pH measurements

pH was not affected by time, or film, but did differ significantly between damaged and undamaged kernels with pH lowered in damaged kernels. This decreased pH produced a shift from an average neutral pH of 7.3 to an acidic pH of 5.5 (Figure 4).

**Figure 4** Measurement of the pH



Notes: Error bars represent the  $\pm$ SE. Harvest and UK arrival,  $n = 18$ , BBD and BBD+5,  $n = 36$ . letters are significantly different groups of Tukey test  $p$ -value  $\leq 0.05$ . Three-way ANOVA (Table 2). BBD – Best before date and BBD+5 – 5 days after the best before date. Oxygen transmission rate – OTR.

**Table 1** Statistical analysis

	<i>Sugars</i>		<i>Starch</i>		<i>FRAP</i>	
	<i>F</i>	<i>Sig.</i>	<i>F</i>	<i>Sig.</i>	<i>F</i>	<i>Sig.</i>
Time	3.20	0.079	2.09	0.154	18.52	<0.001
Film	0.78	0.383	0.87	0.356	8.15	0.005
Damage	*		*		267.33	<0.001
Interaction	A 0.38	0.543	A 0.15	0.698	B 8.00	0.005
df	1, 56		1, 56		1, 125	
	<i>POD</i>		<i>PPO</i>		<i>pH</i>	
	<i>F</i>	<i>Sig.</i>	<i>F</i>	<i>Sig.</i>	<i>F</i>	<i>Sig.</i>
Time	0.37	0.544	44.90	<0.001	0.28	0.598
Film	0.05	0.818	0.349	0.556	2.40	0.124
Damage	138.28	<0.001	85.66	<0.001	511.06	<0.001
Interaction	**	**	B 10.60	0.001	**	
			C 5.97	0.016		
df	1, 112		1, 112		1, 132	

Notes: F values and significance for N-way ANOVA analysis of factor time, film and damage.

\*Sugars and starch were not quantified in damaged kernels.

\*\*None of the interactions were significant.

Interactions: A – time \* film; B – time \* damage; C – film \* damage;

D – time \* film \* damage.

## 4 Discussion

This study has shown that sweet corn produced in Senegal and transported to the UK for sale up to 20 days after harvest, is most vulnerable to post-harvest loss of quality after arrival in the UK, during processing and packaging, where the major loss of sugars and antioxidant capacity occurs. Sweetness is the main organoleptic characteristic of sweet corn; therefore, its preservation during the supply chain is essential in maintaining quality. Sweet corn has a very high sugar content and high respiration rates which make shipping temperatures a key factor in the maintenance of quality and a significant threat when they are not adequately controlled (Riad et al., 2002). In this experiment, the sugar loss during the shipment across 14 d at 4°C was negligible, but when the temperature was raised to 10°C, the loss of soluble sugars became apparent.

The loss of sugar in sweet corn is mainly due to two processes; respiration and starch biosynthesis (Creech, 1968). During the product life, respiration metabolism increases and sugars are rapidly converted into CO<sub>2</sub> and energy (Shao and Li, 2011). Shao and Li (2011) found that only after 10 days of storage at 4°C, the loss of sugars was significant with respect to the initial value. Here we observed that an initial decrease was apparent during the first 6 days of storage at 10°C, and that this reduction was significantly different after 11 days of storage (BBD+5) [Figure 2(a)].

Manleitner et al., (2003) suggested that at lower temperatures the source of energy in sweet corn is starch, meanwhile when a rise in the temperatures occurs, as during

commercial shelf-life, starch is broken down and soluble sugars become the main source of energy. The sweet corn varieties used in the present study were *sh2* mutants (super sweet corn). These mutants have a modification in ADP-glucose pyrophosphorylase (Carey et al., 1984; Creech, 1968), limiting the polymerisation of glucose into starch. This characteristic favours the reduced conversion of monosaccharides into starch, shown in the results of this study as a low sugar loss (14.0%) and a small starch increase (24.2%) independently of the film used. Similar results were found by Smyrniotaki et al., (2010) who observed that the loss of total sugars in *sh2* cultivars stored at 3°C for 10 days was limited to approximately 10%.

These carbohydrate changes, although not desired, may have a small impact on the overall product's characteristics. Additional study of sucrose, fructose and glucose will be carried out in future experiments to further investigate the sugar metabolism and the importance of the different sugars on the quality and organoleptic characteristics of the product.

In this experiment, antioxidant capacity declined during shelf-life and this decline was greater when temperature and oxygen availability were higher. Similar results were found by Riad, (2004) who reported that the antioxidant capacity decreased in kernels stored at 5 °C for 10 days, and this decrease was higher in kernels stored in air versus modified atmosphere. Also, sweet corn was found to have a bigger loss of antioxidants when stored in air compared to vacuum packed (Sitthitrai et al., 2015). These results illustrate the importance of ambient temperature and atmosphere during the supply chain and how these two factors can be manipulated to prevent quality loss and to extend sweet corn shelf-life.

Film selection has also been investigated in relation to postharvest losses in sweet corn (Aharoni et al., 1996; Manleitner et al., 2003; Rodov et al., 2000; Sitthitrai et al., 2015; Sousa et al., 2015). Temperature changes during shelf-life can make it challenging to maintain a suitable atmosphere within the package. Sweet corn stored at 20°C for 24 h can produce an atmosphere with 24% of CO<sub>2</sub> and less than 3% of oxygen (Aharoni et al., 1996). The two films used in this experiment showed that use of low perforation films (film 1), significantly reduce antioxidant losses, thus preserving postharvest quality and nutritional value of the product (Adom and Liu, 2002; Cao et al., 2018; Zhang et al., 2019) [Figure 3(b)].

When sweet corn ends are trimmed, the kernels are severely damaged, losing antioxidant capacity and also leading to a significant pH drop from 7 to 5 (Figure 4). Organic acids can cause a reduction of pH in the intercellular environment, disrupting the membrane permeability and acting as a bactericidal (Mastromatteo et al., 2009; Savatin et al., 2014). In this situation of severe damage, the metabolic imbalance produced cannot be easily restored, and all the biomolecular processes involving lipids, proteins, carbohydrates and DNA may be damaged leading to cell or tissue death (Gill and Tuteja, 2010). In parallel, the damaged kernels at the cut-ends of the cobs have severely reduced antioxidant capacity respect to the undamaged kernels [Figure 3(b)]. This damage means a loss of product quality due to a quicker loss of freshness, reduced nutritional value and higher microbial development. Harakotr et al. (2014) found that the loss of antioxidants during cooking was higher when the kernels were pulled off the cob than when the whole cob was cooked. Similar results have been observed in multiple fresh-cut products (Gil et al., 1999; Hu et al., 2014; Sitthitrai et al., 2015; Todaro et al., 2015) where ascorbate is quickly oxidised after cutting.

Peroxidase activity is highly related to the antioxidant capacity due to its key role in the regulation of reactive oxygen species (ROS) (Henriksen et al., 2002). Previous studies have been focused on the inactivation of the sweet corn peroxidase activity, but none of them have characterised this activity through shelf-life. The results of this study showed an increase of the POD activity during shelf-life, which can participate, modulating the redox status of the cells, leading to a higher antioxidant loss (Figure 3B). The prevention of this increase in the POD activity can reduce the loss of the antioxidant capacity and preserve quality. As suggested by Barrett et al. (1999), postharvest treatment of sweet corn by steam blanching for 8 minutes to eliminate POD activity may be beneficial for an enhanced shelf-life.

The results showed that the POD activity in undamaged kernels increased towards the end of the shelf life, meanwhile the PPO activity was reduced. Even though both enzymes are involved in the response of abiotic and biotic stresses, PPO carries out the oxidation of polyphenol and might have more significant involvement in developing toxicity and protein bioavailability than POD (Taranto et al., 2017) which might have a more important role in controlling redox status and participating in advanced decayed status. Although, sweet corn POD has been found in all kernel parts (Liu et al., 2012), PPO in sweet corn kernels as in wheat might be mainly located in the kernel pericarp as described by Hatcher and Kruger (1993). Cell wall degradation in advanced shelf-life situations (BBD+5), causes a pericarp softening as it happens during frozen storage sweet corn (Liu et al., 2012; Riad, 2004), what could be the cause of the loss of PPO activity in the late stages of the shelf life and in the damaged kernels [Figure 3(c)]. PPO may not have such a significant role in sweet corn postharvest. On the other hand, peroxidase in association with lipoxygenase has been reported to reduce the sweet corn quality and storability so, the precise handling of these enzymes should be considered when aiming to improve the product quality (Inglett and Gardner, 1971; Lee and Hammes, 2006; Rodriguez-Saona et al., 1995; Sitthitrai et al., 2015).

We postulate that damage was the factor responsible for the pH changes in the cut end kernels. This reduced pH 5 in damaged kernels is a sign of the advanced decay of the tissue. The combination of the degradation processes happening at the damaged kernels, and the microbial load at the cut-ends could be responsible for the drop in the pH values. Camacho et al., (2001) suggested that pH could be reduced during sweet corn shelf life due to the microbial load, which in this experiment could be enhanced by the damaged created in the cut-ends.

The alteration of the redox status (antioxidants) and pH (acidity/alkalinity), can be the cause of the loss of enzymatic activity due to protein denaturalisation and the degradation of structural compounds. In contrast, some enzymes might benefit from the lower pH or reduced antioxidants. Liu et al., (2012), observed that the maximum POD activity for waxy corn and sweet corn was at pH 6 and pH 5, respectively. Also, reduced antioxidant capacity can favour a higher H<sub>2</sub>O<sub>2</sub> concentration and POD activity hence further antioxidant loss. In stressful situations, such as at trimmed ends, tissue can show an initial peak of reactive oxygen species (ROS) that when it cannot be subdued by antioxidants or enzymes, leading to impaired metabolism and subsequent tissue death (Vacca et al., 2004). The results suggested that the kernels damaged at the ends of the cob might be in this extreme condition, where antioxidant capacity is exhausted, and all the cell components are being degraded.

## 5 Conclusions

The present study showed that the loss of sugars and antioxidant capacity during the shipment of sweet corn from Senegal to the UK was insignificant. Low temperatures and the modified atmosphere developed in the containers are effective at preserving sweet corn quality during shipping from Senegal to the UK. Similarly, after transport and processing, assessment of sweet corn at the end of the commercial shelf-life (BBD) revealed no significant decline in sugars for undamaged kernels. On the other hand, when kernels were damaged, significant decline in antioxidant capacity and enzyme activity degradation were observed. Thus, we conclude that the integrity of the sweet corn must be maintained to avoid damage and poor postharvest quality during the twenty days to best before date (BBD). At the same time, low oxygen transmission rate films and treatments to prevent antioxidant loss and reduce POD activity are recommended, alongside maintained sweet corn integrity to ensure product quality and long shelf-life in sweet corn.

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