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Artificial fruit for monitoring the thermal history of horticultural produce in the cold chain

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ABSTRACT

There is a need for more realistic monitoring of fruit pulp temperature history throughout the cold chain at a higher spatial resolution inside the cargo. Particularly solutions that are easy to install in a commercial setting are required. For this purpose, a novel kind of fruit simulator – an artificial fruit – has been designed, manufactured and tested. Using a biomimetic approach, it was engineered specifically to match the thermal response of real fruit as close as possible. The artificial fruit is composed out of a thin plastic shell, which mimics the exterior size, shape, surface texture and color of the fruit of interest. This shell is filled with a mixture that has similar thermal properties as real fruit as it is basically composed out of the same components. Two self-powered data loggers with a built-in sensor are integrated in the artificial fruit. These different components of the artificial fruit were combined successfully into a manufactured prototype. The thermal response of an artificial apple fruit during cooling was evaluated against that of 10 real apples. The cooling time of the artificial fruit was within 5% of that of the real fruits. The artificial fruit also had a more accurate thermal response than that of water-filled fruit simulators, with which differences up to 16% were found. The uniformity in size, shape and sensor location of the artificial fruit also enables it to measure fruit pulp temperature in a much more repeatable manner than with real fruit. A particular advantage of the artificial fruit is that it can be packed directly with the fresh produce in a commercial setting, by which multiple locations inside the cargo can easily be monitored. This novel sensor system thus provides an improved method to identify heterogeneities in cargo cooling, and associated quality issues. The artificial fruit is especially of interest for monitoring fruit pulp in precooling facilities, cold stores, ripening facilities and refrigerated containers.

1. Introduction

1.1. Background

Postharvest losses in fresh produce cold chains, from the point of harvest until the product reaches the consumer vary between 13% (Europe) and 38% (sub-Saharan Africa) (Gustavsson et al., 2011). Here, temperature is the single most important parameter affecting produce quality deterioration, ripening rate and shelf life. To maintain fruit quality and to reduce these losses, rapid removal of the field heat after harvest through cooling is thus of key importance, as well as maintaining optimum product temperature throughout the postharvest supply chain. These cold-chain unit operations include forced-air precooling, long-haul maritime transport in refrigerated containers, transport in refrigerated trucks as well as long-term storage in cold rooms prior to distribution to the end client.

Monitoring postharvest fruit temperature history of fresh fruits

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is thus essential to evaluate the efficacy of existing commercial cold-chain unit operations but also to explore new cooling strategies. Typical examples of such recent cooling strategies are flow reversal for forced-air precoolers (Ferrua and Singh, 2009), ambient loading for refrigerated containers (Defraeye et al., 2015b) and intermittent operation of cooling fans in cold storage rooms and refrigerated containers (Ambaw et al., 2016; Lukasse et al., 2011; Thompson, 2004). Fruit temperature measurements are also essential to evaluate and develop new ventilated bulk packaging (Gruyters et al., 2017; O'Sullivan et al., 2016; Wu et al., 2017). Here, the fruit cooling rate is a major design criterion (Defraeye et al., 2015a, 2013), next to mechanical strength (Berry et al., 2017). Fruit temperatures are also indicators of problematic hot spots within the cargo during shipment of commodities with a high respiration rate, such as bananas. Such hot spots can induce spontaneous ripening of the cargo during transport and should be avoided (Jedermann et al., 2014c). In commercial fresh produce export, the fruit core or pulp temperature measurement is used by governmental organizations such as the U.S. Department of Agriculture - Animal and Plant Health Inspection Service (USDA-APHIS) and the South-African parastatal organization Perishable Products Export Control Board (PPECB). These organizations use this data to determine the compliance of the cargo with cold treatment protocols designed to kill specific phytosanitary organisms (e.g. fruit fly, false codling moth). The core of these protocols is that the fruit core temperature must be maintained below a certain temperature threshold for a specific duration. These cold treatment protocols can be applied as land-based treatments but most often are done in-transit from the export country to the target market in refrigerated containers (USDA-APHIS, 2017). Customers (wholesalers) seem also willing to pay higher prices and to purchase larger quantities of fruit when the quality of the cargo is accurately monitored (Choe et al., 2009; Pang et al., 2015). Even insurance companies encourage their clients to monitor the thermal history of their cargo by giving them a discount (Pang et al., 2015; Swedberg, 2011).

1.2. Sensor technology for fruit temperatures

Several sensors/logger systems are currently used to monitor fruit temperature. Wired sensors, such as point probes (e.g. thermocouples), are placed inside the fruit core to measure pulp temperature (Defraeye et al., 2013). These measurements can be done continuously throughout the entire unit operation, for example during transit, or at a certain point in time, for example upon arrival of the cargo. These sensors are standard equipment in refrigerated containers and precoolers. Wireless, self-powered data loggers with a built-in sensor, such as iButtons®, have also been used to measure core temperatures of fruit (Defraeye et al., 2016, 2015b; Hoang et al., 2012). They are typically placed on the fruit surface or inside the fruit core by making an incision.

Smart sensor tags, often based on radio frequency identification (RFID), have been used to measure air temperatures inside the cargo. Some of these devices also included monitoring of metabolic gasses, but such systems are still in a development stage ((EU-Catrene, 2012; Jimenez-Ariza et al., 2014; Laniel et al., 2011; Laniel and Émond, 2010; Pang et al., 2015; Zou et al., 2014)). Depending on the type of device (i.e. active, passive, battery-assisted passive), they log the data on the tag for later wireless readout, or directly transmit the data wireless to an external data logger base station in the vicinity of the tag. Due to the advantage of wireless readout, the main idea behind these sensor tags is that they can be placed on each carton/box of the fresh cargo or at least on each pallet. Both disposable and reusable RFID-based sensors are commercially available from several suppliers, as well as temperature loggers based on Bluetooth technology. There are however several limitations to the current temperature measurements of fruit, particularly for commercial cold-chain operations.

1.3. Current restrictions of temperature measurements

A first problem is that the air or fruit surface temperature is often monitored in commercial operations, instead of the fruit (pulp) temperature (Defraeye et al., 2015a; Jedermann et al., 2014a). A typical example is RFID sensor tags, which are used to log the cold chain's thermal history. Air or fruit-surface temperatures pick up instantaneous changes in ambient cooling conditions, whereas fruit core temperatures lag behind due to the thermal inertia of the fruit. As such, the fruit does not react that fast, in terms of its temperature, on fluctuations in air temperature due to intermittent cooling/ventilation. The fruit core is usually the last location to attain the set temperature so is the most conservative location to measure temperature. Pulp temperatures reflect better the thermal condition of the fruit, and are a better measure for the evolution of the fruit quality and thus shelf life. This is why pulp temperatures – not air temperatures – are measured in several commercial unit operations in the postharvest cold chain. They are used by governmental organizations to decide upon compliance with any phytosanitary cold protocol during overseas or land-based transport, as well as in commercial forced-air precooling (PPECB, 2016a, 2016b; Thompson, 2008; USDA-APHIS, 2017) to asses if the cooling process can be stopped.

A second problem is that typically a limited amount of sensors/loggers is installed inside the cargo in commercial operations, for example 3 PT-100 point probes (connected to the reefer) per 20 pallets in a 40 feet container (Defraeye et al., 2016), or 3–5 point probes per 40 pallets in a precooler (Wu et al., 2017). As such, the heterogeneity of fruit cooling rates for different cartons in the cargo is not correctly picked up and will lead to inhomogeneous fruit quality or possibly non-compliance with a cold treatment protocol. Such heterogeneity has been identified (Defraeye et al., 2016; Dehghannya et al., 2012; Delele et al., 2013a, 2013b; do Nascimento Nunes et al., 2014; Olatunji et al., 2017) and is present at various scales: inside a carton of fruit, between stacked cartons on a pallet as well as between different pallets/palloxes in a container cargo or a storage room. RFID sensor tags could mitigate this problem of picking up the heterogeneity, as they are typically placed at multiple locations. However, these tags do not measure pulp temperature.

A third problem is that sensors to measure fruit pulp temperature are often installed at easy accessible places and do not measure deep inside a pallet or carton. These are, however, the critical locations in terms of cooling rates or high ethylene levels. These issues are caused by the fact that installing and retrieving the sensors inside different pallets is cumbersome and labor/time intensive. For wired sensors, for example, the wiring is intrusive, requires a lot of cabling and typically a connection to an external data logger for continuous measurements. RFID tags, on the other hand, cope with strong signal attenuation, especially within fruit bulks which are densely packed, by which message forwarding can be necessary in a refrigerated container (Jedermann et al., 2014b).

Fourth, measurements tracking the fruit pulp thermal history throughout its entire cold chain, from farm to retailer, are rare, particularly for long (overseas) chains. One reason is the numerous and different stakeholders owning and operating the various equipment, who are sequentially responsible for the cargo during subsequent unit operations. This makes the use of a generic pulp temperature recording platform problematic. The use of wired sensors, transferring between unit operations is hindered by the cabling and the data logger. The small wireless loggers, which are