Quality Manipulation and Monitoring in Processes: 
Product-climate Interaction, Quality Control

B.M. Nicolaï, E. Bobelyn, M. Hertog, D. Marquenie, P. Verboven and B. Verlinden
Flanders Centre/Laboratory of Postharvest Technology
Katholieke Universiteit Leuven
W. Decroylaan 42
3001 Leuven, Belgium

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Abstract
Quality of fresh fruit and vegetables changes dramatically after harvest. In this article, an overview will be given of some recent developments in storage technology, monitoring of quality attributes and control techniques for quality of horticultural produce throughout the distribution chain.

INTRODUCTION
Since long it has been known that the ambient conditions affect to a large extent the quality of fresh fruit and vegetables. This has led to advanced storage technologies, such as mechanical refrigeration and controlled and modified atmosphere storage. In many cases fruit and vegetables can now be stored for extended periods with only limited loss in quality. Recently, much attention is devoted to quality monitoring, tracking and tracing, and advanced control methods to extend the storage life and increase the quality of fresh fruit and vegetables. In this article an overview will be given of some recent and exciting developments in this area.

PRODUCT-CLIMATE INTERACTION
Temperature, relative humidity and airflow
Of all climate parameters, temperature is by far the most important one. Decreasing the temperature reduces the rate of the physiological reactions which affect quality such as the conversion of protopectin to pectin, respiration, starch hydrolysis etc. Cooling has, therefore, been used since ages to extend the keeping quality of fresh produce, and mechanical refrigeration systems are used extensively all over the world.

Recently, much attention has been paid to the effect of air flow rate and distribution, air temperature and humidity on quality of the stored produce. Air movement is important to assure optimal temperature and humidity throughout the conditioned space, preventing hot spots and condensation. However, air flow adversely affects moisture loss: the higher the local flow rate, the higher the transfer rates from product surface to air. Products subject to excessive air velocities tend to dry out quickly, even if the adequate values for temperature and humidity are maintained (Fig. 1a). Products with a high skin resistance (e.g., due to natural wax) to water loss are less sensitive to variations in air velocity (Fig. 1b) and benefit from fast cooling.

Inside air conditioned spaces, the variation in temperature, humidity and air velocity can be large. The local movement of air through the bulk and in between rows of pallets can be very different from one part of the cooling room to another. Models are being developed to support design, optimisation and control of conditioned rooms. With increasing computer capacity and the availability of robust and user-friendly computer codes, 3D models to simulate the room air flow distribution in entire cool rooms and the consequent distribution of temperature and humidity are now being proposed and validated. Such distributed models should take into account flow turbulence in the free air spaces and combined natural-forced convection and flow resistance in bulk products in bins or boxes on pallets. Examples of such models can be found in Moureh et al. (2002) and Hoang et al. (2000). A result of a simulation is given in Fig. 2, outlining the geometry.
with the bins in different rows (Fig. 2a) and the temperature distribution during the cooling phase (Fig. 2b).

Future research in this area should aim at improving the understanding of low airflow inside the bins, the effect of bin stacking, bin design and product stacking inside the bins and its effect on heat and mass transfer. Such investigations are for example being undertaken by Hoang et al. (2003) and van der Sman (2002). Research in other fields also shows promising tools that can be used to understand more clearly airflow inside beds of products. Nijemeisland and Dixon (2001) modelled a packed bed of spheres as part of a chemical reactor and calculated pressure drop and local air velocity within the voids rather than applying volume-averaged relations. Such simulations are also possible for horticultural products in bins especially with non-structured computational fluid dynamics codes. Combining such techniques with techniques to generate random distributions of horticultural products with random shape will improve the simulation of reality.

Gas conditions
Since the seminal work of Kidd and West in the U.K. in 1918, controlled atmosphere (CA) storage has been increasingly used for fruit storage. In CA, the oxygen concentration is reduced, often in combination with an increase in the carbon dioxide concentration. In combination with low temperature storage this reduces the respiration rate and most associated quality deterioration related reactions. However, if the oxygen concentration is too low or the carbon dioxide concentration is too high, fermentation may occur, resulting in off odours and off flavours. Further, some storage disorders have been shown to be related to low oxygen and high carbon dioxide conditions. For example, Conference pears (*Pyrus communis* L. cv. Conference) are particularly sensitive to sub-optimal gas conditions, as they are susceptible to core breakdown. This storage disorder is characterised by the development of brown tissue, which will further develop into cavities so that the fruit can no longer be commercialised. Recently it has been shown unequivocally that the harvest time, the O2 and CO2 concentration in the cool room, the storage temperature, the size of the pear and their interactions are the most critical factors which affect the development of the disorder (Lammertyn et al., 2000). For a proper operation of cool rooms a more profound insight in the metabolic reactions and transport processes inside fruits is mandatory. A mechanistic modelling approach seems most appropriate, as it provides more insight into the biochemical phenomena related to storage disorders. Michaelis-Menten kinetics are widely used to describe the (lumped) respiration/gas exchange of fruits with their environment (Hertog et al., 1998). However, as gas gradients have been observed in fruit, it seems that such a lumped approach is not (completely) valid. Diffusion-type models have been described in the literature for gas exchange between the fruit and the surrounding atmosphere (Lammertyn et al., 2001). Further progress is expected when internal gas conditions could be linked to biochemical reaction fluxes.

QUALITY MONITORING

Logging of climate conditions: temperature, relative humidity and gas composition

Thermocouples are the most flexible and least expensive means of measuring the temperature. However, accuracy is limited. Wire metals must be as pure as possible. Avoid thermal shunting, wire impedance shunting, galvanic action and interfering currents in the wires. These can lead to very large errors, especially over long distances of wire. The reference junction may add a large error when internal electronic compensation is used instead of an ice bath reference. This error can amount to a few degrees if the reference sensor is poorly calibrated or a large temperature difference exists on the acquisition terminal. In the best (and most expensive) equipment this error can be reduced to 0.15 °C. Because of these drawbacks, industry mostly uses resistor type thermometers (RTD) for climate control. These sensors (of which the Pt100, a Platinum 100 ohms
resistor at 0°C, is the most popular) are used because of the large almost linear sensitivity, they are very accurate and do not suffer from reference junction voltages and lead wire voltages (in case of 4-wire RTDs). In general, measurement errors of Pt100 probes should be better than 0.1 °C. RTDs show significant self-heating errors (up to 0.5 °C) in insulating environments, therefore, they are not used for solid temperature measurements.

A variety of devices for air humidity measurement exists. For wet-dry bulb psychrometers, the sample velocity should be well in excess of 3 m/s to obtain a reliable measurement. The sensing elements should, therefore, be mounted where there is adequate circulation, or forced circulation must be provided by means of a fan or rotation of the sensor. Other limitations include the inability to operate under 0°C because of freezing and the inconvenience that it requires a continuous source of water to keep the wick wet.

Capacitance sensors (Fig. 3) are the most popular device in industry because they output an electrical signal directly proportional to the relative humidity of the air. Water vapor needs to penetrate into the dielectric substrate of the sensor to change the capacitance. Individual calibration of each sensor is required, the response time can be slow and condensation may damage the sensor. Another drawback of these sensors is that they do not measure an absolute humidity quantity (such as the dew point).

The optical chilled-mirror dew-point technique is a fundamental measurement, because the saturation temperature determines the saturation partial pressure of the water vapor. These relationships are well established, both experimentally and theoretically. These expensive devices are required for accurate humidity control and calibration checks.

Many commercial companies now provide low cost, autonomous and wireless temperature and relative humidity sensors. The temperature sensors are often Pt-100 and the RH sensors are thin film capacitance sensors. It must be emphasised that the accuracy of the RH sensors is limited and they must be calibrated regularly.

Several sensor types are available to measure the concentration of gases in cool stores. Oxygen sensors are usually based on the paramagnetic properties of this gas, although portable devices are often based electrochemical cells. Carbon dioxide is usually measured based on infrared absorption. Whereas ethylene can be measured conveniently using gas chromatography, gas sensors are now widely available.

**Online quality sensors**

Chlorophyll fluorescence has been shown to provide valuable information about fruit stress. The company Satlantic (www.satlantic.com) has developed a system (HarvestWatch™) which is based on fluorescence measurements. The sensors use low power light sources to stimulate the photo-systems inside the sample of the produce. Detection technology incorporated in the device senses the response from the fruit, or vegetable, and feeds the response back to an analytical software tool where the results are displayed on a graph that is updated each time the sensor assesses the fruit. The operator can look in real time for the changes which may be indicative of, for example, low O₂ stress. If stress is observed, the oxygen concentration can be increased until the stress disappears. According to the company, by using the system very dramatic reductions in the level of oxygen over the storage season have been observed.

During the past two decades, vibration based measurement techniques have been studied for nondestructive evaluation of fruit firmness (De Belie et al., 2000). The fruit is struck with a small hammer, and produces a sound wave, which is recorded using a microphone. A computer, which is hooked up to the measurement device, calculates the first resonance frequency of the time domain signal by means of a Fast Fourier Transform. The higher the resonance frequency, the firmer the fruit. Commercial laptop devices are currently available from AWETA (http://www.aweta.nl/).

**Time temperature integrators**

While proper packaging can easily control other factors such as gas composition
and relative humidity, the temperature of the food depends entirely on the external conditions during distribution and storage. Many manufacturers and consumers desire shelf life and open date labeling. However, the difficulty in controlling and knowing the temperature history of the product during distribution and storage makes true shelf life difficult to predict. Monitoring the temperature during distribution and storage can provide the accurate and reliable information about the time left to the end of shelf life. This approach can correct the sometimes meaningless expiration dates, and lead to better control of keeping quality and decrease food waste. A tool for achieving these goals is a time-temperature integrator (TTI). TTI’s are small, inexpensive devices that show a time-temperature dependent, easily measurable and irreversible change, that can be related to changes in the quality of a food undergoing the same time-temperature exposure (Taoukis, 2001). A range of TTI’s based on different physicochemical principles have been described in the literature (Taoukis, 2001). In Fig. 6 a TTI from Vitsab (Sweden, http://www.vitsab.com) is shown. It is based on a colour change caused by a pH decrease, due to a controlled enzymatic hydrolysis of a lipid substrate. Before activation the lipase and the lipid substrate are in two separate compartments. At activation, the barrier that separates them is broken, enzyme and substrate are mixed and the colour change starts.

The applicability of TTI’s was evaluated for various perishable foods (e.g., Taoukis et al., 1999; frozen strawberries, Wells and Singh, 1985). However, applications in the fresh fruit and vegetable chain are scarce, and more research is required.

Tracking and tracing

There is a general trend with consumers and government. They both want better insight in the origin and history of food products, including those from horticultural origin. Well-designed tracing systems from field to table are required for optimal functioning of quality and process control systems to meet the consumers’ demands.

The current tracing systems mainly aim at meeting regulations and are therefore limited to guaranteeing product authenticity and addressing food safety related issues. Because of the large number of products on the market, automation of relevant product specific data collection in every link of the logistic chain is vital. So-called transponders – miniature electronic information carriers – could be a good alternative for traditional barcodes. Throughout the logistic chain crucial information can be added. Some types of transponders are also capable to automatically log environment variables like temperature (e.g., KSW-Microtec, Dresden, Germany, http://www.ksw-microtec.de/). The challenge will be to deal with individual product streams that are first centralised (at an auction or in storage) and during or after some processing are divided again into separate streams. This will result in heterogeneous units of product that are marketed as one but that, as a matter of fact, consist of subunits of different origin and with a different history.

Current tracing systems are mainly identification systems. The generated information is of static nature and does not contain dynamic information like waiting times, environment variables (e.g., storage temperature) and quality changes. If such information is also available, the system is called a tracking system. Process conditions are relative easy to measure (temperature relative humidity, vibrations, etc.), however, continuous measurement of the relevant product quality aspects is still too farfetched. To solve this problem, dynamic quality change models can be developed to predict product quality based on initial quality and the measured process conditions.

Chain modelling

Several software application packages are available on the market to simulate production and distributions chains of food products. However, in most cases only a limited part of the whole process from raw materials to finished products at the consumer side is considered. For instance, only the production plant is modelled or only the logistics of transport (www.transporter2000.com). Models describing the behaviour of physical processes (e.g., mechanics, electronics, transport, cooling) are well documented and incorporated in commercial software (e.g. CoolVan at www.frperc.bris.ac.uk).
However, the behaviour of biological material such as fruit and vegetables and other food is much more complex and less predictable. Although many sub-models concerning specific aspects of biological material behaviour can be found in the literature, only few attempts to incorporate them in a more comprehensive simulation tool have been made (Nicolaï et al., 1994). The aspect of microbial growth and food safety modelling was reported by Schellekens et al. (1994). Hertog and Tijskens (1998) proposed a model for keeping quality of perishable produce packed in modified atmosphere. Verlinden et al. (2001) developed software that simulates the quality evolution of chicory heads during the entire distribution chain, starting from the production of the crop and ending at a possible short-time storage in a consumer's household fridge.

**Certification**

Since the last 20 years consumers have become more and more concerned about the quality and the safety of all kind of food products (fresh produce of fruits and vegetables, frozen foods,…). Consumers have higher expectations of the quality of the products but they also want to know how the products are produced. This is why the retailers have responded by developing systems to measure, manage and improve the quality of products and the production process more effectively. Standards are used to provide consumers with information about the product, to maintain product quality uniformity, to establish market value, and to prevent economic fraud. (FDA, 2000).

The two major systems currently utilised to manage quality systems in the food industry are Hazard Analysis Critical Control Point (HACCP) and the ISO 9000 series of quality standards. The ISO 9000 system describes 20 elements (e.g., document control, management responsibility, product identification and traceability, inspection and test measuring equipment, training, internal quality audits,…). The basic premise of the system is that the producer defines systems and procedures, developing a quality system for his whole operation, documents this procedures and demonstrates compliance with his own internal standards. Because of the structured nature the ISO 9000 system offers the added benefit that certification can be gained from third party certifying bodies, to demonstrate to customers that you have a documented quality system in place. The ISO 9000 system comprises five separate standards (9000-9004). ISO 9002 covers the quality system for production and installation and is the standard most commonly sought in the food industry. ISO 9001 is the quality system for design/development, production, installation and servicing (Khandke, 2001).

HACCP is a different tool for identifying and controlling product safety hazards, and unlike ISO 9000 is specific to a line of products. HACCP is internationally accepted and is mandatory in many countries. External normalisation companies and agencies are beginning to offer certification services for HACCP (Khandke, 2001). HACCP is a systematic approach to the identification, evaluation and control of food safety hazards. Preventing problems from occurring is the paramount goal underlying any HACCP-like system. These systems focus attention on the parts of the process that are most likely to affect the safety of the product (Lineback, 2002). The application of HACCP is normally described in terms of seven principles which have been formalised by groups such as the Codex Alimentarius of the Food and Agriculture Organisation of the United Nations (Dix, 2001).

**QUALITY CONTROL SYSTEMS**

**Packaging**

MA is generally used as a technique to prolong the keeping quality of fresh and minimally processed fruits and vegetables. In the widest sense of the term, MA technology includes controlled atmosphere storage, ultra low oxygen storage, gas packaging, vacuum packaging, passive modified atmosphere packaging and active packaging. Each of these techniques is based on the principle that manipulating or controlling the composition of the surrounding atmosphere affects the metabolism of the
packaged product, such that the retention of product quality can be optimised. The different techniques come with different levels of control to realise and/or maintain the composition of the atmosphere around the product. While controlled atmosphere storage can rely on a whole arsenal of machinery for this purpose, active packages rely on simple scavengers and/or emitters of gases such as oxygen, carbon dioxide, water or ethylene either integrated in the packing material or added in separate sachets. Passive MA packaging, as an extreme, relies solely on the metabolic activity of the packaged product to modify and subsequently maintain the gas composition surrounding the product.

Although much research has been conducted to define optimum MA conditions for a wide range of fresh food products, the underlying mechanisms for the action of MA are still only superficially understood. The application of MA generally involves reducing oxygen levels and elevating levels of carbon dioxide to reduce the respiratory metabolism. Parallel to the effect on the respiratory metabolism, the energy produced to support other metabolic processes, and consequently these processes themselves, will be affected accordingly. This still covers only part of the story of how MA can affect the metabolism of the packaged produce. The physiological effects of MA can be diverse and complex. In MAP, the success of the package strongly depends on the interactions between the physiology of the packaged product and the physical aspects of the package; MAP is a conceptually demanding technology. Much of the work in the area of MAP has been, and still is, driven by practical needs of industry. This has enabled commercial development based upon pragmatic solutions but has not always contributed substantially to advancing the conceptual basis upon which future innovation in MA technologies depends. As a result, there is a substantial potential for models to contribute to the field of MAP by making the complex and vast amount of, sometimes fragmental, expert knowledge available to packaging industries (Hertog, 2001).

**Dynamic Control System (DCS)**

DCS has been developed and patented by the Agrotechnical Research Institute (Wageningen, The Netherlands) to store fruit at lower oxygen concentrations than conventional controlled atmosphere, while minimising the risk of fermentation. Here to the ethanol concentration in the storage atmosphere is measured and used to determine the optimal conditions for the environment. So far the ethanol concentration has been measured by means of gas chromatography, but new sensors have been developed to detect ethanol concentrations as low as 50 ppb. The oxygen concentration in the storage atmosphere has been reduced in experiments to 0.2% without loss of quality. However, ethylene may affect the readings.

**Surface treatments**

During the past decade, the emphasis in postharvest fruit protection was shifted from using chemicals to various alternative techniques, including biological control (Reddy et al., 1998) and several techniques for surface disinfection, such as ultraviolet radiation (Ben-Yehoshua et al., 1992). Given the actual restrictions of fungicide use in food products, the advantage of these alternative techniques is that no chemicals are involved.

The decontaminating properties of UV-C light are well known, but the potential of ultraviolet light for surface disinfection of fruit and vegetables has been studied only recently (e.g., Marquenie et al., 2002). First, there is the direct effect on the pathogens because of DNA damage. Second, UV-C can induce resistance mechanisms (*hormesis*) in different fruit against pathogens. This induced response is a natural defence mechanism of the plant. Exposure to UV-C also induces the synthesis of protective components such as anthocyanins and flavonoids to absorb the ultraviolet light (Burger and Edwards, 1996), and of antioxidants such as tocopherol and ascorbic acid (Kozak et al. 1999) that act as free radical scavengers. High UV doses, however, can cause damage to the treated produce. Peel damage in citrus, grapes, and tomato have already been described by several authors (Ben-Yehoshua et al., 1992).
Thermal methods have been proposed to inhibit ripening, to prevent chilling injury, to delay fungal growth and to control postharvest diseases and insect pests in fruits (Lurie et al., 1993). In vitro studies have shown that vegetative cells and conidia of most fungi are inactivated when exposed to a temperature of 60 °C for 5 to 10 min (Civello et al., 1997). However, for surface decontamination of fresh fruit, the thermal treatment should be less severe to avoid loss of turgor and quality in general.

CONCLUSIONS

Novel, model based methodologies are now available to evaluate the effect of climate conditions such as temperature, air flow and humidity, and gas conditions on the quality attributes and disorders of stored fruit and vegetables. Together with novel logging en sensor techniques they may be used to fine-tune storage operations, design new cool stores and to diagnose and remediate problems in existing ones.

Tracking and tracing are becoming increasingly important. The all-abundant bar codes are now being replaced by electronic tags - transponders – and now even allow to log climate information such as temperature. This brings quality tracking in reach of practical applications. Time temperature integrators can provide additional and valuable information. Whereas these tools are diagnostic, also quality control systems such as ISO certification and HACCP procedures are important as they function in a pro-active way.

Active control systems such as advanced packaging technologies, dynamic control systems and surface treatments are being developed to increase the storage life and quality of stored produce. Many difficulties still have to be overcome, however, to implement these systems in practice.

But the future of quality looks good.

Literature Cited


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air flow in a cold store by means of computational fluid dynamics, International Journal of Refrigeration 23(2), 127-140

Figures

Fig. 1. Effect of velocity on product weight loss (1°C, 85% RH) during cooling from 20°C for products with different skin resistance to water loss. Note the difference in scale of y-axis.
Fig. 2. Geometry (a) and simulated 3D temperature distribution (b) in a chicory root cold store

Fig. 3. Thin-film capacitance relative humidity sensor
Fig. 4. HarvestWatch fluorescence based system to monitor stress in stored fruit (Courtesy of Satlantic)

Fig. 5. Continuous measurement of apple firmness in experimental container based on acoustic resonance techniques (J. De Baerdemaeker, unpublished)

Fig. 6. Colour change of a TTI from Vitsab (Sweden). White dot (unactivated), green dot (recently activated) and yellow dot (final colour change).