INFLUENCE OF FRUITS AND VEGETABLES ACTIVE PACKAGING ON REFRIGERATION SYSTEMS EFFICIENCY

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Abstract: *The proper design of the container for fresh fruits and vegetables is very important for the correct and rapid cooling of these packaged foods. Both the bulk packaging and the primary packaging must have adequate openings, such as macro-perforations in the film that closes the primary packaging or ventilation windows as in the case of bulk packaging crates (whether cardboard or plastic). Consequently, the heat transfer coefficient will be increased, and a significant reduction in cooling time can be achieved, thus reducing the specific energy consumption (in kWh/kg of produce) in the refrigeration installation during the pre-cooling process, and during storage and transport at marketing temperature. On the other hand, the active packaging of fresh fruits and vegetables can achieve a significant decrease in respiratory activity and, therefore, a reduction in the heat produced (in kWh/kg of produce) by respiration during pre-cooling, cold storage and refrigerated transport.*

Keywords: Energy consumption, product respiration, heat production by respiration, encapsulated essential oils, fresh fruits and vegetables

1. INTRODUCTION. IMPORTANCE OF ENERGY CONSUMPTION IN REFRIGERATION FACILITIES FOR THE PRE-COOLING AND CONSERVATION OF REFRIGERATED FRUITS AND VEGETABLES

Respiration of harvested horticultural products is an exothermic process by which stored organic substances of fruits and vegetables (carbohydrates, fats, proteins, etc.) are transformed into simple end-products (e.g. CO_2 and H_2O) with a energy release (heat). The heat generation can be harmful for the plant tissues, leading to higher temperatures of the product and unsatisfactory consecuences like: reduction of food value, reduction of flavor quality (mainly sweetness), senescence processes, and reduced saleable product mass [1]. The quantity of heat generated differs with the product as observed in Table 1:

Table 1. Heat of respiration of selected fruits and vegetables [2].

Commodity	Respiratory heat generated per unit mass (mW.kg^{-1})			
	0°C	5°C	10°C	15°C
Apples	10-12	15-21	41-61	41-92
Apricots	15-17	19-27	33-56	63-101
Blackberries	46-68	85-135	154-280	208-431
Broccoli	55-63	102-474	--	514-1000
Cabbage	12-40	28-63	36-86	66-169
Celery	21	32	58-81	110
Corn, Sweet	125	230	331	482
Leeks	28-48	58-86	158-201	245-346
Lettuce, head	27-50	39-59	64-118	114-121

Onions	7-9	10-20	21	33
Oranges	9	14-19	35-40	38-67
Peaches	11-19	19-27	46	98-125
Potatoes, mature	--	17-20	20-30	20-35
Strawberries	36-52	48-98	145-280	210-273

The respiration rate of a product depends of temperature (e.g. for each 10 ºC reduction in temperature the respiration rate may be reduced by a factor of 2-5), so the deterioration rate is proportional to the respiration rate of the product. The temperature coefficient (based on Van't Hoff's Law) for a 10 ºC-interval is known as the "Temperature Quotient of Respiration (Q10)" [3], and can be obtained by analyzing the respiration rate at two different temperatures (T) through (Eq. 1):

$$Q_{10} = \frac{Respiration\ rate\ at\ T^{+10\ ^{o}C}}{Respiration\ rate\ at\ T} \tag{1}$$

As the produce temperature augments, the respiration rate increases while the Q_{10} value is reduced, as observed in Table 2.

Table 2. Effect of temperature on Q_{10} and deterioration of horticultural products [1].

Temperature (°C)	**Assumed Q_{10}**	**Relative velocity of deterioration**	**Relative shelf life**	**Loss per day (%)**
0	--	1.0	100	1
10	3.0	3.0	33	3
20	2.5	7.5	13	8
30	2.0	15.0	7	14
40	1.5	22.5	4	25

In addition, plant products produce ethylene, which is known as the "ripening hormone" of plants since it is able to accelerate ripening/senescence of plant products. The ethylene production rate of produce is decreased as the storage temperature is reduced. Furthermore, ethylene, which is an autocatalytic metabolite, augments the respiration rates in nearly all postharvest plant organs [4].

In that sense, the temperature is the most important factor to control the heat production of produce during refrigerated storage through reduction of respiration and ethylene production rates. Furthermore, low storage temperatures highly maintain the quality of fruit and vegetables, extending their shelf life and ensuring the commodity value. However, optimum storage temperature is different for every horticultural product since chilling injuries of produce may appear. For example, tomatoes are chilling sensitive at temperatures below 10 ºC if held for longer than 2 weeks, or at 5 ºC for longer than 6-8 days [1].

A rapid precooling of the horticultural produce after harvest to its optimum storage temperature is crucial to reduce their metabolic rates (i.e. respiration and ethylene production rates). Subsequent storage at these low temperatures must be also ensured to extend the product shelf life. In fact, the average mass loss of the cold chain without precooling is approximately 23 % greater than that of the cold chain with precooling [5]. Among the most used precooling systems are forced-air cooling, room cooling, vacuum cooling, hydrocooling and package icing. Forced-air cooling is considered the most used method in horticultural processing facilities [6], [7]. Forced-air precooling is achieved by forcing cold air across the packages with produce using a potent fan, being originated a pressure gradient across the container openings and around the products (Figure 1).

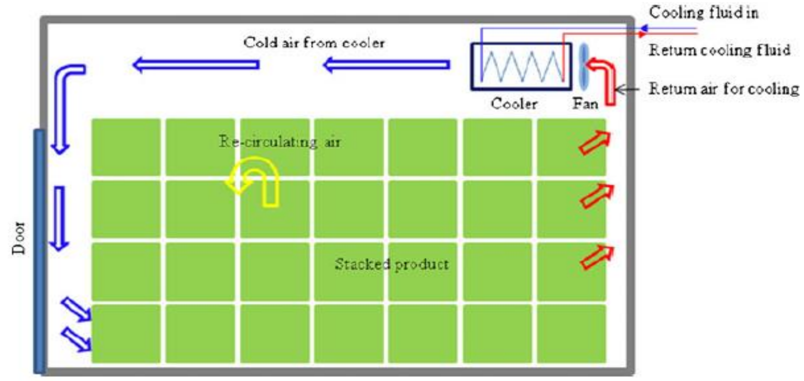

Figure 1. Typical forced-air cooling system of horticultural products [8].

The efficiency of the refrigeration process is primarily assessed by the rapidity and the uniformity in the storage temperature decrease of products compared to the appropriate energy input [5]. Then, an efficient cooling process should be rapid and uniform, being this efficiency assessed based on process velocity using cooling rate or half-cooling time method and temperature uniformity [9]. Complex mechanisms of energy and mass transport are involved in the precooling process and are defined by conservation laws of mass, momentum, and energy [10]. The rapidity and uniformity of precooling process of products may be also enhanced by modifications of air supply parameters like increasing airflow rate, changing airflow direction or lowing cold air temperature. Nevertheless, these modifications may lead to an increase in energy consumption, higher operating costs and the increasing risks of chilling injuries or those related to water losses (shrinkage and wilting).

The effectiveness and energy consumption of the forced-air cooling process is highly affected by the flow field uniformity. The heterogeneity of heat transfer is usually ascribed to the flow heterogeneity, that is directly related to frictional loss as the air flows through containers and packages and passes by fruit during the precooling process [5]. Accordingly, packaging will indirectly increase the energy consumption of the cooling system, being the packaging design (material, vent holes size, position, orientation, etc.) of high importance to ensure optimized cooling rates. In addition, active packaging that releases molecules (e.g. plant essential oils) able to inhibit produce respiration, is an interesting technological approach to reduce the heat production inside packages.

2. RELATIONSHIP BETWEEN VENT HOLES AND DESIGN OF PRIMARY PACKAGING AND BULK PACKAGING, AND THE COOLING RATE OF FRESH FRUITS AND VEGETABLES

Packaging is a key food processing unit operation with the objetcives of containment, protection, preservation, storage and distribution of food [11]. The fresh fruit and vegetable market uses diverse package materials and designs, being corrugated fiberboard cartons and reusable plastic containers frequently used. Among the advantages of corrugated fiberboard cartons are lightweight, completely recyclable, biodegradable, cost- effective, and damping mechanical impacts and vibrations. Packages usually handled by hand are frequently limited to 25 kg in wooden, plastic or corrugated fiberboard cartons. Products within these packages can be disposed of in single or multiple layers [10].

Packages of horticultural products are designed with vent holes to facilitate the removal of heat of product respiration with a proper airflow during the produce cooling process (Figure 2A). The total vent area, the position of the vent holes, and their shape influence the produce cooling rate and the refrigeration uniformity and therefore, the energy, material usage, and the carbon footprint of the industry. In that sense, an optimized package may allow an appropriate airflow while avoiding excessive water loss of produce (due to high transpiration rates) that leads to wilting and shriveling of products. In addition, the design of vent holes on the walls of the package must also ensure a sufficient mechanical resistance of packages, of high importance during handling operations like palletization and stacking of packages [10]. The alienation of vent holes in stacked packages is crucial to ensure adequate airflow in the tunnel horizontal airflow arrangement in forced-air cooling rooms. In this disposition, the top and back sides of the tunnel are enclosed by an air-tight sheet, being located the fan at the front termination of the tunnel to pull chilly air through the stack (Figure 2B).

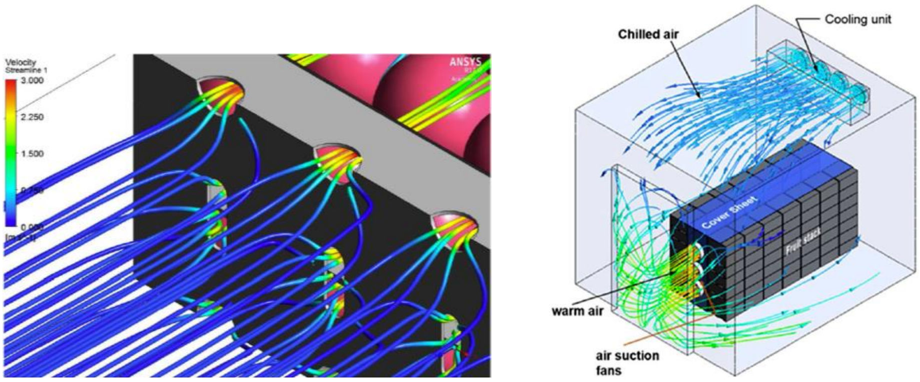

Figure 2. Detail of airflow through vent holes of a typical corrugated fibreboard package (A) and forced air- cooling tunnel (B) [10].

Package design and evaluation should employ a multiparameter approach giving a holistic assessment of all functionalities and parameters to help avoid contradictions in the design requirements. In that sense, mathematical modeling allows precise control of operating parameters while giving crucial information like the airflow, mechanical strain, mechanical stress and temperature patterns in the stack of fruit under refrigeration conditions; providing mechanisms and performance details of the processes [10].

In particular, computational fluid dynamics (CFD) is widely used for packaging design, being the finite volume method the most often used type of CFD for fresh horticultural products. CFD is an approach with which the appropriate geometry is discretized and the governing partial differential equations (Navier–Stokes equations) for conservation of mass, momentum and energy are solved on a discrete mesh on the geometry using numerical methods such as the finite volume method or the finite element method [12]. The basic CFD heat transfer model is implemented with the respiration and transpiration of the product and heat gain/loss from evaporation/condensation of water to model airflow coupled with moisture transport [10]. The most used commercial software in studies of CFD with horticultural products is ANSYS®. Overall, CFD allows increasing forced-air cooling efficiency by the combination of a certain percentage of container opening area and vent positioning with airflow rate. Nevertheless, the compromise between cooling efficacy and mechanical resistance must be ensured.

3. ACTIVE PACKAGING AS A TECHNIQUE TO REDUCE THE RESPIRATORY ACTIVITY OF FRESH REFRIGERATED FRUITS AND VEGETABLES

Active packaging is an efficient technology that allows extending the shelf-life of produce through a controlled release of bioactive compounds of different nature like antimicrobials, antioxidants, etc. Encapsulation of bioactive compounds within inclusion complex with cyclodextrins (CD) is a method that may highly protect bioactive compounds from degradation reactions due to temperature, oxidation and moisture preserving their properties. Particularly, the most important CDs at the industrial level are α– and β–CD, being the latter one highly extended due to its lower cost. The release of the bioactive is favored, among other factors, by relative humidity, as the high RH of cold rooms for fruit and vegetables [13].

Plant essential oils (EOs) are natural extracts from plants highly accepted by the actual consumer with well- known antimicrobial properties. Most EOs, as well as their major compounds (e.g. geraniol, citronella, carvacrol, thymol, etc.), are accepted as food additives in the EU, being EOs and EO compounds classified by the EU as "natural flavoring substance" and "flavoring preparation", respectively [14], [15]. Nevertheless, little attention has been paid to other properties of EOs like their ability to inhibit the activity of several plant enzymes. In particular, released EOs from active packaging inhibited the activity of ACC[1] oxidase and consequently lowered the contents of ACC, the ultimate substrate for the ethylene biosynthesis (Figure 3) [16]. In addition, EOs released from active packaging inhibited the activity of other enzymes like polygalacturonase and pectin methylesterase, which is involved in the integrity of plant cells, and polyphenoloxidase, which is related to color changes of the product [17]. In that sense, the EOs released from active packaging in the vapor phase leads to lower respiration and ethylene production rates (Figure 4), and consequently lower heat production by the stored horticultural products.

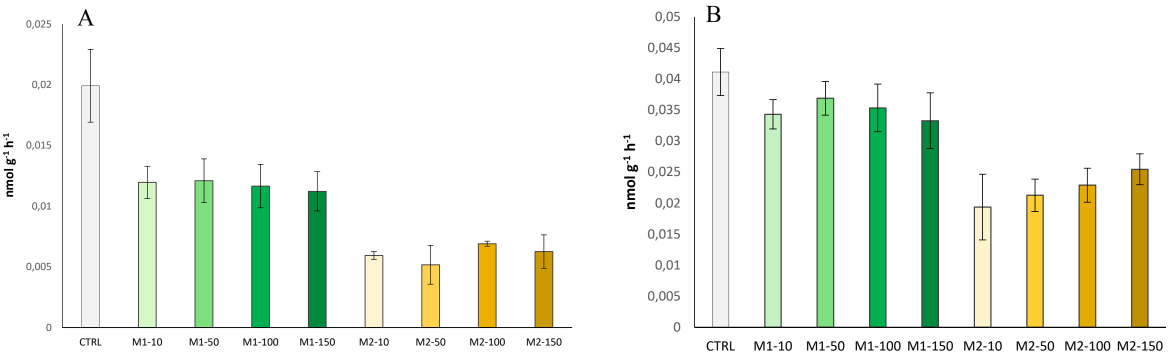

Figure 3. Ethylene production (A) and 1-Aminocyclopropanecarboxylic acid oxidase activity (B) of broccoli florets with active paper sheets containing two different essential oils mixes (M1, carvacrol:spearmint EOs 80:20; or M2, carvacrol:oregano EO:cinnamon EO 70:10:20) at different doses (10, 50, 100, and 150 mg m^{-2}) at 2 °C (mean ± SD) [16].

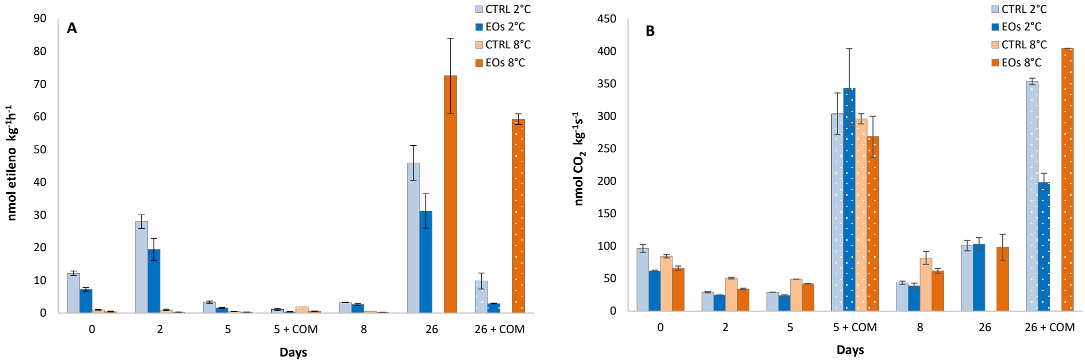

Figure 4. Ethylene production (A) and CO$_2$ production (B) during cold storage periods (2 and 8 ºC) and complimentary commercialization simulations (COM; 4 days at 22 ºC) of flat peach with or without active paper sheets (including βCD-encapsulated EOs) (mean ± SD) [17].

4. QUANTIFICATION OF THE REDUCTION IN SPECIFIC ENERGY CONSUMPTION OF REFRIGERATION INSTALLATIONS BECAUSE OF THE USE OF ACTIVE PACKAGING SYSTEMS

The heat generated by the respiration of the produce has to be evacuated to maintain a constant temperature inside the cold room. In addition, heat inputs through the enclosures (walls, floor, ceiling and doors), heat is given off by the people who work inside the chamber, motors and lamps will also have to be evacuated. It would be necessary to consider the flow of heat that enters the system through air infiltrations (like door openings).

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[1] 1-aminocyclopropanecarboxylic acid

Reductions of respiration and ethylene production rates of flat peaches and broccoli with active packaging reached up to 30-50 %, with the correspondent inhibition of the activity of key enzymes involved in respiration pathways [16], [17]. According to Table 1, such respiration rate reductions with active packaging would imply drops of heat generated by the product of 10-30 mW kg^{-1}.

5. CONCLUSIONS

The use of active packaging with essential oils leads to a reduction of the heat generated by the product due to respiration. Consequently, the energy consumption of the refrigeration system is reduced being increased the efficiency of the cooling process. Accordingly, using active packaging will allow reducing other methods used to increase the cooling efficiency like increasing airflow rate, changing airflow direction or lowing cold air temperature. In addition, the related risks of those methods (chilling injury, shrinkage and wilting of the product) are reduced with this green technology based on plant essential oils release from packages.

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