Equipment Innovations in Postharvest Handling and Minimally Processing of Fresh Fruit and Vegetables

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1. Introduction

Fresh fruit and vegetables are constituted by living tissues which carry on metabolic processes related to ripening and senescence. Quality of these products includes a combination of attributes, such as appearance, texture and flavor, as well as nutritional and safety aspects, that represent their added value to the final consumer. They are important for human diet as they represent an important source for bioactive compounds which are known to be beneficial for human health and wellbeing [1;2]. This health- promoting quality of vegetables are associated with the composition of phytochemicals (including, vitamins C, A and E) or bioactive substances necessary for stimulation of desired metabolic processes. Phytochemicals include the phenolic and carotenoid compounds in addition to nitrogen-containing (e.g. polyamines) and organosulfur compounds (e.g. isothiocyanates) which are currently receiving attention. Many factors have a role on the final quality of fresh produce. Genotype, growing conditions, cultural practices, and maturity stage at harvest may greatly influence the initial quality; on the other hand, postharvest handling and storage, including product fate throughout the distribution chain, markedly determine its final quality.

Postharvest handling of these products is aimed to conditioning for final market: cooling the product (i.e. removing the field heat) to proper temperature for each product, grading the product to remove those unsuitable for the market and to classify the rest according to regulations and/or to specific agreements, and packaging in unit which provide protection, identification, and proper information to the consumers. Conditioned product will be then stored and/or shipped to more or less distant markets. In some cases product can be stored before final packaging, especially for those commodities which are usually held in storage for long time, including, among others, apples, pears, and kiwifruits.

Minimally-processed products (also known as fresh-cut products) are defined as 100% edible fruit and vegetables that are trimmed, washed, cut, mixed and packed in order to increase consumer's convenience. Quality attributes degrade faster than corresponding intact produce as a result of damage caused by minimal processing, which accelerates many physiological changes that lead to a reduction in produce quality and shelf-life [3]. Shelf life is in fact often a matter of days or, in some cases, of weeks. Moreover, minimally processed plant tissues also represent a better substrate for growth of microorganisms, including spoilage bacteria and foodborne pathogens. One important point related to safety of fresh-cut produce is that the preparation process does not include a "killing step", or a treatment which determines a negligible final microbial count. For this kind of product, safety mostly depends on good agricultural practices, on washing, and on cold chain reliability.

As a response to consumers' demand for fresh-like and easy to prepare products, a wide variety of minimally processed fruits and vegetables has been developed during last decades [4]. Fresh-cut fruits and vegetables represent a rapidly growing sector in the fresh produce industry. The main factor that has promoted and maintain fresh-cut sales is the technology: permanent innovation is necessary to drive more and more growth in this sector [5]. For all these reasons fresh minimally-processed produce have represented a very interesting food system where the need of improvements is of paramount importance.

Main objectives of recent innovations in postharvest handling have been the following: (i) reducing the cost of operations; (ii) increasing automation and work capacity; (iii) reducing environmental impact; (iv) increasing safety and well being of labour force; (v) reducing the impact on quality.

Main innovations will be described with information on their impact on final quality

2. Optical approaches for quality evaluation of fruits and vegetables

The use of non-destructive methods is already widely developed for the early detection of fruit defects, for the classification of fruits and vegetable based on variety, maturity stage and origin and for the prediction of main internal constituents, mainly soluble solids and acids, and physical properties like firmness [6]. The analysis of the image obtained by digital cameras allow to identify characteristics present at the surface of the fruit. A number of studies in the past decades have highlighted the possibility of classification of fruits by color with computerized analysis systems [7;8]. In addition to this application there are also several studies related to the correlation between the image and the level of ripeness of the fruit [9] with the aim of removing, from the sorting line, the products that do not meet the required standards.

The use of optical sorters based on processing and analysis of digital images is nowadays widely applied in the fresh produce industry. Especially fruits (e.g. apples and pears, peaches and nectarines, plums, kiwifruits, citrus, etc.) and many vegetables (including tomatoes, melons, and asparagus) are routinely graded for size and shape, color, and surface defects through affordable, reliable, versatile, and user-friendly processing lines.

Furthermore RGB color images have been used in order to recognize and classify defect in rocket leaves at reception [10]. The operation, which is routinely performed by humans on a limited sample randomly taken from the incoming product, consists of a visual assessment of individual leaves, segregating the sound from the defected ones, the latter being furtherly classified for defect type which will have a different weigh in the final score attributed to the whole lot. Defective classes included yellow, rotten, top-burned, broken leaves, and other kind of shape related defects, including flowered, long-stem leaves, and shootings. Two different algorithms were developed, one aimed to describe morphological defects (shape/dimension) and a second one focused on pixel features related to color and texture, in order to make the same operation through image analysis which would effectively sort and recognize leaves according to the most frequent defect categories evaluated upon reception (**Figure 1**).

Particular attention in recent years have received research on the interaction of visible and near infrared (NIR) light with different types of fruit. NIR spectroscopy is categorized among the simplest non-destructive techniques as it requires no sample preparation and permits several constituents to be measured simultaneously. NIR spectroscopy is based on the absorption of electromagnetic radiation in the wavelength range of 780–2500 nm [11]. VIS-NIR and NIR spectra analysis allowed to efficiently predict important compositional features of several fruits and vegetables including sugar contents (or Brix degree) and maturity other attributes [12]. Piazzolla et al. [13] showed thorough reliability to monitor spectra changes related with ripening and to the prediction of total soluble solids, pH, titratable acidity, phenols and antioxidant activity of table grapes. In a previous work the same authors also showed the feasibility of using a visible and near infrared spectral scanner with a detector in the region between 400-1000 nm to discriminate between grapes harvested at different times [14].

Classification of fruits for sweetness, in addition to other previously mentioned physical features, is nowadays possible with a number of commercially available sorting lines which uses “NIR technology” with a high level of classification efficiency and user satisfaction.

Same principle is also used for foreign bodies detection on ready-to-use baby leaves processing lines. Sorting machines equipped both with NIR technology and RGB chlorophyll analysis are commercially available for very accurate detection of foreign bodies in products that naturally have high chlorophyll content, being able to discard foreign bodies that are even the same colour as the good product. The product is fed on a tilted conveyor belt used to bring the product to the “vision zone" to be inspected and, if necessary, ejected if same conditions are displayed in both vision and the reject zones (**Figure 2**). The technology has also been applied on to a salad greens harvester designed to provide control on harvested leaves right from the field (or greenhouse), ensuring the processing plants receive a product already without the coarsest foreign bodies.

Hyperspectral imaging is a combination or integration of imaging and spectroscopic techniques for the quantitative prediction of physical and chemical characteristics of the food samples as well as their spatial distribution [11]. The use of hyperspectral imaging to reveal more information on pre-harvest history of fresh produce is an interesting field of investigation for its potential application to make initial screening of critical features of incoming product, or to add to the amount of available information to the product, or to be implemented as a complementary method to the official ones, for real-time inspection. Amodio et al. [15] used hyperspectral imaging to predict the internal concentration of soluble solids, individual sugars and organic acids, phenols, and antioxidant activity of fennel heads in relation to different sheath layers and harvest time. This allowed also to map the constituent concentrations on the hyperspectral images showing the increase of soluble solids, phenolics and antioxidant activity from the external to the internal leaves, or, in another work, to map vitamin C and phenol contents in rocket leaves [16]. Always through the analysis of hyperspectral imaging it was possible to discriminate artichoke heads according to variety, harvest date, and time in storage. More recently Amodio et al. [17] assessed suitability of NIR spectroscopy for discriminating in different classes strawberry fruits produced by three different fertility management systems (e.g. conventional, organic based on input substitution, and organic based on manure and cover crop amendment), and this implicates possibility for this tool to be a promising support for the traceability and authentication of organic produce. This is also supported by earlier work of Sánchez et al. [18] who successfully applied NIR spectroscopy for the classification of asparagus by conventional vs. organic methods.

3. Processing plant automation to reduce costs and increase food safety

Fresh-cut fruit and vegetable processing may be very expensive as many of the operations are performed by humans and use of machines have been difficult due to low standardization of raw material. Processing consists of main and complementary operations, the flow may vary depending on the type of commodity, and in particular way on the part of the plant concerned, which can be leaves, roots, tubers, bulbs, fruits (immature or ripe), stems, flower buds, inflorescences or flowers [19]. The presence of peeling, washing operations and cutting, then depends not only on the type of product, but also on the final product that should be obtained. The leaves, for example, remain intact for baby leaves (rocket, lambs lettuce, baby spinach), or undergo the cutting as in the case of various lettuces and radicchio; fruits with edible peel like apples and peaches may also undergo the operation of peeling according to final product specification. In **Figure 3**, a diagram of fresh-cut processing operations is shown from harvest to final distribution [4]. Processing takes place essentially in three macroareas of the plant: cooling operations and storage of raw materials, processing area, and final product storage area. All environments must be refrigerated, including processing area. Product flow must be unidirectional from the first to the last environment, even using a series of physical barriers, to prevent recontamination. The processing area is divided into two zones, called *low care* and *high care*, meaning that the care for the product increases as it moves from the receiving area to the raw material (low care) to the packaging area (high care). The various areas must be separated by physical barriers, usually masonry walls or panels laminates. In the low care area operation of selection, peeling and cutting of the product take place, while in the high care area the operations of washing, drying and packaging. Each of these areas can have one or more processing lines whose level of automation can range from fully automated, to completely manual. Usually manual operations are allowed only in the low-care area, while after washing (i.e. in the high-care area) presence of humans is only considered for inspection and control. The presence of humans increase the risk of contamination of the product so, whenever processing automation is possible, manual operations are progressively disappearing. Salad processing lines have been more subject to plant automation and nowadays commercial processing lines are available where most of the operations are completely automatic, with the exception, in some cases, of initial trimming of adult salad types like lettuce and radicchio, where decoring and removal of older, external leaves are still performed by humans, who also make an important visual inspection of the product for the presence of foreign bodies (i.e. insect, snails, etc.). For baby leaves processing plants are completely automatic and in this case optical sorters for foreign body removal are necessary (see **Figure 2**).

Plant automation for fresh-cut processing of fruits have been more difficult to apply given the very high level of bruising susceptibility or the large size of the raw material and the difficulty of performing efficient peeling and decoring operations compatible with shelf-life as a fresh-cut produce, where thermal enzyme inactivation is not possible. For this reason fresh-cut fruit are still frequently processed by manual operations and this of course affects the cost of processing. In the past few years process automation for fresh-cut fruit have progressively increased: for some products many of the operations (peeling, cutting, decoring) are performed by machines although equipments are still manually feeded and, in some cases, some manual completion of the operations are still needed. For some products (i.e. fresh-cut apples) completely automatic processing lines are available, with very large working capacity, and very high standard of quality of the operations. In all cases (fresh-cut fruits and vegetbles) the implementation of fully automated processing lines are only justified by very large operational capacity.

4. Recent evolution in Controlled-Atmosphere (CA) storage technology

The safe concentration ranges of O_2 and CO_2 for storage of nearly all fruit and vegetables have been identified, but commercial application of CA storage is limited to few products. Most use is on apples and pears, less on cabbages, sweet onions, kiwifruits, avocados, persimmons, pomegranates, and nuts. Atmospheric modification during long-distance transport is used with apples, asparagus, avocados, bananas, broccoli, cane berries, cherries, figs, kiwifruits, mangos, melons, nectarines, peaches, pears, plums, and strawberries. CA is limited for many products because it requires significant capital investment [12]. Structures must be air tight and refrigerated, with precise temperature control and equipment to modify the atmospheres. The volume of these storage rooms is also large to maximize the value of the equipment. Therefore, the return on investment requires long lived commodities that are stored for months, not days or weeks, hence the suitability of fruit such as apple because it is stored in large quantities for up to a year in some cases. The economic importance and long term storage potential of the apple has been a driver for development of new CA technologies. Standard CA, in which O_2 and CO_2 concentrations are maintained in the 2-3% range, has increasingly become replaced by ultralow O_2 (ULO). Some cultivars in certain growing regions can be routinely stored in low O_2 concentrations between 1 and 1.5% if high quality storage rooms and computerized monitoring and maintenance of gas levels are available. More recently, dynamic CA (DCA) storage, which is based on the principle of lowering O_2 to lowest concentrations that are tolerated by the fruit, without causing excessive anaerobic respiration, to further improve quality maintenance, has been developed. Advances in technologies allow 'sensing' of the fruit responses to low O_2 by the fruit as it reaches the anaerobic compensation point beyond which fermentation occurs. The available technologies are DCA-chlorophyll fluorescence (DCA-CF; HarvestWatchTM) [20], ethanol (dynamic control system (DCS) [21], and respiratory quotient [22]. Regardless of the sensor system used, the O_2 is typically increased about 0.2% above the critical threshold to avoid damage to the fruit. While DCA can be applied to any chlorophyll containing product, and has been investigated on fruit such avocados and pears, it is used mainly on apple fruit [12].

5. Innovation in refrigeration fluid for cooling equipments

The need for a lower environmental impact of production processes also have stimulated research into the use of natural refrigerants in cooling equipment. After the progressive ban of the use of fluorochlorocarbons (CFC) and hydrochlorofluorocarbons (HCFC) due to their contribution to the deplection of stratospheric ozone layer, also the use of the presently allowed hydrofluorocarbons (HFC), which are the most widespread refrigerating gases on the market, are critically considered due the elevate carbon footprint in their production as they greatly contribute to the greenhouse effect. HFCs, while efficient refrigerants, have a global warming potential (GWP) thousands of times greater than that of carbon dioxide (**Table 1**). At present there is no legal requirement to phase out their use although the EU's F-Gas regulation introduces a number of measures to manage equipment containing HFC (such as leak testing), but there are no indications of a ban either now or in the future. Austria and Denmark have however put in place stricter controls than other EU members. Possible use of CO_2 has a natural refrigerating fluid has been explored in the past [6] in order to develop cooling equipment to be implemented in commercial refrigeration. However, the design and development of refrigeration compressors with the use of CO_2 present considerable problems, mainly related to:

- high operating pressures and consequent high end-of-compression temperatures (even with refrigeration systems having evaporation temperatures around -10 °C it is easy to reach end-of-compression temperatures close to 200 °C, which would be too high for the compressor);
- greater mechanical stress as differential pressures may be from 5 to 10 times higher;
- high thermal stresses, which entail the choice of suitable materials for components (i.e. valve and lubricants);
- high solubility of the refrigerant in polyester type oils with consequent decrease in the lubricating power of the oil-refrigerant mixture that is formed;
- need to contain the level of noise and vibrations within acceptable levels.

On the other hand CO_2 has a specific volumetric thermal capacity from 5 to 10 times higher than that of conventional fluids which would contribute to a more efficient performance.

A prototype was realized and tested for cold storage of fresh produce [23] using the following solutions:

- an evaporative panel combined with the condenser with the purpose of reducing the temperature of the condenser of additional 5 ° C;
- an electronically controlled rolling valve replacing the thermostatic valve determining an improvement in the coefficient of performance (COP);
- an intermediate liquid receiver that allows to separate the liquid CO_2 from the gas flash obtaining a cycle with higher efficiency.

The system was been designed to operate in a trans-critical cycle mode in case of high environmental temperature (>31 °C), while for lower temperatures it operates in a sub-critical cycle mode.

Refrigerating units using CO_2 as fluid are commercially available nowadays although their use in southern Europe latitude might have some limitations in terms of energy efficiency as CO_2 has a very low critical temperature (around 30 °C) while "traditional" refrigerating gases have very high critical temperatures and remain in a liquid state at temperatures above 50 ° C. In Italy, using CO_2 as a refrigerant involve the plant to work in a trans-critical cycle mode and this would result in a greater consumption of electricity compared to traditional fluids. Currently, for the refrigerating machines that work in the trans-critical cycle mode for single systems like a single cold room not exceeding the power output of about 30 kW (i.e. cold room for fresh produce of about 500 m^3), the average cost, to date, would be about 2/3 times the standard cost.

6. Conclusions

Maximum postharvest quality can be achieved by understanding and managing the various roles that all factors play on fresh produce. It starts as early as when the cultivar is chosen. In addition, the fresh-cut produce sector requires raw materials that are able to tolerate all the processing steps such as washing, cutting, drying, and packaging. The last decade has represented a time of great innovation for the postharvest equipment; most notably the development of optical technologies enabling to evaluate internal quality of individual fruits and to reveal more information on pre-harvest history of fresh produce, thus adding more service and value to consumers. In addition to this the complete automation of manufacturing processes is presently contributing to reduction of processing cost and to increase of food safety. Novel storage innovations like dynamic controlled atmosphere is contributing to extend commercial life of fresh produce, maintaining a better quality and reducing food losses. Finally, innovation in refrigerating equipments is contributing to reduce environmental impact of fresh produce industry and increase its sustainability.

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FIGURES

Figure 1 - Examples of image analysis output for correct classification probability for sound and defected rocket leaves, according to different type of defects. *Suorce: [11]*

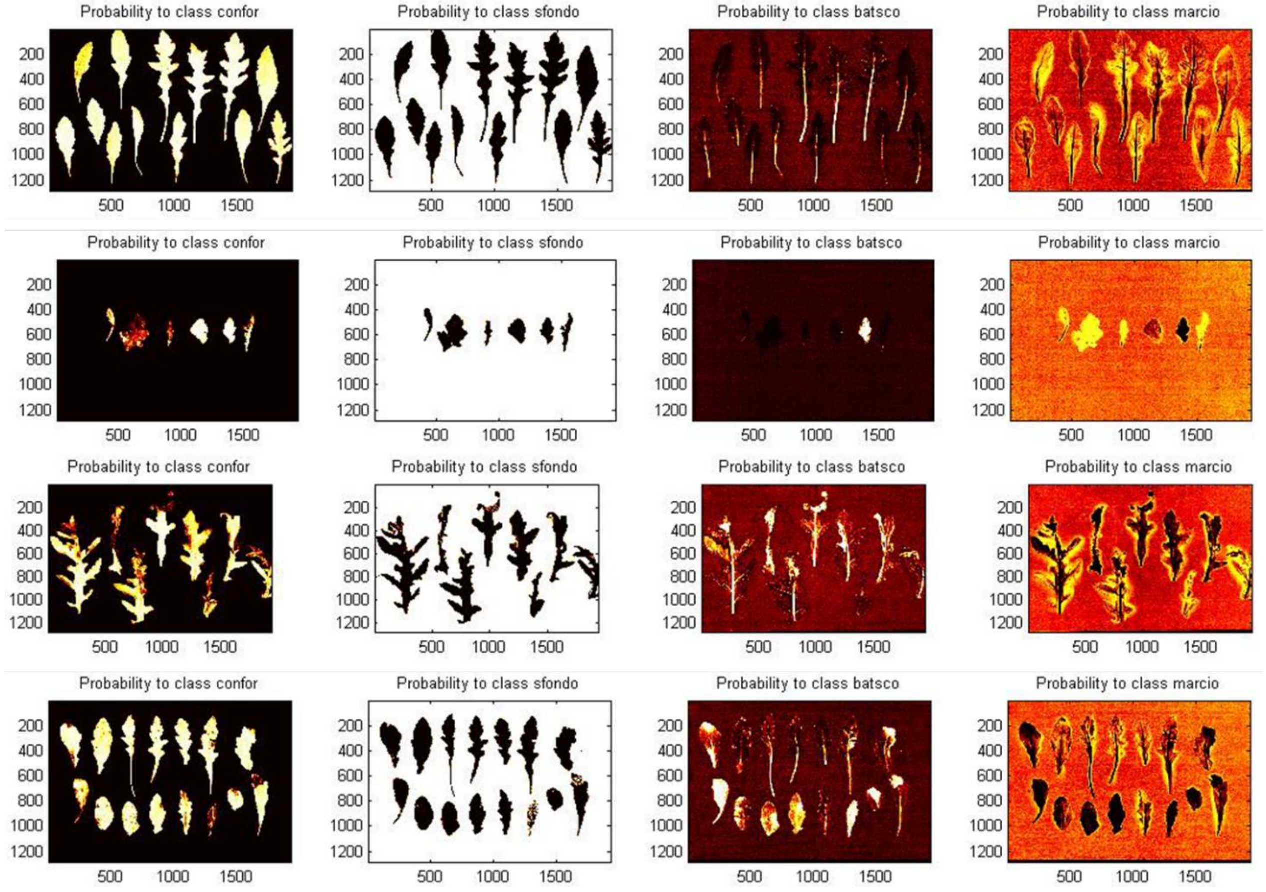
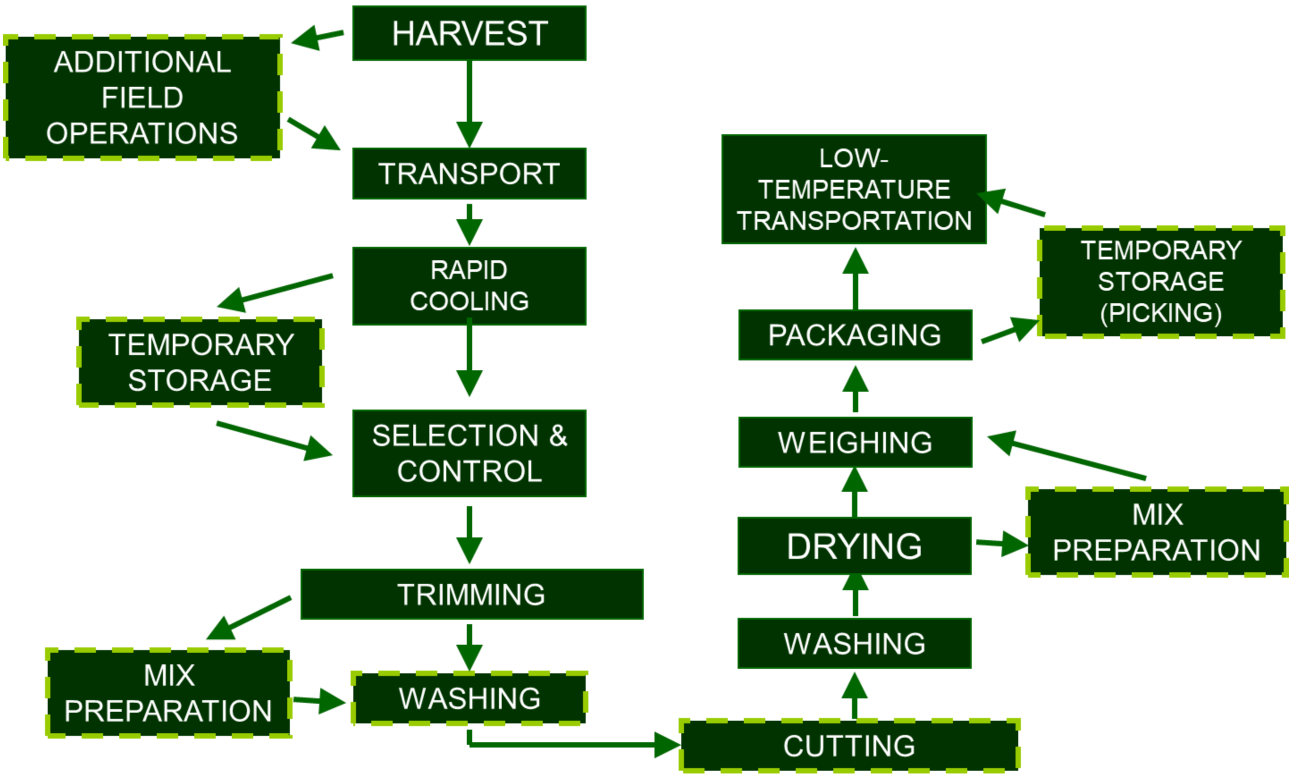


Figure 2 - Foreign body sorting machine on a ready-to-eat baby leaf processing line.

Figure 3 - Flow diagram of processing operations for fresh-cut fruit and vegetables from harvest to distribution (dashed box may represent optional operations). *Source: [4], translated.*



TABLES

Table 1 - Global Warming Potential (GWP) values of some commonly used potentially used refrigerating fluids.

TYPE OF FLUID	GWP	NOTES
CO_2	1	Reference
R134a	1430	Hydrofluorocarbon (HFC)
R410A	2088	Mix of R32 (50%), R125 (50%)
R404A	3922	Mix of R125 (44%), R134a (4%), R143a (52%)
R600a (butano)	0	Hydrocarbons (HC), explosive
R290 (propano)	3	Hydrocarbons (HC), explosive
CH_4 (metano)	21	Hydrocarbons (HC), explosive