clean technologies

Review

Potential of Released Essential Oils from Active Packaging to Reduce Refrigeration Needs of Fruit and Vegetables

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Abstract: The energy efficiency of fruit and vegetables refrigeration facilities can be increased through the reduction of heat generated by produce (in kWh/kg). Ethylene production in fruit and vegetables is closely linked to their respiration rates. Clean technologies that can reduce ethylene production of fruit and vegetables are needed to relax (increase) the setpoint temperature of cold rooms. The heat produced may be reduced by up to 50% when ethylene concentrations surrounding the produce are reduced from 0.1–1 to 0.001–0.01 μL L^{-1} during the storage of some vegetables. There is a need to find green alternatives to ethylene scavenging techniques (of high cost and chemical origin) such as, for example, active packaging with encapsulated essential oils. Hence, respiration and ethylene production rates of flat peaches and broccoli were reduced by up to 30–50% with active packaging with essential oils. It would imply a lower produce heat generation of 14–30% with the consequent energy savings in the refrigeration systems of horticultural facilities. Consequently, the potential of essential oils released from active packaging to reduce the energy consumption related to respiratory heat of produce is hereby firstly reviewed and proposed as a clean technology to extend the postharvest life of fruit and vegetables.

Keywords: energy use; produce respiration; respiration heat; encapsulated essential oils; fresh fruit and vegetables

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1. Impact of Produce Heat Generation during Respiration on the Refrigeration Needs

Respiration is the chemical process by which fruits and vegetables (F&V) convert sugars and oxygen into carbon dioxide, water, and heat, as observed in Equation (1) [1,2]. The heat generated by product respiration has to be eliminated to keep a constant temperature inside the cold room, which implies a high energy consumption in the horticultural facilities, during transport and retail. In addition, other heat contributions are heat inputs across the enclosures (walls, ground, ceiling, and gates) and heat produced by workers, motors, and lamps.

$$C_6H_{12}O_2 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{generated heat (2667 kJ)} \quad (1)$$

Heat generation can be detrimental to plant tissues, increasing the produce temperature and leading to inadequate consequences such as a decrease of food value, reduction of flavor quality (predominantly sweetness), senescence, and decreased marketable product mass, among others [3]. In addition, the production of certain compounds by the horticultural products (e.g., ethylene) and their accumulation in the surrounding atmosphere lead to an acceleration of senescence processes, and consequently to the reduction of the product shelf life.

The respiration rate of a product depends also on the product temperature. In that sense, the refrigeration needs of cold rooms for horticultural produce may take into account the calculations of the heat generated by the product, which will be different depending on the storage temperature. The CO_2 production during respiration at different temperatures

(T in °C) is described in Equation (2). Published respiration coefficients f (carbon dioxide production vs. temperature correlation coefficient) and g (carbon dioxide production vs. temperature correlation coefficient) of Equation (2) for different types of produce are shown in Table 1.

$$CO_2\ production\ rate \left(\frac{\text{mg CO}_2}{\text{kg}\cdot\text{h}}\right) = f \times \left[\frac{(9 \times T)}{5} + 32\right]^g \quad (2)$$

Table 1. Respiration coefficients (f and g) of different horticultural products obtained via a least-squares fit to published data [2,4].

	Respiration Coefficients	
	f (×10^{-4})	g
Apples	5.687	2.598
Blueberries	0.725	3.258
Brussel sprouts	27.24	2.573
Cabbage	6.080	2.618
Carrots	500.2	1.793
Grapefruit	35.83	1.998
Grapes	0.7056	3.033
Green peppers	3.510	2.741
Lemons	111.9	1.774
Lima beans	9.105	2.848
Limes	2.983×10^{-4}	4.733
Onions	3.668	2.538
Oranges	2.805	2.684
Peaches	0.1300	3.642
Pears	6.361	3.204
Plums	0.8608	2.972
Potatoes	170.9	1.769
Snap beans	32.83	2.508
Sugar beets	85.91	1.888
Strawberries	3.668	3.033
Tomatoes	2.007	2.835

f (carbon dioxide production vs. temperature correlation coefficient); g (carbon di-oxide production vs. temperature correlation coefficient).

In addition, the temperature coefficient (based on Van't Hoff's law) for a 10 °C-interval is known as the "Temperature quotient of respiration (Q_{10})" [5] and can be obtained by analyzing the respiration rate at two different temperatures (T) as described in Equation (3).

$$Q_{10} = \frac{Respiration\ rate\ at\ T^{\ +10°C}}{Respiration\ rate\ at\ T} \quad (3)$$

Hence, quality degradation of products, and consequently reduction of their shelf life, is related to Q_{10} as observed in Table 2. When the product temperature increases, respiration augments while Q_{10} decreases.

Table 2. Effect of temperature on Q_{10} and deterioration of horticultural products [3].

Temperature (°C)	Assumed Q_{10}	Relative Velocity of Deterioration	Relative Shelf Life	Loss per Day (%)
0	-	1.5	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	14	25

The heat generation by horticultural produce can be then related to the CO_2 production during respiration in accordance with Equation (1). From Equation (1), it was deduced that, during respiration, 10.1 J of heat is generated for every milligram of CO_2 produced. The amount of heat generated depends on the product as well as the storage temperature. The quantity of heat generated due to the product respiration is different depending on the product, as well as the storage temperature. Table 3 shows respiratory heat generated by different horticultural products during storage at different temperatures.

Table 3. Respiration heat of selected fruit and vegetables [6].

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
Apricot	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
Sweet corn	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	-	17–20	20–30	20–35
Strawberries	36–52	48–98	145–280	210–273

2. Ethylene Production and Needed Energy Consumption for Its Removal in the Plant Product Facilities

Plants and their products produce ethylene (C_2H_4), a volatile hormone known as the "ripening hormone", which is responsible for produce ripening/senescence processes [7]. Ethylene biosynthesis is triggered by several factors, such as high storage temperatures and low oxygen levels (Figure 1). In addition, ethylene is autocatalytic, which means that its endogenous biosynthesis may become exponential if ethylene concentrations are accumulated around the product. The main effects of ethylene on plant products are:

- Accelerated senescence and maturation
- Induction of physiological disorders (e.g., foliar disorders in leafy vegetables)
- Formation of isocoumarins (bitter flavor)
- Sprouting of tubercules
- Abscission of leaves, flowers, etc.
- Other quality degradation (e.g., asparagus hardening, etc.)
- Other effects in plants: stimulates the germination of dormant seeds, changes the direction of seedling growth, can stimulate flowering, etc.

The product shelf life may then be highly reduced if ethylene production is not reduced or accumulated ethylene in the air surrounding the product is not removed using ethylene scavengers [8–10]. For example, an increment of ethylene concentration from 0.001 to 0.01 uL L^{-1} in a package of 10 kg of green beans led to a reduction of the product shelf life from 24 days to 14 days at 10 °C [11]. The shelf life reduction due to the ethylene increment from 0.001 to 0.01 uL L^{-1} would imply an increment of energy consumption (related to the needs of removing produce heat) of refrigeration facilities of 1460 J day^{-1} to counterbalance those higher ethylene concentrations [9]. The shelf-life reduction of several horticultural products is observed in Figure 2 under different ethylene concentration atmospheres and storage temperatures.

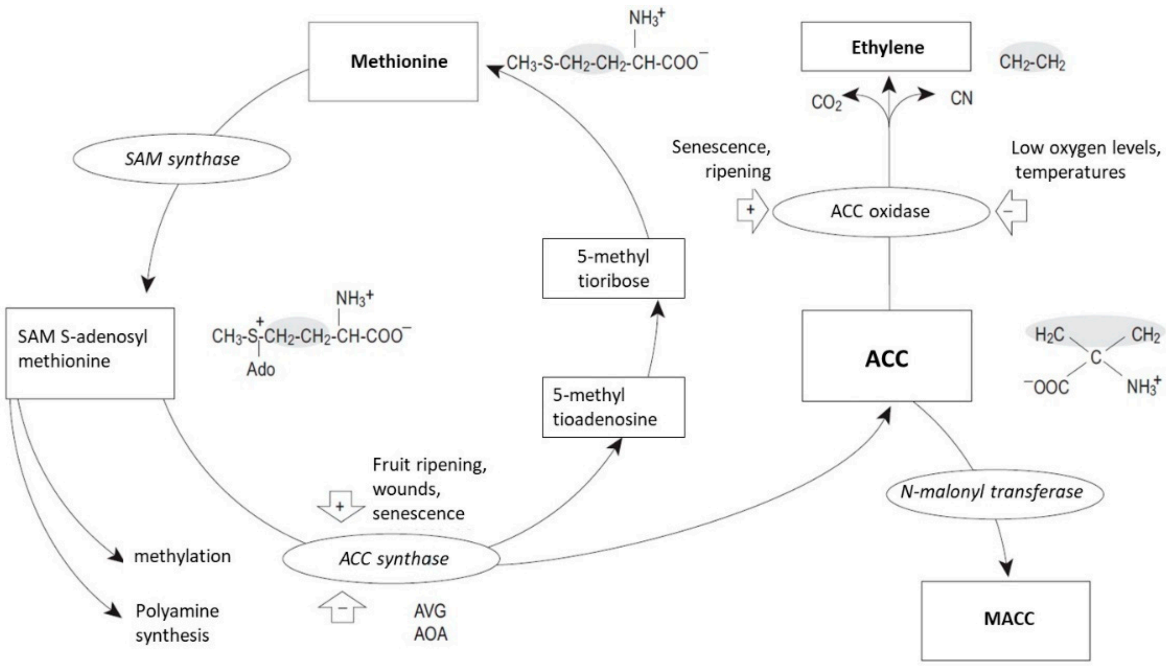


Figure 1. Ethylene biosynthesis pathway. SAM, S-adenosyl-L-methione; ACC, 1-aminocyclopropane-1-carboxylic acid; ACS, 1-aminocyclopropane-1-carboxylate synthase; MACC, 1-(malonylamino) cyclopropane-1-carboxylic acid; ACO, 1-aminocyclopropane-1-carboxylate oxidase.

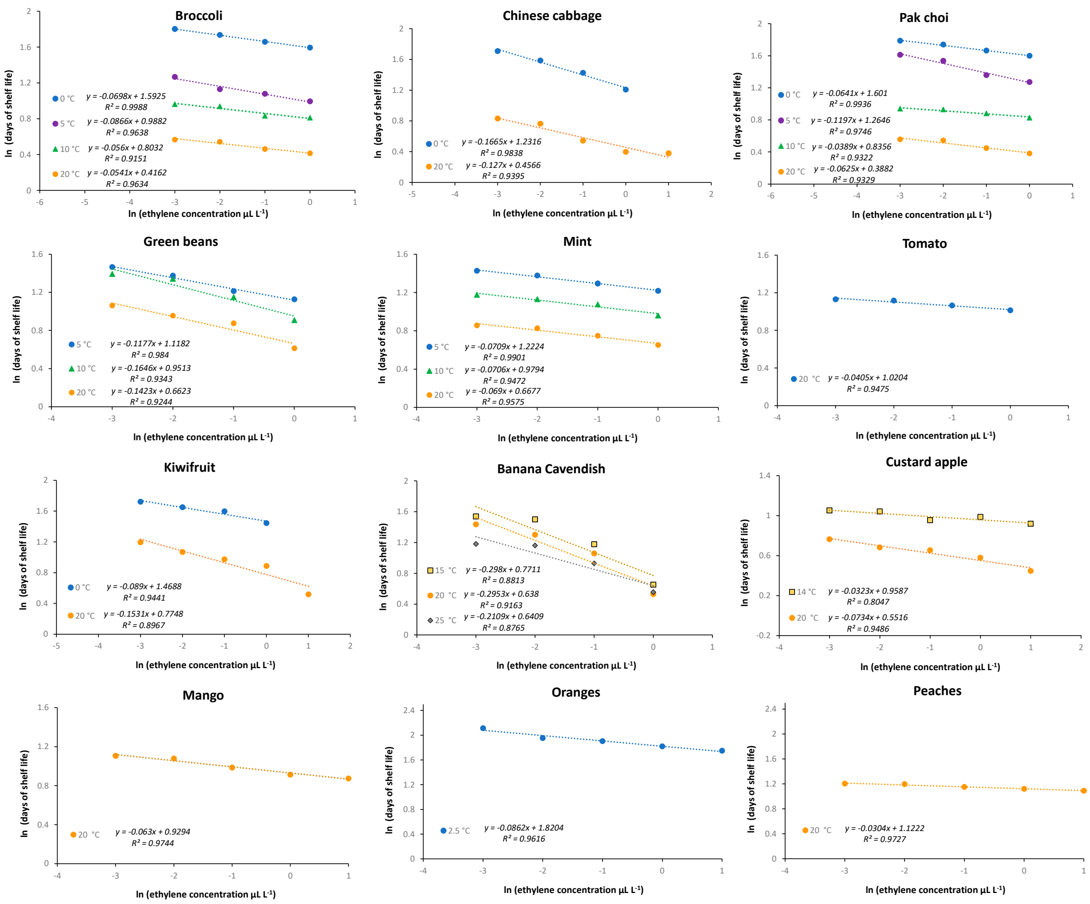


Figure 2. Effect of ethylene concentrations in storage facilities on the shelf life of fruit and vegetables (elaborated from [11–13]). The corresponding equations of linear regression lines and R^2 values are also provided.

The threshold atmospheric level below no physiological effects on horticultural produce has been widely reported to be 0.1 uL L^{-1}, although that concept was developed at a time when the analytical sensitivity for ethylene analysis was very low [9]. Hence, even concentrations as low as 0.001 μL L^{-1} are able to induce product ripening [11]. Such concentrations are far higher in the postharvest chain, for example: (i) Morris et al. [14] reported mean ethylene levels of 0.2 μL L^{-1} in lettuce cardboard packaging; (ii) Schouten [15] found in a shipment within a closed truck and a ventilated trailer of mixed vegetables mean ethylene levels of 5.9 and 0.68 μL L^{-1}, respectively; (iii) Wills et al. [13] conducted a larger study in handling and storage areas in different Sydney F&V wholesale markets, produce distribution centers, supermarket retail stores and domestic refrigerators (total of 700 atmospheric samples collected), being common an ethylene concentration of 0.1 μL L^{-1} in many areas, rising these levels up to 0.2–1 μL L^{-1} in fruit storage chambers. Overall, those findings imply that there is no "safe" level of ethylene that does not induce a deleterious effect on the F&V during postharvest life, resulting any reduction in the ethylene concentration in an increase of the product shelf life [9].

Removal of ethylene using ethylene scavengers is an expensive solution and many of the commercial ethylene scavengers were found to be insufficient to maintain a low ethylene atmosphere for any prolonged period as reported in the publication of Reid and Dodge [16]: "New ethylene absorbents: No miracle cure". In such a scenario, the ethylene removal in the atmosphere of refrigeration facilities by automatically programmed air renovations and a reduction of ethylene production by reduction of product metabolism through lowering the storage temperature are the most common postharvest techniques used, which implies important energy consumption expenses.

Another alternative to reduce the ethylene effects on produce is the 1-methylcyclopropene (1-MCP), a synthetic molecule with physical similarity to the ethylene molecule but a higher affinity for the ethylene receptors of the plant product leading to the inactivation of the ethylene enzymatic system [17]. In many countries, 1-MCP is commercialized for various types of produce, although it is a relatively low-cost option and limited to certain produce (e.g., several fruits such as papaya and banana, and even different varieties for the same fruit can behave differently) [9].

In that sense, reduction of the produce metabolism with low storage temperature seems to be the most common technique to reduce ethylene production and respiration rates.

3. Refrigerated Storage as a Conventional Postharvest Technology to Extend the Shelf Life of Plant Products

Temperature control is the most usual postharvest technique to control quality changes in horticultural produce increasing its shelf life. Refrigeration facilities have a high energy consumption by the refrigeration system to maintain constant the setpoint storage temperature. For example, 40% of the total energy input (≈2 MJ kg^{-1}) from production to retail of apples corresponded to the long-term storage of apples [9,18]. The energy consumed is governed by the heat that enters the room (i.e., the heat load) and the efficiency of the refrigeration system to remove the heat from the room (i.e., the coefficient of performance). It is commonly considered that energy savings of up to 50% are possible through the proper specification, use, and maintenance of refrigeration equipment [9,19].

A rapid pre-cooling of the horticultural products once harvested to their optimal conservation temperature is critical to decrease the product metabolic rates (i.e., respiration and ethylene production ratios), as well as the subsequent storage at these low temperatures. The mean weight loss within the cold chain with no pre-cooling is around 23% higher compared with that of the pre-cooling + cold storage [20]. The most applied pre-cooling techniques are forced-air-cooling, room-cooling, vacuum-cooling, hydro-cooling, and package-icing. Forced-air-cooling is considered the most utilized method for horticultural storage installations [21,22]. Forced-air-pre-cooling is reached by forcing cold air through the packages including products employing powerful fans, which leads to a pressure gradient through the package apertures and over the product (Figure 3).

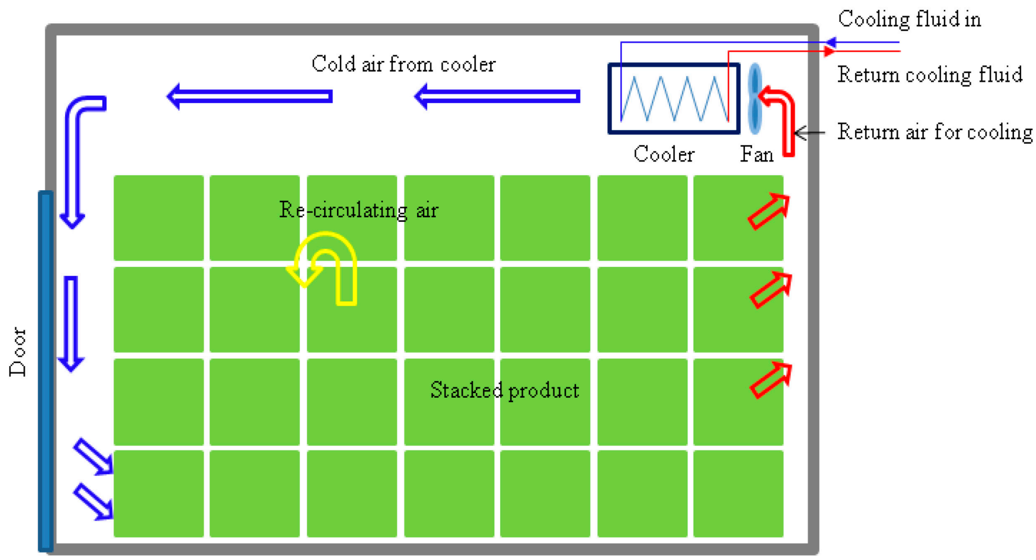


Figure 3. Typical forced-air-cooling schema of horticultural produce [23] (Reprinted with permission from the journal's editors).

The efficiency of the cooling procedure is principally evaluated by the rapidity and the homogeneity in the storage temperature reduction of produce in comparison with the suitable energy input [5]. Then, an effective cooling procedure must be fast and homogeneous, being this efficiency evaluated centred on the processing speed utilizing the cooling rate or the half-cooling-time method and temperature uniformity [24]. Complex processes of energy and mass transport are implicated in the pre-cooling procedure and follow the conservation mass laws, momentum, and energy [25]. The speed and homogeneity of the pre-cooling procedure of produce may be as well improved by changes in the air source factors such as rising airflow ratio, adjusting the airflow route, or reducing the temperature of the cooling air. However, these changes may induce an increment in energy use, greater operational costs, and the growing risks of physiological disorders of the product such as chilling injury (Figure 4A) or those linked to water losses (shrinkage and wilting) (Figure 4B). For instance, tomatoes have chilling sensitivity at temperatures lower than 10 °C if they are maintained longer than 14 days, or at 5 °C further than 6–8 days [3].

(**A**)

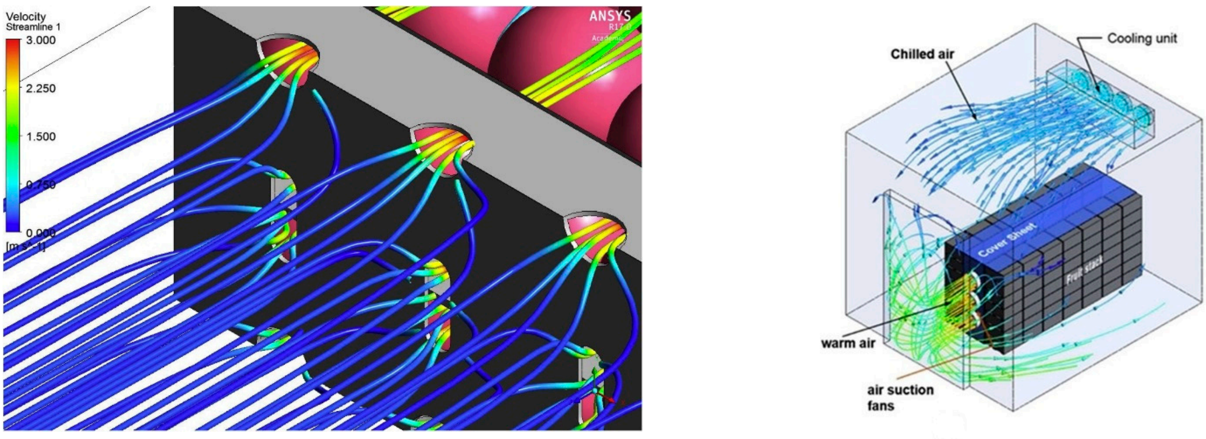
(**B**)

Figure 4. (**A**), Surface pitting of cherry tomatoes after 3 weeks at 2.5 °C (followed by 1 week at 20 °C) (left) compared to control (12.5 °C for 3 weeks, followed by 1 week at 20 °C) (right) [26]. (**B**), shrivelled plum (left) after five weeks at −0.5 °C (followed by 20 days at 20 °C) compared with control samples (right) (same storage conditions but with an edible coating to avoid water losses that occur in the storage rooms due to increase product transpiration due to the airflow from evaporators) [27].

The efficiency and energy use of the forced-air-cooling is greatly altered by the flow field homogeneity. The heterogeneous heat transmission is typically attributed to the flow heterogeneity, which is linked to frictional loss when the air flow crosses the containers and packages and contact the produce surface during the pre-cooling process [20]. Consequently, packaging will indirectly raise the energy use of the refrigeration system, the container design (material, vent hole size, position, orientation, etc.) being of great significance to guarantee improved cooling rates.

Packaging is a crucial food processing unit operation with the objectives of containment, defence, conservation, storage, and product distribution [28]. The fresh F&V market utilizes different packing materials and designs, corrugated fiberboard cartons and recyclable plastic packaging being commonly utilized. Amongst the advantages of corrugated fiberboard cartons are lightweight, entirely recyclable, biodegradable, cost-effective, and reduce mechanical collisions and vibrations. Containers generally hand-managed are often restricted to 25 kg in wooden, plastic, or corrugated fiberboard cartons. Produce in these containers may be arranged in single or multiple layers [25].

Packaging of horticultural produce is intended with vent holes to accelerate the elimination of heat from the product respiration using an appropriate airflow through the produce cooling procedure (Figure 5A). The total vent area, vent hole position, and their shape affect the product cooling speed and the cooling homogeneity, and, consequently, the energy, material use, and industrial carbon footprint. Hence, optimized packaging should permit a suitable airflow whilst preventing high water losses (>5%) of the products (due to elevated transpiration rates), which may produce wilting and product shriveling. Additionally, the vent hole design on the packaging walls has to ensure as well a sufficient mechanical resistance of the containers, which is of great significance through handling operations such as palletization and container stacking [25]. The alignment of vent holes in stacked containers is essential to guarantee sufficient airflow in the tunnel horizontal airflow layout in forced-air-cooling facilities. In this disposal, the upper and back tunnel walls are surrounded by an air-tight layer, being positioned the fan at the front tunnel end to remove cold air across the stacked packages (Figure 5B).



(**A**) (**B**)

Figure 5. Airflow across vent holes of a standard corrugated fiberboard packaging (**A**) and forced-air-cooling tunnel (**B**) (Reprinted with permission from [25], Copyright Elsevier (2020)).

Packaging design and assessment should utilize a multiparameter methodology offering a holistic evaluation of all functionalities and factors to avoid inconsistencies in the design conditions. Hence, mathematical modeling permits detailed control of operational factors whereas providing critical information such as the airflow, mechanical strain, mechanical stress, and temperature profile in the stack of produce under cold storage situations; giving mechanisms and performance details of the procedures [25].

Particularly, computational fluid dynamics (CFD) is commonly utilized for packaging design, being the finite volume method the most applied CFD type for horticultural produce. CFD is an method that discretizes the proper geometry and the governing partial differential equations (Navier–Stokes equations) for the mass conservation, momentum, and energy are resolved on a discrete mesh on the geometry using numerical methods, such as the finite volume or the finite element approaches [29]. The basic CFD heat transfer model is implemented with the respiration and transpiration of produce and heat gain/loss from evaporation/condensation of water to model airflow paired with the moisture transport [25]. The most utilized commercial software in CFD studies with horticultural produce is ANSYS®. Generally, CFD permits incrementing forced-air cooling efficiency by the combination of a specific percentage of package opening area and vent position with the airflow rate. However, the compromise between cooling efficacy and mechanical resistance must be guaranteed.

4. Ethylene Reduction as an Alternative to Reduce the Energy Needs in Refrigeration Facilities

The reduction of ethylene action in F&V leads to important energy savings due to the relaxation of the refrigeration temperatures. For example, McCormick et al. reported that the use of 1-MCP in Gala apples allowed to increase the storage temperature from 1.5 to 4 °C without noticeable effects on the fruit quality during 5.5 months of storage [30]. Those authors reported that the energy consumption of the refrigeration facility was reduced by 35% due to the rise of the setpoint temperature from 1.5 to 4 °C during the storage of apples. Relaxation of refrigeration temperatures of broccoli 11.6 → 14 °C (from 11.6 °C to 14 °C), 6.3 → 8.7 °C, and 3.3 → 5.6 °C were possible when accumulated ethylene in the refrigeration facility was reduced from 0.1 to 0.001 μL L^{-1} (Figure 6). As observed in Figure 6, good correlations (R^2 > 0.95) were observed for all plant products when comparing storage temperatures (ln temperature) with ethylene concentrations (ln of ethylene concentrations).

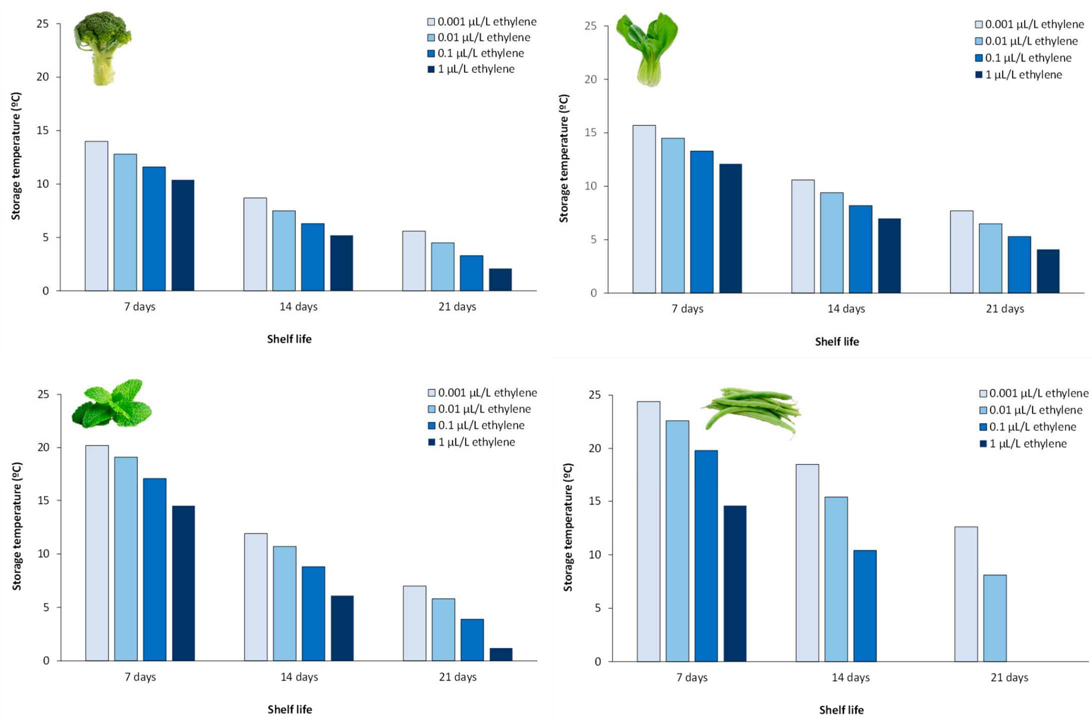


Figure 6. Effect of reduction of ethylene concentrations to increment the storage temperature in refrigeration facilities to maintain the shelf life of broccoli, pak choi, mint, and green beans (elaborated from data published by Lie et al. [11]).

The reduction of ethylene concentrations during the storage of green beans for four days had a stronger inhibitory effect on respiration as the temperature increased [11]. In that sense, energy savings of 50% (related to product respiration) were observed when ethylene concentrations of 0.1–1 μL L^{-1} during storage at 20 °C of green beans were reduced to 0.001–0.01 μL L^{-1} (Figure 7). At lower temperatures, energy savings even of 43 and 34% were still found when ethylene concentrations were reduced (from 1 to 0.001 μL L^{-1}) during storage at 10 and 5 °C, respectively (Figure 7).

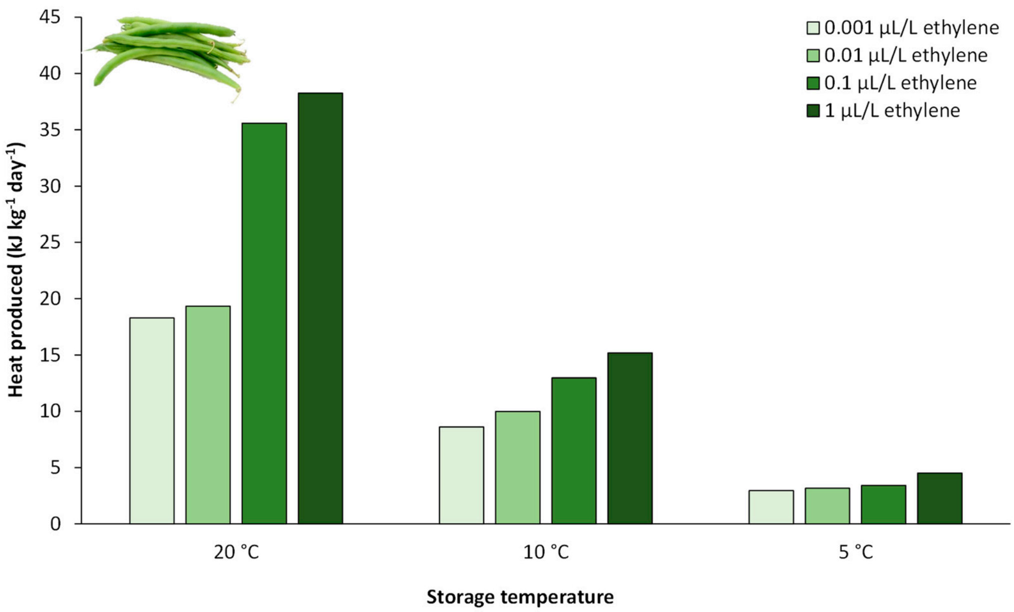


Figure 7. Heat production from the respiration of green beans after 4 days stored under different ethylene concentrations and temperatures (heat production is calculated according to Equation (1) and from data published by Lie et al. [11]).

Several postharvest technologies can be applied to reduce ethylene production of F&V, such as modified atmosphere packaging [31], edible coatings [32], UV-C radiation [33], natural antimicrobial treatments (e.g., essential oils) [34], 1-MCP [35], etc. Among them, plant essential oils (EOs) are an excellent clean technology to reduce ethylene production of F&V since EOs are natural products and highly accepted by consumers. Nevertheless, their high volatility and oxidation make necessary their encapsulation, being active packaging with encapsulated EOs an interesting technological approach to reduce ethylene production, and consequently the ethylene concentrations in the surrounding atmosphere of F&V.

5. Active Packaging with Encapsulated Essential Oils: A Clean Technology for Reducing Energy Needs in Refrigeration Facilities

Active packaging is an efficient technique that permits extending the product shelf-life through a controlled delivery of bioactive compounds of diverse nature such as antimicrobials, antioxidants, etc. The great antimicrobial properties of EOs are well recognized since ancient times, although their use in F&V is very restricted due to their low solubility in aqueous solutions during sanitizing washing treatments. In that sense, active packaging with EOs presents a different approach since EOs are released at low doses to the atmosphere surrounding to the food product and concentrated on the F&V surface where it is needed, and protect it from deterioration. Nevertheless, such EOs release at low doses from the active packaging must be ensured through an optimized EOs encapsulation (e.g., with cyclodextrins) and incorporation into the packaging material.

Encapsulation of bioactive compounds in inclusion complexes with cyclodextrins is a technique that highly preserves bioactive compounds from degradative reactions owing to temperature, oxidation, and moisture protecting their activities. Specifically, the most important cyclodextrins at the industrial level are α- and β-cyclodextrin, being the latter one widely used owing to its low price and goo encapsulation efficiency [36]. The delivery of bioactive compounds is encouraged, amongst other reasons, by relative humidity, such as the high relative humidity of cold rooms for F&V [37].

Plant EOs are natural extracts from plants well 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 EOs compounds classified by the EU as "natural flavoring substance" and "flavoring preparation", respectively [38,39]. Interestingly, ethylene production and respiration rate of horticultural products were reduced with EOs treatments as observed in different studies [34,40,41]. Inhibition of ethylene production and respiration rates may be linked to reduced microbial growth. Nevertheless, this hypothesis is not always true when different EOs components are studied. For example, inhibition of microbial growth by thymol, menthol, and eugenol led to lower ethylene production, although it was not true for eucalyptol (Figure 8). In that sense, further research is needed for studying the effect of a wider range of EOs and their components, and even their combinations, on the ethylene production of F&V during storage.

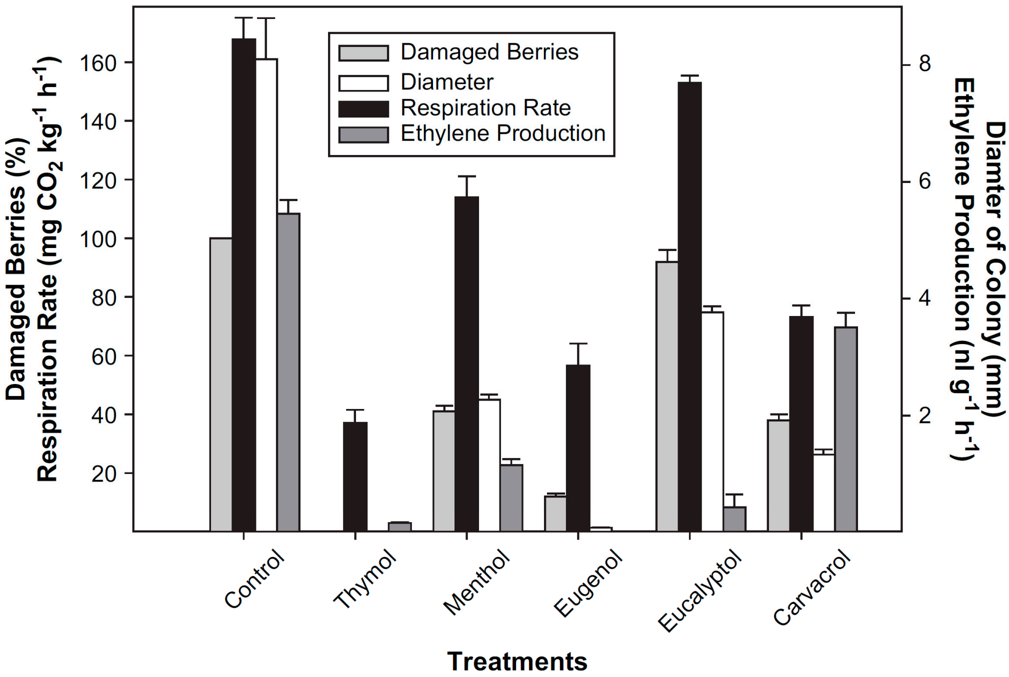


Figure 8. Effect of active packaging with several essential oils vapors concentrations (0.5 mL L^{-1}) in the respiration rate of grapes (expressed as CO_2 production), ethylene production, decay incidence (% damaged berries, and dimension (diameter of colony)) after 4 days at 25 °C (Reprinted with permission from [34], Copyright Elsevier (2008)).

The possible effect mechanism of EOs to inhibit the ethylene production of produce may be found through inhibition of the activity of the key enzymes of the ethylene biosynthesis pathway (Figure 1): 1-aminocyclopropanecarboxylic acid (ACC) oxidase and ACC synthase (ACS). It was early found that different EOs components (with doses as much as low as 4 nL mL^{-1}) reduced ethylene production in apples after 4 h, which was correlated with lower ACC production: the ultimate substrate for the ethylene biosynthesis [42]. The release of EOs from active packaging reduced the activities of other enzymes such as polygalacturonase and pectin methylesterase (implicated in the integrity of plant cells) and polyphenoloxidase (associated to produce color degradation) [43]. Nevertheless, the activity of ACO and ACS enzymes after treatments with EOs has not been studied previously.

Recently, we monitored the effect of some EOs on the ethylene production and ACO activity of broccoli and flat peach [43,44]. In particular, it was observed that those parameters were highly reduced with single and combined EOs (Figures 9 and 10). Hence, the energy consumption due to air renovation (to eliminate ethylene and other volatiles accumulated inside cold rooms) and heat removal produced by the product respiration may be reduced using active packaging that releases EOs to the surrounding atmosphere of the packaged produce.

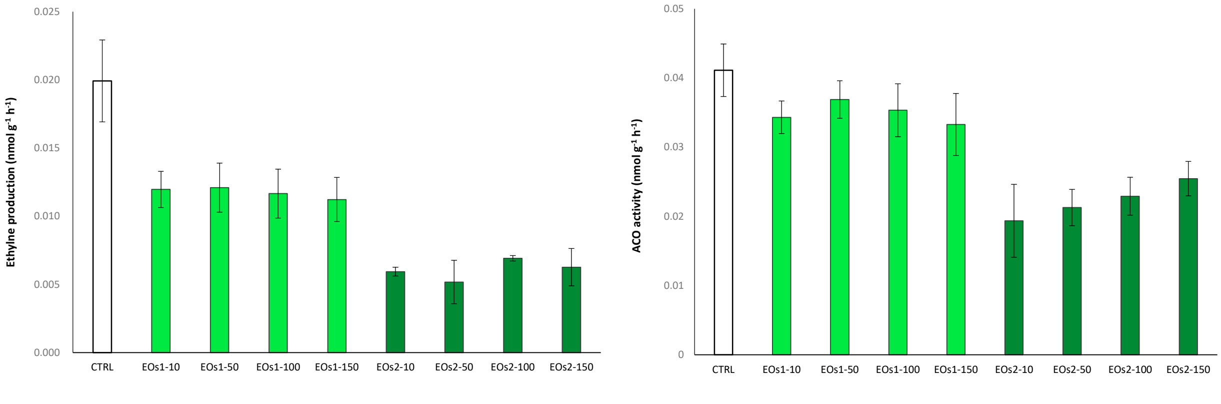


Figure 9. Ethylene production (**A**) and 1-aminocyclopropanecarboxylic acid oxidase activity (ACO) (**B**) of broccoli florets with active paper sheets including two different EOs mixes (*EOs1*, carvacrol:spearmint EOs 80:20; or *EOs2*, carvacrol:oregano EO:cinnamon EO 70:10:20) at different doses (0 (CTRL), 10, 50, 100, and 150 mg m^{-2}) at 2 °C (mean ± SD) [44].

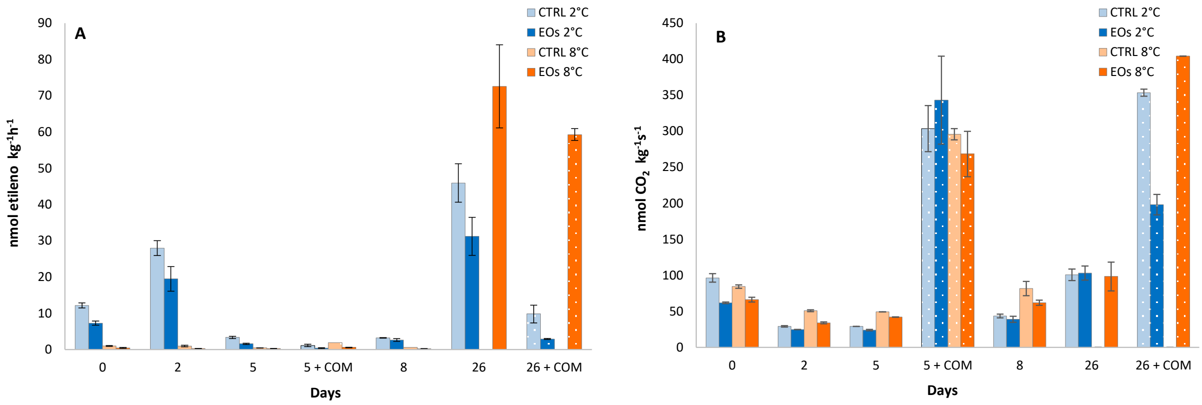


Figure 10. Ethylene production (**A**) and CO_2 production (**B**) throughout refrigerated storage periods (2 and 8 °C) and complimentary commercialization simulations (*COM*; 4 days at 22 °C) of flat peach with or without active paper sheets (including encapsulated EOS) (mean ± SD) [43].

Reductions of respiration and ethylene production rates of flat peaches and broccoli using active packaging including EOs achieved up to 30–50% and inhibiting the activities of key enzymes participating in the respiration pathways [43,44]. Figure 11 represents the heat production (calculated by the heat produced from respiration) and ethylene production rates during storage at 8 °C of flat peaches within active packages. As observed, the reduction of ethylene production rates of 1.0 → 0.3 and 0.5 → 0.3 nmol kg^{-1} h^{-1} would imply a reduction of heat production from flat peaches of 33 and 14% after 2 and 5 days of storage at 8 °C, respectively (Figure 11).

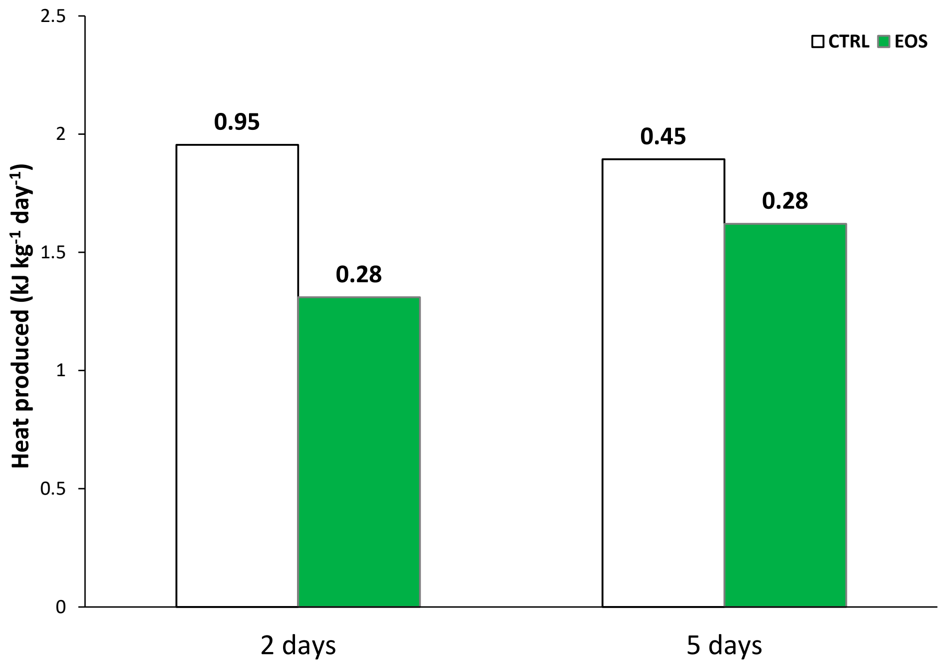


Figure 11. Heat production related to the respiration of flat peaches after 2 and 5 days at 8 °C. Heat production is calculated according to Equation (1) and from data previously published [43]. The numbers on the bars are the ethylene production rate (nmol kg^{-1} h^{-1}).

6. Conclusions

Clean technologies are needed to be combined with refrigerated storage to relax the setpoint temperature of storage rooms for fruit and vegetables and consequently reduce the energy consumption of the refrigeration system to remove the respiratory heat of produce. Attention must be paid to the ethylene production rate of produce since its reduction may also lead to the reduction of the product respiration. Essential oils are natural products with high acceptance by consumers, which can be used to reduce respiration and ethylene production rates. In that sense, active packaging including essential oils may lead to a decrease in the produce heat owing to respiration. As a result, the energy consumption of the refrigeration system necessary to remove the respiratory heat is decreased being enhanced the efficiency of the cooling process. Consequently, the use of active packaging will allow to reduce the use of other techniques to augment the cooling efficiency, such as the increment of the airflow rate, altering the airflow guidance, or reducing the cold air temperature. In addition, the associated risks related to refrigeration in sensitive produce (chilling injury, shrinkage, and wilting) are reduced when the setpoint temperature is increased when clean technologies, such as active packaging with essential oils, are used.

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