Extending the shelf-life of fruits and vegetables in retail stores – Assessment of an innovative controlled atmosphere solution

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Abstract

Fruits and vegetables (F&V) waste in retail stores linked to consumer dissatisfaction has led to an increased interest in new preservation solutions to extend the shelf-life of fresh produce. In this study, the potential of controlled atmosphere (CA) combined with optimal temperature and relative humidity (RH) for short-term storage periods was assessed using an innovative prototype, to understand its impact on F&V shelf-life extension. Seven types of F&V were stored at 4°C and optimal RH with and without CA for 3 to 7 days. Browning was delayed for mushrooms and chicories under CA, allowing to extend their shelf-life after 3 days of storage. The quality of strawberries was positively affected by CA, with a firmer texture and a potentially better visual quality. Lower weight losses resulting in slower deterioration were observed for leafy greens, mushrooms and white asparagus. With the recorded gas consumption, the prototype is financially viable only for small F&V with high-added value, like strawberries or organic chicories, and its environmental impact potentially positive for strawberries and negative for lettuce and asparagus when considering four environmental indicators.

Keywords: Food waste, fruits, vegetables, controlled atmosphere, innovation, shelf-life, quality, viability, environmental impact.

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Lund, May 2019

Mathieu Casanovas

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List of acronyms and abbreviations

ACC	1-aminocyclopropane-1-carboxylate
CA	controlled atmosphere
CAS	controlled atmosphere storage
CPET	crystalline polyethylene terephtalate
DALY	disability-adjusted life years
ED	ecosystem diversity (ReCiPe indicator)
F&V	fruits and vegetables
GHG	greenhouse gases
GWP	global warming potential
HH	human health (ReCiPe indicator)
LCA	life cycle analysis
LCI	life cycle inventory
LCIA	life cycle impact assessment
LDPE	low density polyethylene
LLDPE	linear low density polyethylene
MA	modified atmopshere
MAP	modified atmosphere packaging
PA	polyamide
PET	polyethylene terephthalate
PVC	polyvinyl chloride
PVDC	polyvinylidene chloride
RA	resource availability (ReCiPe indicator)
RH	relative humidity
USD	United States dollar

1 Introduction

1.1 Food waste & consumer dissatisfaction in the fruits and vegetables (F&V) supply chain

The agricultural sector in France represents a major source of revenue and employment for the country, and plays a central role in the European Union as the major contributor to the agricultural value on the continent with 18% in 2014 (Interfel, 2016). This study from Interfel highlights the essential role of fruits and vegetables (F&V) in this sector, accounting for 12,7% of the overall EU agricultural value in 2014 and employing almost half a million people. In 2016, the overall production rose up to 7 950 000 tons, of which 5 100 000 of vegetables and 2 850 000 of fruits. Concerning retailing, two thirds of this production was sold as fresh produce while the rest was processed before reaching the consumer.

The main characteristics of the F&V supply chain are its rapid turnover due to high perishability of the produce and the necessity to maintain the cold chain to ensure safety and quality from farm to fork (Figure 1). However, due to the many stakeholders involved, the variety of products and the handling conditions, more than 50% of the F&V production goes to waste at different stages of the supply chain (FAO, 2011). F&V waste is a global problem, occurring within different main stages of the supply chain (Figure 2). While post-harvest handling and transformation contribute greatly to F&V waste in developing countries, agricultural production and consumption at home participates the most to waste in developed countries, respectively 20% and 13%. This difference can be explained by a scarcity of food and lack of infrastructures in the developing countries compared to developed countries. Concerning F&V waste at the retail stage, it ranges from 5 to 10% of the overall F&V production depending on the countries. In the EU, F&V represents almost 50% of the food waste generated by households (De Laurentiis *et al*, 2018). This translates to important economic loss, with F&V amounting to 1,6% of the total expenses of an average French households (RPUE, 2018).

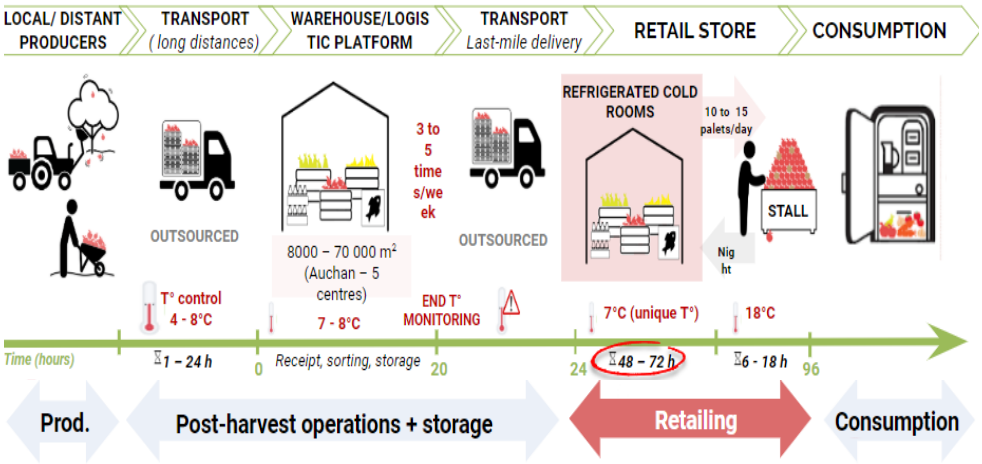


Figure 1: F&V supply chain and waste streams per stakeholder

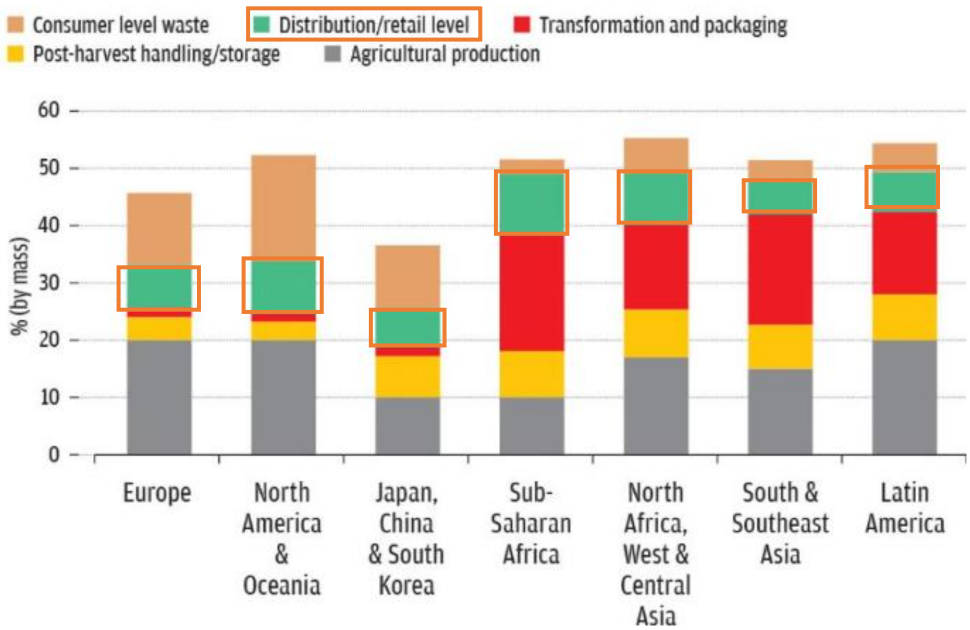


Figure 2: Losses and wastage of F&V at different stages in the value chain (FAO, 2011) – *Waste at the distribution & retail level accounts from 5 to 10% of the total losses depending on the region.*

F&V waste is being tackled at most of the stages of the supply chain since the past decades in order to avoid unnecessary land use, greenhouse gases (GHG) emissions and economic losses. In production, where F&V are thrown away due to pests, to bad handling during treatment and to harvest and weather conditions, the selection of resistant cultivars and new ways of farming like permaculture are some answers to food waste.

During consumption, inappropriate storage conditions, temperature abuse and damaged quality of the F&V are responsible for waste. Due to the private nature of in-home consumption, it remains hard until today to efficiently tackle this waste.

Finally, at the retail stage, waste is directly linked to freshness and visual quality, which are the most important criteria for consumers when choosing a product (Oliver Wyman, 2014). When these are not anymore satisfying, retailers usually take the decision to withdraw the fresh produce from the stall, to keep good reputation and avoid customer dissatisfaction. However, when asked about how they perceive freshness of F&V in retail stores, 75% of French consumers admit being dissatisfied (FranceAgrimer, 2016). A poor quality of the products can be explained by temperature abuse, non-optimal storage conditions and mishandling. Corrective measures exist to reduce F&V waste, like better managing of the orders, discounting damaged products, giving non-acceptable products to charities or sending them to compost plants (Comerso, 2018).

However, for fresh F&V in bulk, there is a lack of preventive solutions upstream during storage. Currently, products are still stored at a unique temperature with no control over other environmental parameters like relative humidity or gas composition, which influences greatly F&V quality. Some solutions rely on individually wrapping the products, like it is the case for cucumber, but no solution is currently being used to improve storage conditions of fresh F&V in bulk in the retail stores.

Looking at the discrepancy between F&V quality importance in the retail stores and current storage conditions in cold rooms, Air Liquide identified an opportunity to develop a solution aiming at better controlling environmental conditions during storage**,** such as temperature, relative humidity (RH), and gas composition through controlled atmosphere, with the ambition to reduce F&V waste and economic losses for the whole supply chain.

1.2 Air Liquide solution: from ideation to prototype development

1.2.1 Ideation and prototype conception

From the literature and field research presented above, two main places of interests in the retail stores were identified to implement a new solution: the cold rooms where F&V are stored upon arrival from the distribution center, and the stalls were F&V are displayed for up to two days.

From this ideation phase emerged three main ideas, taking into account the storage requirements of F&V and the practicity of use for the customers. The first idea aims at improving temperature regulation in the storage room by creating separate areas with different optimal temperatures using air curtains. With this solution, temperature abuse would be minimized. The second idea consists in creating a controlled environment in temperature, RH and gas composition using an airtight hood surrounding pallets in the cold room. This solution could be combined with the first one to have a global control of the temperature in the whole storage room and not only below the hood. Finally, the last solution consists in developing a smart cabinet for F&V where products on the stalls could be displayed at optimal preservation temperature, thus allowing storage in the shop for longer periods with sustained quality.

1.2.2 Prototype description

Among these three solutions, the second solution was further investigated and a first version of a prototype was developed (Figure 3). This solution relies on controlled atmosphere technology by gas flushing and allows to reach a gas composition adapted to each F&V. At the same time, temperature and RH are adjusted externally, thus creating optimal environments of preservation tailored to each F&V. The prototype consists in a removable hood positioned on top of a semi-pallet (800 x 600 mm) loaded with F&V. This hood can automatically move upwards to allow picking of the products, and downwards to allow storage in optimal conditions. Once closed, a mixture of gas is flushed into the hood until the desired atmosphere is obtained. An automatic system allows to monitor and maintain the gas composition at any moment. Due to the use of non-breathable gas mixture in the hood, safety measures are embedded in this solution. For instance, the structure cannot be pulled up fully until an acceptable level of CO_2 is reached inside the hood. Thus, a purge of air using suction effect has been included in the prototype.

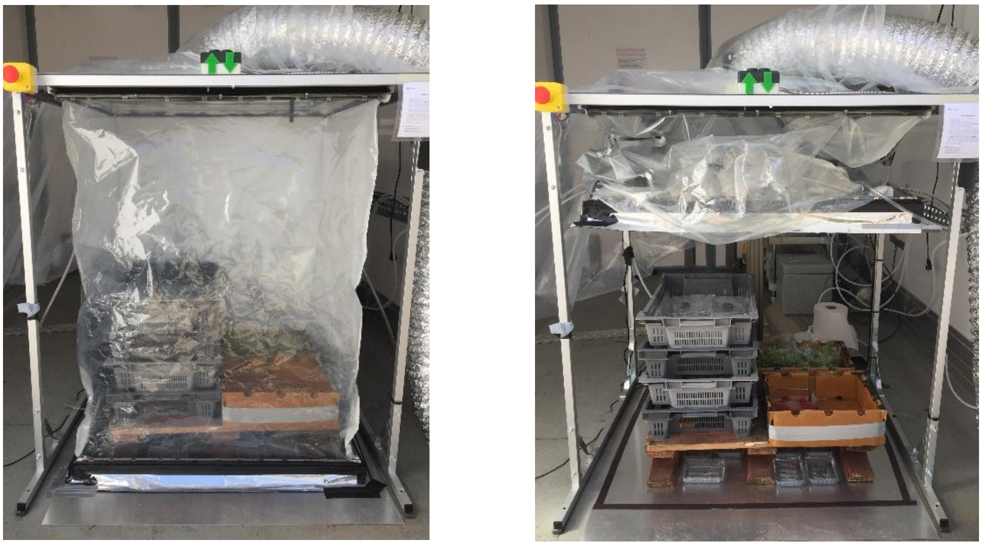


Figure 3: Current prototype developed by Air Liquide – *Closed position (left) and open position (right)*

This solution differentiates itself from other solutions by its practicity and its rapidity of execution. It is conceived for daily openings, allowing rapid flushing and purging to avoid unacceptable picking time for the workers in the retail stores. It is a complete solution with objective to slow down F&V quality loss during storage in retail shops by better controlling the environmental conditions.

1.3 Research question and scope of the study

1.3.1 Problem description

Until now, most studies on controlled atmosphere storage (CAS) in the literature only considered long periods of storage under modified atmosphere for several days or weeks. However, these are not suited to the conditions in supermarket where products in bulk are only stored for few days. Currently, there is no study in the literature focusing on the impact of CAS over short periods of time, while it could represent a potential solution to the F&V waste retailers are currently facing in their stores.

To fill this gap, this study aims at assessing the potential of CAS of F&V during short periods of time, using the prototype developed by Air Liquide as a support. Besides technical feasibility, the question of financial and environmental viability arises and will be investigated. The results of this study will further guide prototype development to ensure the business will support the industrialization of the prototype.

Therefore, the main research questions for this thesis are:

"How does controlled atmosphere combined with optimal temperature and relative humidity impact F&V quality and shelf-life during short-term preservation?"

"What is the financial and environmental impact of the prototype?"

1.3.2 Objectives of the study

The main objectives are defined for this study:

- Assess the impact of the prototype on F&V quality and shelf-life compared to the current situation in retail stores. Shelf-life will be assessed via quantitative and qualitative methods including consumer acceptability.

- Determine the financial viability and environmental impact of the developed solution based on the food waste avoided and daily gas consumption.

In addition, a preliminary assessment will be done to review several materials preselected by Air Liquide for the prototype hood and to select the best one based on their barrier properties and folding endurance.

1.3.3 Delimitations of the study

It was decided to perform the experiments on as many kinds of relevant F&V as possible rather than to focus only on a few ones, as this study was an exploratory work to identify F&V positively affected by the prototype. 4 different vegetables and 3 different fruits were tested in duplicates.

Due to this numerous types of products, the limited space available inside the prototype and the limited available manpower, only a small number of samples were tested every day for qualitative and quantitative measurements. This entailed that no statistical difference between prototype and control samples results could be determined, as a minimum of 30 samples would have been necessary to characterize the distribution of samples. Thus, all results presented in this study are trends, and further experiments with a sufficient amount of samples must be performed on promising F&V to obtain results that could be statistically analyzed.

Moreover, the results regarding financial viability and environmental impact were entirely based on the gas consumption of the prototype developed by Air Liquide, which was designed at half the scale of the intended final product. All the results presented in this study are thus only valid for this prototype, and might be totally different for the real-size prototype as gas consumption might vary.

Finally, delivery costs and rental of the gas cylinders were not taken into account when assessing the cost of daily gas consumption.

2 Literature review

2.1 Fruits & vegetables freshness: biology and assessment

2.1.1 F&V lifecycle and ageing

During its lifetime, a fruit goes through three main development phases: growth, maturation or ripening and senescence. When it comes to fruit preservation, maturation is crucial. It is during this phase that a fruit undergoes its most important physical and biochemical changes that will determine the final organoleptic and visual properties of the fruit (Paliyath *et al*., 2009).

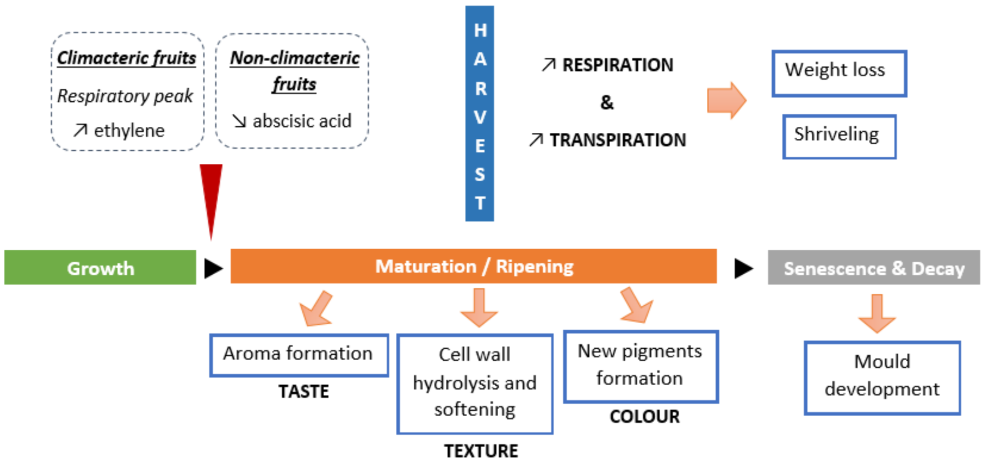


Figure 4: Fruit life cycle and ripening reactions (Paliyath *et al.*, 2009; Rhodes, 1978)

Maturation is genetically scheduled and is associated with ripening reactions leading to modifications in taste, color and texture (Rhodes, 1978). The change in taste in fruits is due to starch hydrolysis as well as organic acids oxidation, causing a global increase in free sugars and formation of specific aromas depending on the species. On the other hand, the chlorophyll presents in the unripe fruits is gradually degraded and new pigments are synthetized, like anthocyanins in strawberry or carotenoids in tomatoes. These pigments are responsible of the change in colour during ripening and can help determining visually the stage of ripeness of a fruit. (Woodward, 1972; Arias *et al.*, 2000). Finally, pectins present in the cell wall of the fruit are hydrolysed during maturation, leading to a loosening of the cell walls and a general softening of the fruit skin (McAtee *et al*., 2013).

Maturation is commonly triggered by a change in balance between several phytohormones, namely auxine, abscisic acid or cytokinine. For certain fruits, called climacteric fruits, maturation is triggered by an important initial respiratory activity and the synthesis of a specific volatile phytohormone, ethylene. This hormone will modulate ripening reactions, catalyze its own production and allow maturation of climacteric fruits post-harvest, as it is the case for bananas. The maturation of non-climacteric fruits, like oranges or berries, stops after harvest, and ethylene can cause physiological disorders in non-climacteric fruits like stains and loss of green color (McAtee *et al*., 2013).

Once a fruit is harvested, two other phenomenon will also dramatically influence the fruit texture and nutritional composition: respiration and transpiration. Next to the ripening reactions involving several kinds of hydrolytic and synthetizing enzymes, the fruit plucked out from the tree will keep on breathing, thus consuming oxygen and the free sugars made available by hydrolysis of the starch during maturation to produce energy, carbon dioxide and water. Respiration will also affect vitamin C concentration, with a decrease of 50% in concentration in 24 hours for certain fruits like apples (Lee & Kader, 2000). Depending on the external environment and humidity, fruits will also perspire due to a difference in water potential between the fruit and the atmosphere. Transpiration can lead to important weight losses and wilting.

For vegetables, due to the different biological origins of this group, development processes are diverse. Usually, maturation of vegetables occurs during the whole growth of the vegetables and not suddenly as it is the case for fruits. Senescence will finally occur, with production of phytohormones and enzymes causing wilting and tissues degradation.

2.1.2 F&V freshness and shelf-life definition

2.1.2.1 F&V acceptability and freshness

"*An important aspect of the acceptability of fruit or vegetables is the appearance of the commodity; the color, its shape and the absence of blemishes, and these are the basis of the systems of grading currently in use.*" (Rhodes, 1978)

F&V acceptability is subjective and linked to human appreciation. F&V freshness can be defined as the perceived satisfaction level of a product and has been based for decades on visual qualitative observations as described by Rhodes (1978). Texture and visual appearance have been generally acknowledged to influence F&V freshness, with several deterioration phenomenon leading to freshness depreciation: skin softening, surface dehydration, translucency for cut F&V, discolorations, moulds (Rojas-Graü *et al*, 2009). Such phenomenon depends on the maturity stage of the product, and can be influenced by several parameters that will be discussed in the following section. Taste seems not to have a significant influence on F&V freshness perception (Péneau *et al*, 2007).

In order to make the evaluation of F&V freshness more accurate and reproducible, several studies tried to find correlation between qualitative observations and quantitative measurements. For several fruits, instrumental firmness, juice release and water loss were found to be positively correlated with freshness attributes identified by consumers such as crispiness and firmness (Péneau *et al*, 2007; do Nascimento Nunes, 2015). For leafy greens, water loss was found to be the main physico-chemical parameter linked to freshness. (Jung *et al*, 2012). Other studies proposed a combined qualitative and quantitative methods to assess F&V freshness, consisting in the establishment of a scale based on subjectively visually determined levels of acceptance to evaluate freshness (Jung *et al*, 2012; Matar *et al*, 2018a).

2.1.2.2 F&V shelf-life

Shelf-life of F&V can be defined as the minimum acceptable freshness (Matar *et al.* 2018a). It corresponds to the shelf-life in retail stores until when the product is considered "marketable", and not the shelf-life until when the product is safe to be consumed. In practice, F&V shelf-life is determined arbitrarily by the F&V section leader based on appearance and experience.

Shelf-life is often determined subjectively and not always linked to consumer acceptability, which is however essential as discussed above. In a recent study by Matar *et al* (2018a), shelf-life includes consumer acceptability by combining visual deterioration evaluation with consumer's willingness to purchase, thus defining a minimum acceptable deterioration used to determine shelf-life.

2.1.3 **Factors impacting F&V freshness**

Freshness is directly linked to the maturity stage of F&V. Once the optimal state reached, it is important to slow down as much as possible the ripening reactions, respiration and transpiration. To do so, several parameters are essential to monitor.

2.1.3.1 Temperature

Temperature is an essential parameter to maintain the quality of F&V after harvest. Maturation and respiration metabolic activities requires the action of several enzymes whose activity is highly dependent on temperature. As most of the enzymes in F&V have an optimal temperature usually above 20°C, decreasing the temperature is the most efficient way to slow down maturation and respiration reactions which negatively affect nutrient composition and water content. Moreover, for a similar reason, low temperature will slow down the development of parasites as well as a concomitant decrease in transpiration.

Optimal temperature range varies depending on each species, and applying a too low or too high temperature might be responsible of physiological disorders or increased metabolic activities. For instance, too cold temperatures for exotic fruits like persimmon might cause chilling injuries and a softening of the skin (Salvador *et al*., 2007).

2.1.3.2 Relative humidity

Relative humidity (RH) affects transpiration and thus water loss in F&V. Optimal preservation range for most of the F&V are between 85 and 100% RH, conditions that are most of the time not maintained during the supply chain as stakeholders rarely have the choice to store all produce in their unique optimal condition (Paull, 1999). Produce below those optimal RH values will undergo hydric stress leading to water losses and a depreciation of the visual and organoleptic properties of the produce. In high-value added products, transpiration can represent a considerable loss of revenue. In the case of *Melanosporum* truffles, water losses usually amount to 1g per truffle per day, which is unneglectable regarding the selling price of 1500 euros/kg (Masse, 2018).

On the other side, high RH above 95% can lead to microorganism development on certain products like red berries having a high water content and a soft skin (Sousa-Gallagher *et al.*, 2013). Finally, hydric stress will accelerate ethylene production and cause a faster maturation of climacteric fruits.

2.1.3.3 Atmosphere composition

As stated above, F&V are breathing, which causes nutrients depletion and ultimately produce depreciation. Controlling the atmosphere composition and particularly the oxygen (O_2) and carbon dioxide (CO_2) levels helps regulating respiration rate. The normal atmosphere composition is of 20.9% O2, 0.03 % CO2 and 79.07% N2. (Widory & Javoy, 2003) Reducing the O_2 concentration from 21% in the air to below 10% slows down the respiration reactions that are dictated by Equation 1. For F&V, whose metabolites are carbohydrates, the respiratory quotient, i.e. ratio between CO_2 produced and O_2 consumed is 1.

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O$$

Equation 1: Respiration equation

Low oxygen availability affects positively the activity of the 1-aminocyclopropane-1-carboxylate (ACC) oxidase, responsible of the oxidation of the ethylene precursor, thus slowing down maturation in climacteric species (Gorny & Kader, 1996).

On the other hand, increasing CO_2 concentration from 300 ppm in the air up to 50.000 ppm will have a similar effect than low O_2 level on respiration. Moreover, high CO_2 levels will negatively influence the ACC synthase involved in ethylene precursor production (Gorny & Kader, 1996). CO_2 in important concentrations also has a bacteriostatic effect, thus preventing the growth of microorganisms and parasites.

Extreme concentrations should be avoided as they can have deleterious effects on F&V. Indeed, extremely low O_2 levels will cause asphyxia and trigger products anaerobic fermentation. Similarly, extremely high CO_2 levels will cause off-flavour (Kim *et al*, 2009).

Finally, respiration rate varies greatly between species and cultivars, thus leading to different optimal atmospheric conditions (Zhuang *et al*, 2014).

2.1.3.4 Optimal biological preservation environments for F&V

Air Liquide teams determined patented optimal environments of storage for F&V aiming at slowing down as much as possible maturation, respiration and transpiration. Four environments were identified following a similar classification as the one presented in Figure 5, but also including gas composition.

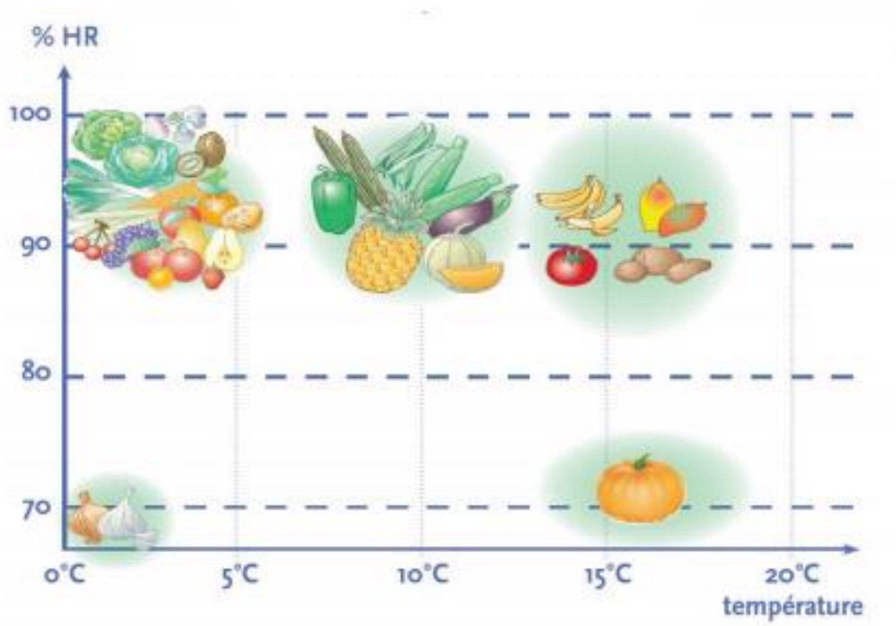


Figure 5: Biological optimal preservation environments (CTIFL, 2011)

2.2 CA and F&V preservation in bulk: current solutions on the market

2.2.1 CA technology

The impact of atmosphere composition on fresh produce was first discovered in 1821 by Jacques Etienne Bernard who identified the effect of low O_2 concentrations on fruit maturation. It is only in the beginning of the XXth century that the potential of modifying the atmosphere gas composition was really investigated, and only became trendy in the 1970s (Dilley, 1978).

Since then, many studies on the modification of the atmosphere composition have been conducted for almost every fresh produce, and its effects on delaying and slowing down maturation are commonly recognized (Fagundes *et al*, 2015; Thompson *et al*, 2018). The optimal atmospheric composition varies according to the product packed and highly depends on the respiration rate of the product, the gas permeability of the packaging material, the volume of headspace present inside the package and the storage temperature (Soltani *et al*, 2015). Low concentration of O_2 and high concentration of CO_2 are usually used, however hyperbaric concentrations corresponding to high level of O2 have also been identified to slow down ripening in some cases (Kader & Ben-Yehoshua, 2000).

An important distinction when characterizing storage with modified atmosphere composition depends on the way the atmosphere is monitored. There are three different possibilities: controlled atmosphere storage (CAS), active modified atmosphere packaging (MAP) and passive MAP. CAS refers to a storage where the atmosphere composition is directly controlled by gas injection, and supposes the use of an airtight compartment. Active MAP consists in a packaging in which the atmosphere surrounding the product is initially removed or replaced by gas flushing before sealing in vapor-barrier materials, as it is the case for meat preservation (McMillin, 2008). Finally, there is no direct atmosphere modification in passive MAP, which relies only on equilibrium between respiration rate of products and selective gas permeability of packaging polymeric films. Ethylene absorber can also be used in addition to atmosphere modification to slow down maturation of climacteric fruits (Robertson, 2006).

In this study, controlled atmosphere storage (CAS) in bulk will be investigated.

2.2.2 Current solutions on the market for CAS

CAS of products in bulk is not widely spread as it represents important investments, and is only used for F&V that can withstand long storage periods, like apples and pears (Bodbodak & Moshfeghifar, 2016).

Currently on the European markets, two solutions are available for long-term storage of F&V in bulk under CA and MAP. The first one is a CAS solution consisting in a LDPE plastic tarpaulin covering pallets of fruits in warehouses (Figure 6a). It can automatically adjust gas composition by injecting the gas quantity needed. Such a solution is designed to keep F&V for a long period and thus is not opened once put in place. Two companies in Europe sell this type of equipment, Absoger with Palicontrol® and Van Amerongen with Palliflex®.

The second solution uses passive MAP and consists in a hermetic plastic box with openings featuring patented polymeric films. Depending on the product stored, which can range from apples to asparagus and flowers, the number of openings can be adapted. Such a solution is commercialized in France by Janny MT and targeted for warehouses (Figure 6b).

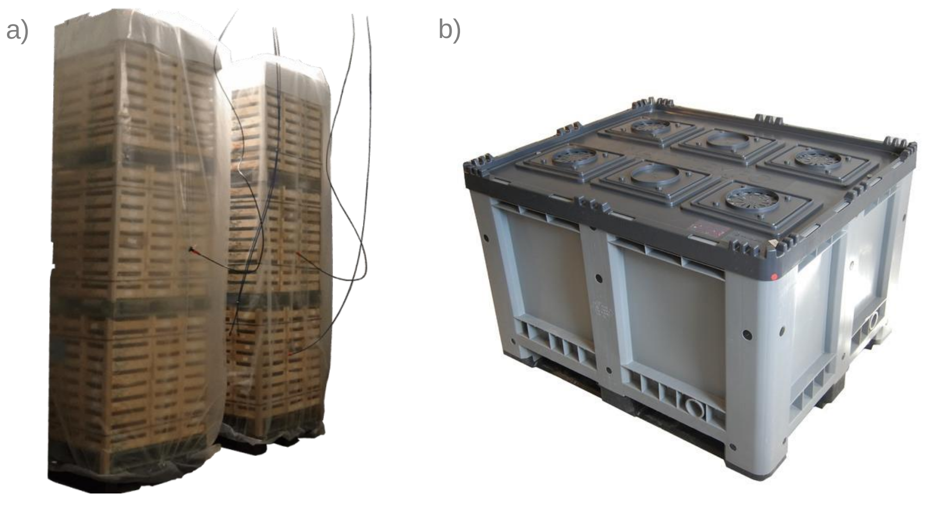


Figure 6 a & b: CAS solutions for F&V in bulk (Palliflex on the left, Janny MT on the right)

Air Liquide solution differentiates itself from these modified atmosphere options by its different target user, i.e. operators in retail stores and not warehouses, and its daily opening cycles, which cause an intermittent and short storage period under modified atmosphere.

Overall, F&V are sensitive to numerous environmental parameters which regulate their maturation, respiration, transpiration and deterioration. While temperature has the greater impact, modified atmosphere has been proven to slow down F&V metabolism and positively affect F&V preservation. Until now, long-term CAS storage is used in the industry for F&V such as apples and pears, and impact of short-term CAS storage is yet to be explored.

Following this literature review, it was speculated that short-term CAS, combined with optimal temperature and RH conditions, would have a positive impact on F&V freshness and could potentially extend their shelf-life.

3 Methodology

3.1 Overall research procedure

This study relied on a novel equipment developed by Air Liquide and had for objective to assess the impact of preserving F&V in optimal environments with CA during short storage periods (Figure 7).

Before involving any product, the first step was to evaluate the ability of the prototype to reach expected atmosphere compositions and maintain them durably over repeated cycles of use. The focus was put on testing preselected plastic laminates for resistance and gas permeability over time, and ensuring airtightness.

Once the functionality of the prototype validated, the second step was to test its impact on the quality and shelf-life of 7 different F&V, selected depending on their perishability and optimal conditions of preservation. Experiments were performed in duplicate in two optimal environments of preservation with similar temperature and RH, each time under normal atmosphere and under CA with the prototype. The impact of different storage solutions on the quality and shelf-life of the F&V was assessed by both qualitative visual evaluation and quantitative methods. Consumer acceptability was also taken into account to give an idea of the potential such an application can have on F&V shelf-life and food waste.

Finally, an eco-efficiency analysis was conducted to determine the amount of food waste avoided necessary to compensate the costs-in-use of the prototype and its environmental impacts. The focus was limited to gas consumption during the experiments and food waste avoided. This allowed to determine if the solution could be economically viable and environmentally acceptable.

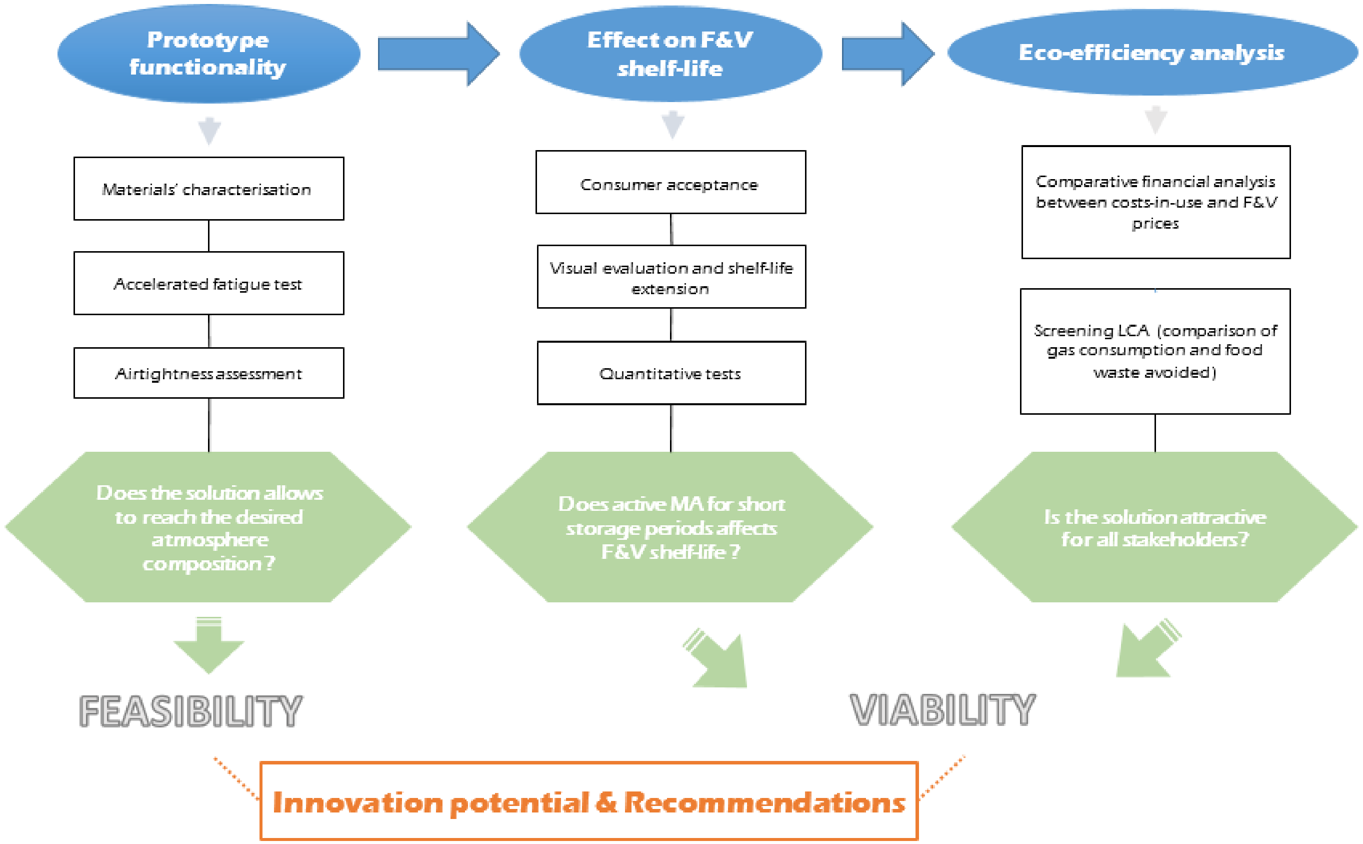


Figure 7: Research procedure based on the prototype's case study

3.2 Preliminary work – Prototype functionality test procedure

Plastic polymers are widely used in industry for their versatile barriers and mechanical properties. Depending on the chemical and physical structure of the polymers, different barriers properties can be obtained. The most used plastic polymers are polyolefins and substituted olefins like PET. For certain uses, several plastic polymers are combined together, giving the laminate specific barrier and physical properties that could not be obtained with a single plastic polymer. Functional plastic laminates are widely used in the food industry, and particularly in modified atmosphere packaging. (Robertson, 2005).

The experiment had for objective to evaluate the potential of different materials to be used for the prototype's hood under normal conditions of use, i.e. 3 openings per day. Prior to this study, Air Liquide had already sourced three different plastic laminates that could be potentially used on the prototype:

- **PP016 -** PET/Aluminum/PA/LDPE
  (respective thickness: 12/7/12/100 µm)
- **PP100_21 -** Metalized PET/LDPE
  (respective thickness: 12/100 µm)
- **PPCC1 -** CPET coated with PVDC/LLDPE
  (respective thickness: 12/2gsm/100 µm)

Requirements for the solution were an efficient gas and water barrier in order to maintain constant humidity and atmosphere composition inside the prototype and limit gas consumption; a good resistance to puncture that could occur in the retail environment when handling pallets, with a possible risk of perforation due to potential contact with the wooden pallets or sharp edges; and a good resistance to repeated folding that occurs when loading products in the prototype.

To achieve this, two analysis were performed:

- A comparison of the data sheets of each material, comparing the material properties (puncture resistance, oxygen and water vapor transmission rate) to characterize each plastic laminate.

- An accelerated folding endurance test coupled with leakage detection, with objective to simulate repeated folding cycles that would occur by using the prototype.

The folding endurance test was inspired from the standard test method ASTM D2176 for folding endurance of paper using a M.I.T. Flex Tester. As this equipment was not available, a testing machine presented in Figure 8 was designed to mimic repeated folding in an accelerated way on one precise point of the plastic laminate.

Figure 8: Machine for accelerated folding cycles – *Plastic laminates are hold by a static clamp and a clamp linked to a rotor which allows to fold the material 6o times per minute.*

Samples prepared with the machine were folded for an hour at a speed of 60rpm (corresponding to approximatively 3 years of use). Next to this, samples folded by hand 120 times (corresponding to two months of use of the prototype with three openings per day) were prepared, in order to simulate a more homogenous folding compared to the localized folding obtained with the machine. All samples prepared included the welded corner area of the plastic laminates, identified as the weakest point. Six repetitions were done for each material and folding method.

Finally, leakage and explosion tests were performed on unused, hand-folded and machine-folded samples, using the micro-leak and burst analyzer Exos Leak, Abiss, France. For this test, the prepared samples were hermetically closed in sachets of 20x7 cm using the welding machine C300, Multivac, Germany. To prevent puncture when inserting the injection needle, a bolt was inserted in every sachet (Figure 9).

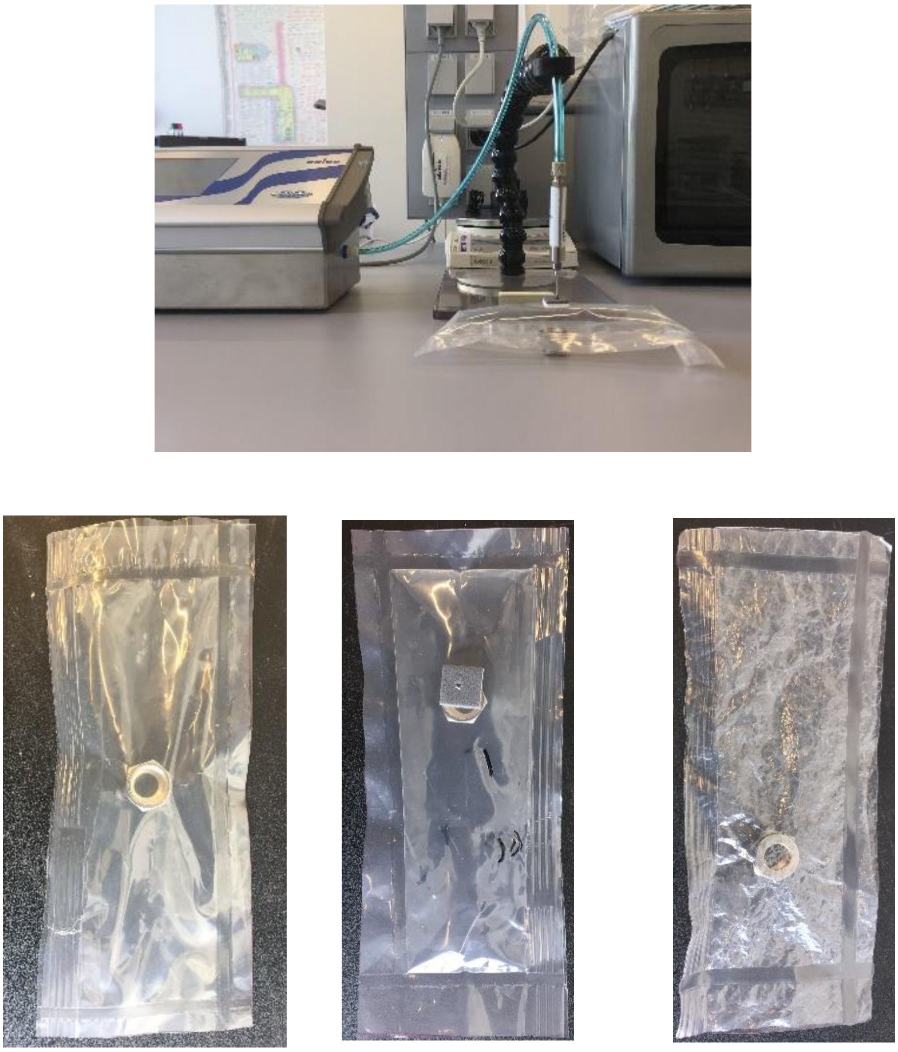


Figure 9: Micro-leak and burst test experimental setting (top) and PPCC1 samples tested (bottom, from left to right: unused, machine-folded and hand-folded)

The leakage test consisted in measuring the average flow rate of gas that needed to be injected to maintain a constant overpressure of 50 mBar inside the sachet. The results were translated in an equivalent diameter in micrometers, corresponding to the maximal size of a pinhole allowing such a leakage flow rate.

The explosion test was performed by injecting gas at a constant flow rate of 250L/h and had for objective to test welding resistance.

3.3 Shelf-life evaluation test procedure

In-house experiments on F&V were conducted in Paris Innovation Campus to determine if optimal conditions of preservation under the prototype could impact F&V quality and shelf-life compared to current supermarket cold rooms' conditions.

3.3.1 Sampling

Special care was given to the sourcing of the F&V. Only products sourced with the same wholesaler, Halles Paris Sud in Rungis wholesale market, and originating from the same batch were ordered, with objective to minimize variability coming from upstream in the supply chain. However, due to availability with the wholesaler, the variety and place of origin of certain products were different from one duplicate to another (Appendix A).

The experiments were performed on seven different products selected for their perishability and based on interviews with F&V experts in retail stores from the Parisian region. Leafy greens (lettuce and chicory), white asparagus, mushrooms, grapes and red berries (strawberries and raspberries) were identified as the most perishable and wasted F&V.

The selected products were grouped together depending on their different optimal storage conditions, based on the biological classification developed by Air Liquide. All fruits used were not climacteric. Two different environments, differing by their gas composition, were considered, and included the following products:

- Environment 1: Organic salad, chicory, white asparagus and mushrooms
- Environment 2: Strawberries, white grapes and raspberries

3.3.2 Experimental setup

The experimental phase took place during one month and consisted in four experiments, i.e. two duplicates for each environment. The products were stored in a refrigerated truck divided in two compartments, one for the control samples and one where the prototype was installed.

For each experiment, two batches were tested in parallel: one control batch, stored at high RH (higher than 80%) and ambient atmosphere composition, and a batch under the prototype, which will be called "prototype batch", with controlled atmosphere composition and a RH supposed to remain higher than 80% due to transpiration of the F&V in a closed environment. No embedded humidity system was used in the prototype. Both batches were kept at a set temperature of 4°C, supposed to remain constant. This temperature corresponds to the optimal temperature for the F&V considered. Control conditions were already more appropriate for the F&V than actual retail stores' cold rooms conditions, where temperature and RH are not as precisely monitored. These environmental parameters were measured and monitored during all the experiment using calibrated sensors.

3.3.3 **Experimental protocol**

Each experiment lasted between 3 to 11 days, with variations due to week-ends and public holidays. Upon arrival, the F&V were examined, sorted in two equal batches and non-satisfying samples were removed, with objective to have uniform initial samples. For each product within each batch, a limited amount of products were specifically marked for weight measurement. During the cold storage, prototype was opened two times a day, as it would be the case in retail stores' storage rooms. Samples were taken for analysis every 24h until the end of the experiment.

Next to this, to simulate what is happening in the retail stores, a certain amount of samples from each batch were taken out of the refrigerated truck every day after 48 hours of storage, to be stored at ambient conditions (20°C and low RH) for 24 hours before being analyzed.

3.3.4 **Freshness evaluation**

3.3.4.1 Methodology

3.3.4.1.1 Qualitative measurements

Concerning the qualitative tests, a grading scale for each product was defined depending on the overall visual product quality. Inspired by the method described by Matar (2018b), each sample analyzed was visually graded according to the scale, and an overall score repartition could be determined, instead of the "overall percentage of deterioration" determined by Matar (2018b). In parallel, photographs of the different grades of products were presented to an online panel to know their purchase intent. Combining consumer perception and visual grading allowed to determine shelf-life differences between control and prototype batches.

3.3.4.1.2 Quantitative measurements

For the quantitative tests, basic measurements related to F&V freshness were performed: weight loss for assessing transpiration and respiration, Brix and nutrients measurements for sugar level and vitamin C content, pH measurement for acidity, and texture analysis for assessing the softening of the products. The methods used for each measurement will be described in the following paragraphs.

Each test was performed on a limited number of samples (5 to 10 samples), due to space and time constraints.

3.3.4.2 Consumer acceptability

A specific grading scale ranging from grade 1 to grade 4 in order of decreasing quality was developed for each product (Appendix B). Grading scales were based on visual quality attributes such as color, browning, firmness, shriveling and wilting (Nunes & Emond, 2007; Lill, 1980).

Once the scales established, 50 consumers were contacted via an online questionnaire (Appendix C**),** and were either students or Air Liquide employees between 20 and 40 years old.

They were asked about their purchase intent for each product's grade, with a forced choice between two answers (YES or NO). In the case they would not be willing to buy a product, they were given the possibility to explain their reasons. Products were presented in a monadic sequential order, appropriate method for evaluating acceptability (Morin-Delerm, 1999). This allowed to determine a level of acceptability in percentage of consumers willing to buy for each grade. Products were deemed as partially acceptable for a level of acceptability lower than 75%, and unmarketable below 50% of acceptability.

Consumers were also asked whether they could see a difference between selected control and prototype samples collected at the same time. These consumer results were used to support the visual observations.

3.3.4.3 Visual evaluation

All F&V tested were visually assessed and graded using the scales previously developed. Assessments were performed as objectively as possible by the same operator to reduce experimental variability.

To determine shelf-life extension, percentages of unmarketable products, based on the level of acceptability of each grade as defined by the consumers previously, were determined at each time for both control and prototype samples. For products sold in bulk (i.e. salads, chicory, mushrooms, asparagus, grapes), unmarketable products were considered as waste. For products sold in packs (i.e. strawberries and raspberries), all products were considered as waste if there were more than 25% of unmarketable products.

3.3.4.4 Weight and water loss measurement

Marked samples from both batches stored in the refrigerated truck were weighed daily throughout the whole experiment, and percentage of weight lost was determined.

3.3.4.5 Texture analysis

The firmness of samples was tested using the Durofel fruit firmness analyzer from Setop-Giraud Technologies, France. This equipment consists in a cylindrical flat probe linked to a spring and pressure analyzer, which records the necessary strength needed to push the probe in the fruit until a stop. Results were given in Durofel units, with one Durofel unit corresponding to $16 g/cm^2$ for the probe used. The measurements were all done by hand by the same operator.

3.3.4.6 Brix measurement

Brix level were measured on a juice of several samples prepared using the HR1861 whole fruit juicer, Phillips, The Netherlands. A bead of juice was taken with a micropipette and introduced in a hand-held refractometer with automatic temperature compensation, Atago, Japan. A single value was visually determined per juice.

3.3.4.7 pH measurement

pH was measured once for each juice from blended bulk samples using a pH meter.

3.3.4.8 Nutrient analysis

Total sugar content and vitamin C concentration were determined for both control and prototype Gariguette strawberries samples respectively at 0h, 72h and 96h of cold storage. Analysis were performed by the CTIFL chemical laboratory located in St-Rémy-de-Provence, France. Sucrose, glucose and fructose levels, as well as ascorbic & dehydroascorbic acid levels were titrated by HPLC.

3.4 Eco-efficiency analysis procedure

3.4.1 **Cost analysis**

The daily consumption of gas by the prototype (in Sm^3) during every experiment was monitored using the gas mixer MAP Mix Provectus, DanSensor, USA, and was converted in weight using density at 15°C. The daily consumption was determined based on the average consumption rate during intermittent gas flushing and the quantity of gas needed for two daily injections, which occurred after each opening of the hood to go back to modified atmosphere conditions.

Next to this, costs in-use were estimated based on Air Liquide L50 gas cylinders. On the other hand, F&V prices were averaged based on prices found online for 5 main retailers in France in May 2019 (Appendix D).

For each product considered, the quantity of product (in kg) necessary to compensate the cost of daily gas consumption was determined. This quantity was then related to the maximal amount of F&V that could be stored under the prototype. A conversion table linking quantity of F&V in kg to their share in % of prototype's volume capacity for each F&V was created (Appendix E). These calculations were based on using standard secondary packaging for each F&V, and considering the prototype was entirely filled by only one type of product.

3.4.2 **Environmental analysis**

3.4.2.1 Goal of the screening Life Cycle Analysis (LCA)

The screening LCA performed had for objective to determine the environmental impact of the utilization of the prototype considering a balance between the environmental impacts of the daily gas consumption and F&V production.

3.4.2.2 Scope of the screening LCA

The LCA considered two systems:

- **Gases used for CAS**

  This system considered compressed gas in cylinders from production until the customer warehouse, including liquefaction, cylinder filling and transportation. End of life was not considered.

The functional unit was the kg of gas delivered at the customer warehouse. We considered that 90% of the gas contained in the cylinders was used, as the customer installation never uses 100% of the gas contained in the cylinder.

- **F&V**

This system considered selected F&V (strawberries, white asparagus and lettuce) from production until end-of-life, including farming, harvesting, transportation and bio-waste valorization. Food waste disposal was not considered.

The functional unit was the kg of F&V.

3.4.2.3 Life Cycle Inventory (LCI)

For both systems, only data from EcoInvent 3.4 database were used, with allocation by cut – off. These were the parameters taken into account in the LCI:

- **Gases**

Only the energy (electrical energy for manufacture and transportation) was considered in the LCI. The French electricity mix and a freight by lorry (EURO6 Diesel, >32 metric ton) on a distance of 200 km from the production plant to the filling center and 400 km from the filling center to the customer's site were considered. The impact of construction of plants to separate gases of interest from the air and liquefy them was considered as neglectable (less than 1%). Moreover, the cylinders construction was also considered as neglectable as they were supposed to be used for a very long time (more than 50 years). It is important to notice that the results were country-dependent. If the electricity mixes of other European countries had been considered, the impact might have increased and more than double the total carbon footprint, as the electricity mix of France is mostly powered by nuclear energy and has a low carbon footprint.

- **F&V**

For lettuce, global figures including inputs necessary for production, compensation for losses, cooling during operation and transportation, transportation and biowaste generated were taken into account.

For white asparagus, figures from France including inputs necessary for production (i.e. fertilizers, pesticides, packaging, seeds, manure and irrigation) and transportation were considered.

For strawberries produced under heated greenhouse, figures from Switzerland including inputs necessary for production, energy for heating and transportation were considered.

For all F&V, freight by lorry (EURO6 Diesel, >32 metric ton) for 400 km from production site to retailer was considered.

3.4.2.4 Life Cycle Impact Assessment (LCIA) and interpretation

Reference methods chosen were IPCC 2013 GWP 100 a V1.03 for assessing global warming and ReciPe for assessing damages to human health, resources availability and damages to ecosystem.

Four indicators were considered: global warming potential (GWP) in $kgCO_2eq$, damages to human health (HH) in DALY, damages to ecosystem diversity (ED) in species/year and damages to resource availability (RA) in USD (Figure 10).

ReCiPe is a method which combines the eighteen midpoint category factors usually used in LCIA in only three harmonized endpoint indicators: damages to human health, to ecosystems and to resources availability due to climate change (Appendix F). The endpoint factors also take into account a set of choices related to future management and technology development, with three different scenarios: egalitarian, hierarchist (which is the scientific consensus) and individualist (Zelm, 2009). The factors are here determined considering the hierarchist/egalitarian scenario.

Impact category		**Indicator**	
Name	**abbr.**	**name**	**unit**
damage to human health	HH	disability-adjusted loss of life years	yr
damage to ecosystem diversity	ED	Loss of species during a year	yr
damage to resource availability	RA	increased cost	$

Figure 10: Overview of the ReCiPe endpoint categories and indicators (Zelm, 2009) – *ReCiPe method was developed in the Netherlands in 2008 and give information on the effects of climate change on three global impact categories.*

The values for each indicator were determined per functional unit for both systems. Next to this, the volume of gas used (in Sm^3) by the prototype during every duplicate was monitored, and was converted in weight using density at 15°C. A daily gas consumption could then be determined for each environment, based on the average consumption rate during intermittent gas flushing and the quantity of gas necessary for two daily injections after opening the hood.

Finally, the minimal quantity of F&V that must be saved per day by the prototype to compensate the impact of its daily gas consumption was determined. It was assumed that by avoiding food waste, less food production would be needed. This explained why the scope of the F&V LCA was from farm to end-of-life.

3.5 Experimental constraints

Different constraints due to unforeseeable events that occurred during the experimental phase influenced data gathering and duplicate validity. They must be stated prior to presenting the results.

- Duplicates could not be considered as such and were not directly comparable for the following reasons:
  - Different varieties and categories of F&V were used from one duplicate to another for certain products: strawberries (Ciflorette vs Gariguette cultivar), organic lettuce (category I vs category II).
  - Different places of origin were observed for most of the products from one duplicate to another: grapes (South Africa vs India), strawberries (Brittany vs South of France), and organic lettuce (South-East of France vs Provence).
  - Different initial maturity were identified for some products: strawberries, chicory, mushrooms, and grapes.

Hence, each duplicate had to be considered as a unique experiment in the following results section. Moreover, it was not possible to determine an absolute shelf-life in days for a fruit based on these experiments, as the initial maturity and variety varied between duplicate. In order to get around this issue and still being able to conclude on shelf-life extension, grades were used for visual evaluation. This allowed inside an experiment with a specific variety and initial maturity to assess the evolution of product quality of both control and prototype samples over time and determine potential shelf-life extension.

- Only a limited number of samples could be tested every day for qualitative and quantitative measurements (5 samples per environment per day for the voluminous product like salad, chicory; 2 samples for the grapes; 10 samples for the smaller products like mushrooms, strawberries, and raspberries). In the case of weight loss measurements, due to time constraints, only 2 values consisting in the mean of several products were obtained per environment for the smaller products (grapes, mushrooms, raspberries).

This was due to business' request, limited storage space available and limited manpower available, as all the measurements had to be done on the same day by only one person. Hence, it was not possible to determine any statistical difference between measurements, which would have required 30 samples minimum to ensure the normal distribution of samples, requirement to use the Student t-test. The results presented in the following section thus only include standard deviations in some cases and trends.

- Screening LCA could not be conducted for all F&V selected, due to limited data in the EcoInvent 3.4 database.

4 Results and discussion

4.1 Prototype functionality evaluation

This section has for objective to present which one of the preselected plastic laminates was the most suitable for the prototype and evaluate the airtightness of different closures solutions.

4.1.1 Material data sheet analysis

Looking at the specifications data sheet of the three preselected plastic laminates presented in Appendix G, the material PP016 presented a significantly lower oxygen transmission rate (OTR) and water vapor transmission rate (WVTR), and higher puncture resistance than the two other materials, which presented OTR value 10 to 10^2 higher and a puncture strength half lower. These enhanced properties for the PP016 material could be explained by the presence of aluminum which considerably decreases gas permeability, and polyamide which gives good strength and toughness (Robertson, 2005).

From analyzing the physical properties of the different laminates, PP016 would be the best suited material to use for the hood of the prototype.

4.1.2 Accelerated folding wear test

As there was no parameter in the materials’ specifications allowing to conclude on the resistance to folding, a folding endurance test was performed on the different plastic laminates, after which gas permeability was assessed and potential micro-leaks identified. The following results gather for each material and each folding method the corresponding equivalent leak diameter.

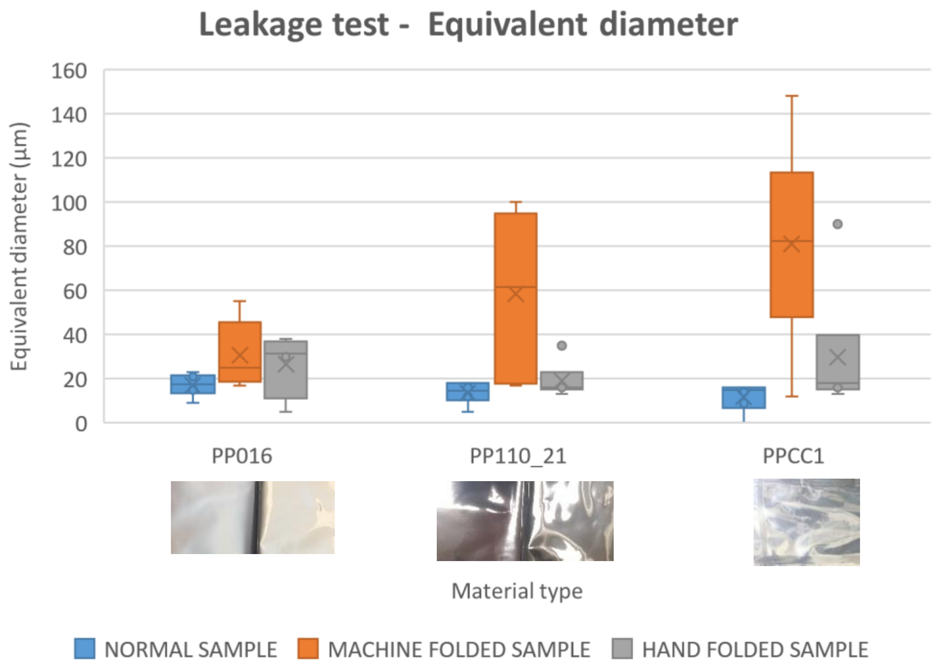


Figure 11: Micro-leak identification for three plastic laminates – *A box and whiskers plot shows the arithmetic mean (X), the median (line dividing the box in two parts), the extreme values (end of the whiskers) and the different quartiles (delimited by the whiskers and box). For instance, the box contains 50 % of the results. This allows to show the distribution of samples and to account for the extreme values which have here a physical relevance.*

Repeated folding increased leakage through the material, either for a short (hand-folded) or long (machine folded) period of use (Figure 11). While all unused samples presented a very low equivalent diameter (<20µm) corresponding to minimal micro-leaks, hand-folded samples presented slightly higher median values, which remained between 20 µm and 40µm for all the laminates. Values up to 90 µm were reached for PPCC1, which showed that this material was more sensitive to folding than the others.

Concerning the machine-folded samples, values were significantly higher than for unused and hand-folded values for PP110_21 and PPCC1 materials. The median equivalent diameter tripled compared to its initial value of 20µm for PP100_21, and quadrupled for PPCC1, for which most of the values were significantly more important than PP016 values. The trend observed previously on PPCC1 was confirmed, with a maximal equivalent diameter up to 150µm.

Concretely, leaks have an important impact on oxygen and water vapor diffusion through a material. For high barrier materials, as it is the case for the three laminates, the effect of leaks should not be neglected, moreover than it is accentuated at lower temperatures (Chung, 2003). The micro-leaks observed here, which remained acceptable below a level of 200µm for machine-folded samples, could become significant and unneglectable on the overall hood surface, where several folded points would be present. This was confirmed during the experimental phase, when a macro perforation was formed in PPCC1 plastic laminate, showing the inadequacy of this material for the prototype.

Concerning the burst tests, no bursting as well as no rupture due to the formation of a hole occurred for PP016, showing an excellent resistance to bursting, coherent with its important welding strength (Appendix G). On the other side, for the other laminates, all the samples either bursted or holes were formed. For PP110_21, one third of the machine folded samples did not burst, due to the formation of small holes near folded weak points. For PPCC1, two thirds of the machine folded samples did not burst, due to the formation of small holes near folded weak points during the burst test.

Overall, PP016 was the most resistant material to repeated folding cycles, with a very limited increase in gas leak over time and a good sealing strength, contrary to the other materials, and particularly PPCC1. For the experimental phase, it was decided to use a hood made of PP016 on three sides and PPCC1 on one side. The later material was used despite its poorer physical properties for its transparency, which was a desired characteristic to facilitate operations with the F&V and impact as little as possible the logistical activities in the retail shops.

4.1.3 Airtightness assessment

Once the whole prototype connected to the appropriate gas supply network, different airtightness solutions were assessed. With the hood in low position, the ability to reach low gas concentration values and to reach the quantity of gas needed to maintain a constant atmosphere composition in the hood were evaluated. Two solutions were tested: a PVC single-sided foam tape solution (RS Components, 2019) and a dual magnetic solution.

The foam solution did not allow to reach the required low gas level after 15 min, making it unsuitable for the prototype, while the magnetic tape allowed to reach the desired level of gas in an acceptable time and to maintain it with intermittent gas flushing. This solution was used on the prototype for the experimental phase.

4.2 Shelf-life extension evaluation

4.2.1 **Evolution of environmental parameters**

The experimental phase was based on the comparison of the quality of F&V stored in optimal conditions of preservation (including gas composition, temperature and humidity) and stored in control conditions.

To evaluate the effect of short-term CA only, gas composition had to be the only parameter changing between the control and prototype batches. It was thus important to monitor closely the temperature and RH conditions in the control and prototype batches for each duplicate, to check if this was true and guide further conclusions.

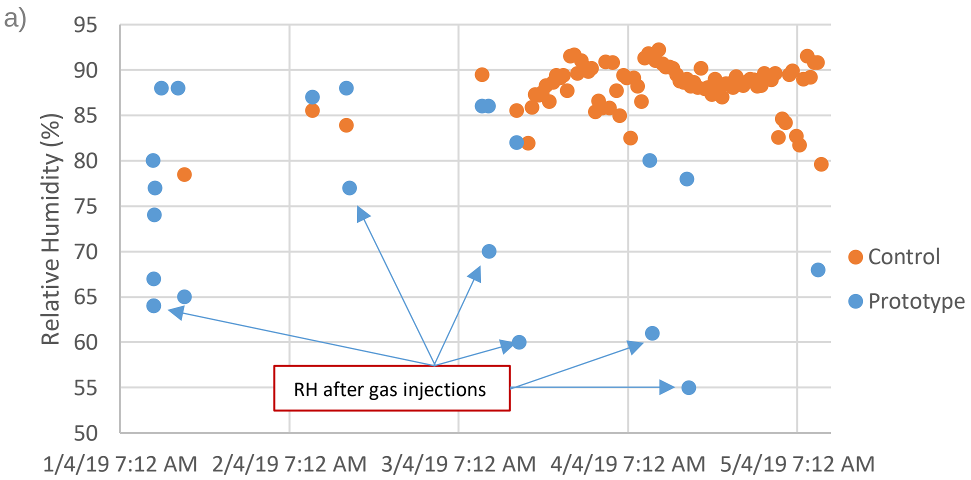
4.2.1.1 Temperature

Several temperature sensors were installed at different spots in both control and prototype compartments in the refrigerated truck to monitor temperature evolution. For both duplicates of environment 1, temperature remained throughout the whole experiment between 3 to 5°C, with peaks up to 6°C in the prototype compartment corresponding to the daily openings of the truck for samples collection and prototype opening. For the duplicates of environment 2, temperature remained approximatively around 4°C during the whole experiments, with peaks up to 9°C in the prototype compartment corresponding to the daily openings of the truck for collection of samples and prototype opening, and minimums up to 2°C in the control compartment (Appendix H). Higher maximal temperatures could be explained by warmer external temperatures during environment 2 experiments, and punctual lower values in the control compartment could be due to automatic defrost of the cooling system. Overall, the set temperature of 4°C was maintained during all four experiments.

Concerning the samples stored at ambient conditions, the temperature was constant at 21°C, slightly higher than the usual temperature in retail stores (around 18°C) (Appendix I).

4.2.1.2 Humidity

Relative humidity was monitored in the control compartment and inside the prototype hood using external and embedded sensors. For all environments and duplicates, a noticeable difference of 10 to 20% was observed between control and prototype RH (Figure 12 and 13).



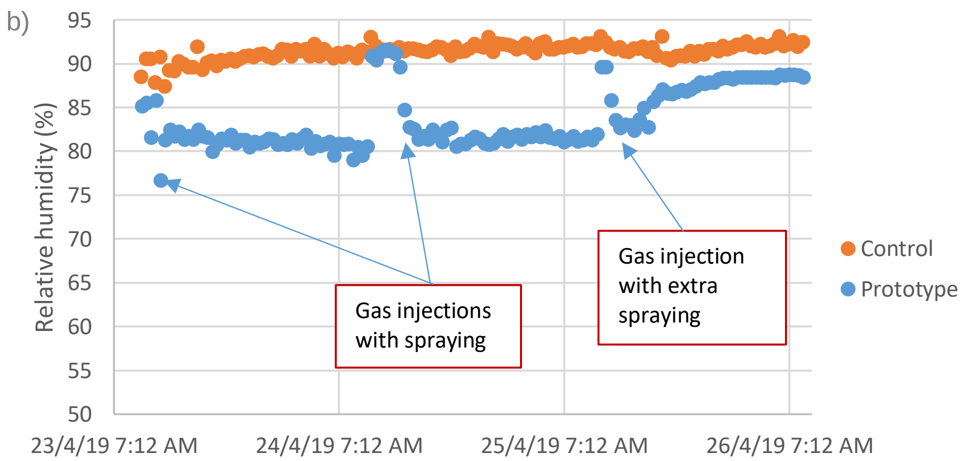


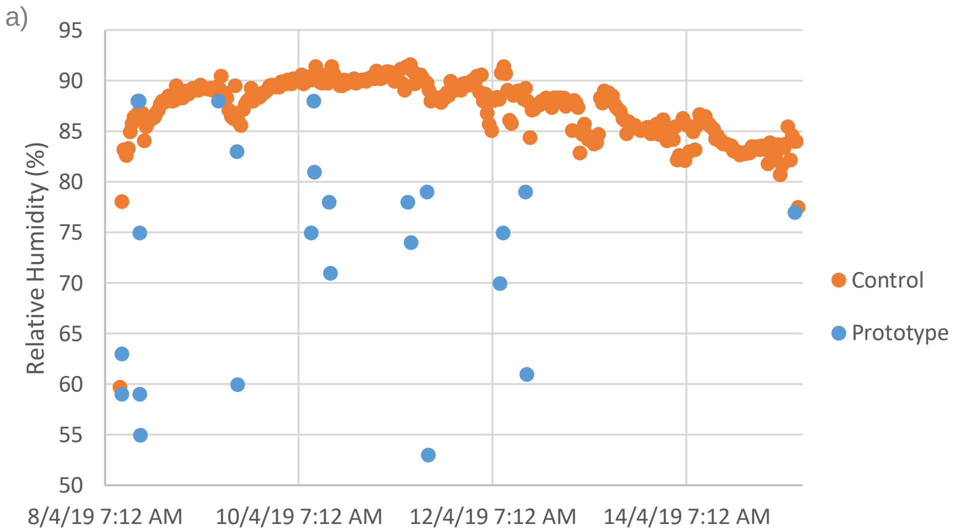
Figure 12 a & b : RH evolution for environment 1 duplicates – Figure 12a: Environment 1 Duplicate 1, with low RH value after initial gas injection / Figure 12b : Environment 1 Duplicate 2, limited RH decrease after initial gas injection - *Close dots were measured by a calibrated RH sensor acquiring data every 30 min, spaced dots were measured twice a day during samples collection in the refrigerated truck, using a manual RH sensor for the control samples and the embedded prototype sensor for the prototype samples. All sensors were previously calibrated.*

For Environment 1 Duplicate 1, the RH in the control compartment was relatively stable and ranged between 80 to 90%. On the contrary, the RH inside the prototype ranged from 55-75% right after each gas injection when closing the hood, to 90% when opening the hood (Figure 12a). This first observation highlighted the negative influence of CA via gas flushing on the RH inside the prototype, leading during each initial injection to a decrease of 10 to 30% in RH in a few minutes.

For Environment 1 Duplicate 2, thin droplets of water were sprayed on the control and prototype samples after every collection of samples and hood opening, in order to increase locally the RH and counteract the negative effect of gas flushing on the RH. This allowed to lower the difference in RH to only 10% between control and prototype compared to the first duplicate, and to avoid an important decrease of RH after each gas injection, with a lowest RH of 75% compared to 55% in the first duplicate (Figure 12b). Continuous RH measurements inside the prototype's hood showed that after each gas injection, the RH remained at a lower level than the initial RH before injection, at a value of approximatively 80%.

This results could be explained by the intermittent gas flushing necessary to maintain the desired atmosphere inside the hood, which continuously dries the air and might be balanced by the evaporation of thin droplets and the respiration and transpiration reactions of the F&V. Moreover, an increase of the RH inside the hood was observed after the last injection for the second duplicate, before which extra spraying had been performed. This could be due to the extra available water inside the prototype, which could compensate the RH decrease caused by gas flushing.

For both environment 2 duplicates, similar behaviors were observed, with a stable RH between 80 to 90% in the control compartment and a RH stabilized around 70% after injection inside the prototype (Figure 13a&b). For these duplicates, spraying was not performed to avoid the developments of moulds on the berries, except before a long period of storage of 4 days when thin droplets were sprayed. It could be noticed that if spraying seemed to have had no effect on the average RH value of 70% inside the prototype, it allowed to prevent the important decrease in RH right after the gas injection (Figure 13b). Hence, it seemed that water available by spraying allowed to compensate partially the drying effect of the initial gas flushing, while respiration and transpiration mechanism allowed to compensate the intermittent gas flushing necessary to maintain the desired atmosphere composition, with a stable RH value in the prototype depending on the products stored. This value was around 70% for the berries and 80% for the leafy greens, which could be explained by a difference in respiration/transpiration rate between those two types of F&V, with a higher respiration/ transpiration rate for the leafy greens (Fonseca *et al*, 2002). Finally, it could be seen that when the intermittent gas flushing stopped due to empty gas bottles, it was directly followed by an increase in RH in the prototype above 80%. This corroborated the theory of a balance in RH between respiration rate and intermittent gas flushing.



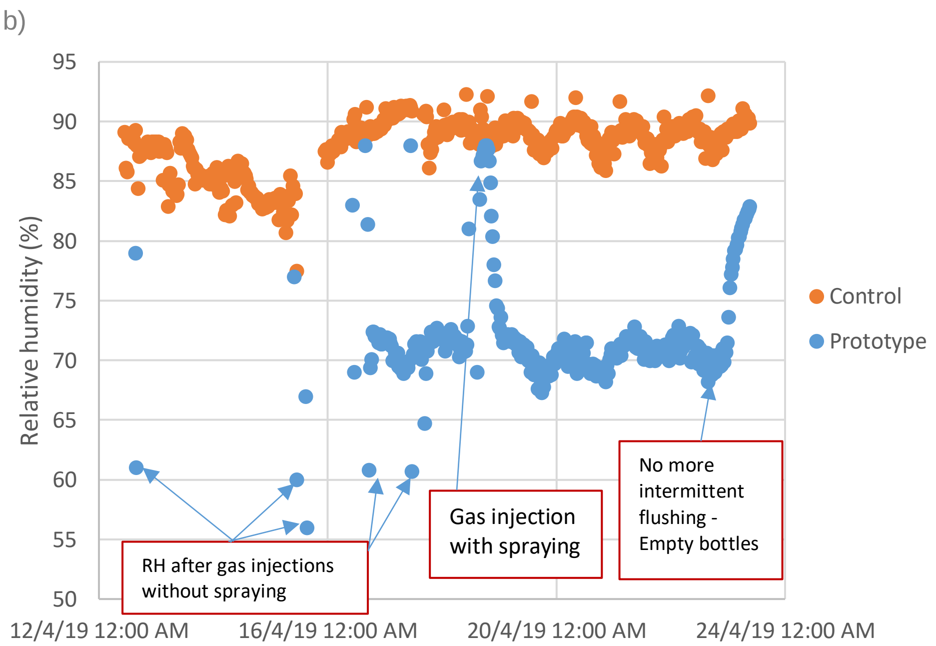


Figure 13 a & b: RH evolution for environment 2 duplicates – Figure 13a: Environment 2 Duplicate 1, with low RH value after initial gas injection / – Figure 13b : Environment 2 Duplicate 2, influence of spraying and intermittent gas flushing on RH

Concerning the samples stored at ambient conditions, the RH was considerably lower than the RH in the refrigerated truck and varying between 20 to 50% (Appendix I).

Overall, this study on the evolution of RH inside the prototype revealed several important points:

- The samples inside the prototype remained for all the experiments at a lower RH than the control samples. Hence, comparable RH conditions between batches were not respected. This was taken into account for the interpretation of the shelf-life results, as a lower RH than the optimal RH of 85-90% is expected to have a negative impact on F&V quality and appearance.

- The RH inside the prototype seemed to be dictated by a balance between the drying effect of intermittent gas flushing and the respiration rate of F&V. Hence, depending on the F&V stored, a constant RH value could be observed in the prototype during intermittent gas flushing.

- Spraying thin droplets allowed to prevent sharp decreases of RH after each initial injection of gas.

4.2.2 **Consumer acceptability & qualitative visual evaluation**

4.2.2.1 Consumer acceptability

Consumer purchase intent was determined for each F&V grade based on their percentage of acceptability (Figure 14). Overall, the decrease in grade quality was correlated with a notable decrease in acceptability. This showed that the grading scales developed based on literature were matching with consumer perception of the products.

However, if a lower grade meant lower acceptability by the consumers, this did not always mean lower purchase intent and increased unmarketability. For chicory and mushrooms, there was a change in acceptability between grade 2 and grade 3, with unmarketable products from grade 3 onwards (Figure 14). The same occurred for strawberries but between grade 3 and grade 4. For grapes, white asparagus and lettuce, a decrease in acceptability appeared already from grade 2, while only grade 4 was unmarketable. Finally, for raspberries, all grades were marketable. To better understand where these differences came from, consumers were asked to justify their choice whenever they would judge a fruit non-acceptable.

Strawberries

Color and visible bruises were the main characteristics impacting acceptability of strawberries. Fruits of light colour were considered as unripe and thus not attractive, and fruits presenting visible damages on their skin were rejected. Darker red color and slight surface bruises were not seen as impacting negatively acceptability. Grade 4, which corresponds to visibly damaged fruits, was deemed as unmarketable.

Raspberries

Light pink drupelets and a heterogeneity of color were the main reasons discouraging consumers to buy raspberries. Hence, acceptability was impaired already from grade 2, corresponding to fruits presenting light pink drupelets. However, consumers did not make any difference between grade 2, 3 and 4 samples, which all remained marketable. This was mostly due to the fact that raspberries' grades were determined using texture parameters, which could not be assessed visually by consumers.

Grapes

Color and aspect of the grapes were essential to determine marketability. A loss in acceptability was observed with darkening of the color of the grapes, fruit visual softening and appearance of moulds. Hence, grade 3, which refers to yellow to brown grapes with a soft texture, was assessed as partially acceptable, and grade 4, which considers mouldy grapes, was deemed as unmarketable.

Percentage of acceptability	*Grade 1*	*Grade 2*	*Grade 3*	*Grade 4*
Strawberries	81,7	98,0	84,0	44,9
Raspberries	96,7	67,3	68,4	66,3
Grapes	98,0	92,0	59,2	32,7
Chicory	84,0	84,0	48,0	14,0
Mushrooms	96,0	84,7	43,5	19,0
Lettuce	99,0	66,0	54,0	6,1
Asparagus	88,0	81,8	53,1	50,0

Figure 14: Consumer purchase intent for F&V grades – Results based on 50 answers from untrained consumers – *Percentages correspond to the percentage of consumers interviewed that would buy the F&V grade. : acceptable products (more than 75% acceptability); : partially acceptable products (between 50 -75% acceptability);* *: unmarketable products (below 50% acceptability)*

Chicory

Most of the consumers interrogated were rarely or never eating chicory. Hence, a majority of them did not really know how to judge chicory's quality, even perceiving greening of the leaves as a sign of unripeness, while it is recognized by the retailers as a major sign of deterioration. Despite this, consumers seemed to agree that browning and loosening of the leaves negatively impacted the acceptability of chicory, thus judging grade 3 unmarketable and grade 4 totally unacceptable, with only 14% of acceptability.

Mushrooms

Browning of the cap and opening of the gills seemed to be the most important parameters influencing purchase intent of mushrooms. As soon as there were visible dark brown spots, mushrooms were not considered as marketable anymore. Hence, grade 3 was deemed as unmarketable while grade 4, referring to mushrooms with wrinkles, was seen as totally unacceptable, with only 6% of acceptability.

Lettuce

Freshness based on crunchiness and the absence of wilting were the main drivers of lettuce acceptability. The acceptability was impaired as soon as the lettuces started to wilt slightly (grade 2 and 3), and were unmarketable after a certain degree of wilting (grade 4).

White asparagus

The decrease in freshness and acceptability for the consumers was linked to browning. Visible browning on the whole stem impacted acceptability in a certain extent, with grade 3 and 4 being on the limit of marketability.

4.2.2.2 Visual evaluation and shelf-life extension

For each product and each experiment, control and prototype samples were visually assessed every day and a repartition of their grades and thus quality was determined. In this section, two graphs are presented for each product and duplicate: the evolution of the grade repartition for cold storage only, and for cold storage until 48h followed by ambient storage, to mimic the display conditions in retail stores (Figure 15 to Figure 23).

For each product, the grades found were related to their acceptability and marketability to conclude on potential food waste avoided and shelf-life extension.

Finally, differences observed by consumers between control and prototype samples at specific times of storage were used to strengthen or refine the grading results (Appendix J).

Strawberries – Ciflorette variety (Duplicate 1)

There were no visible differences between visual quality of prototype and control samples for Ciflorette strawberries. The overall quality decreased over time for both environments due to normal senescence of the fruit, with a similar grade evolution and less than 15% of unmarketable products for both environments after a week of cold storage (Figure 15a). As expected, quality also decreased faster in ambient conditions compared to cold storage, with around 40% of unmarketable products after 96 hours of cold storage and 24h of ambient storage (Figure 15b).

A lower quality for prototype samples was expected due to a lower RH which should enhance respiration and transpiration and greatly affect strawberries' visual quality like firmness, discoloration, loss of turgidity (do Nascimento Nunes, 2008). However, there was no difference between batches. This could mean that CA storage partially balanced the negative effect of lower RH on strawberry quality by slowing down the biochemical and physiological changes related to senescence, thus giving the visual impression there was no difference between batches. Hence, if both batches were to be stored at the same RH, a better quality over time would be expected for the prototype samples.

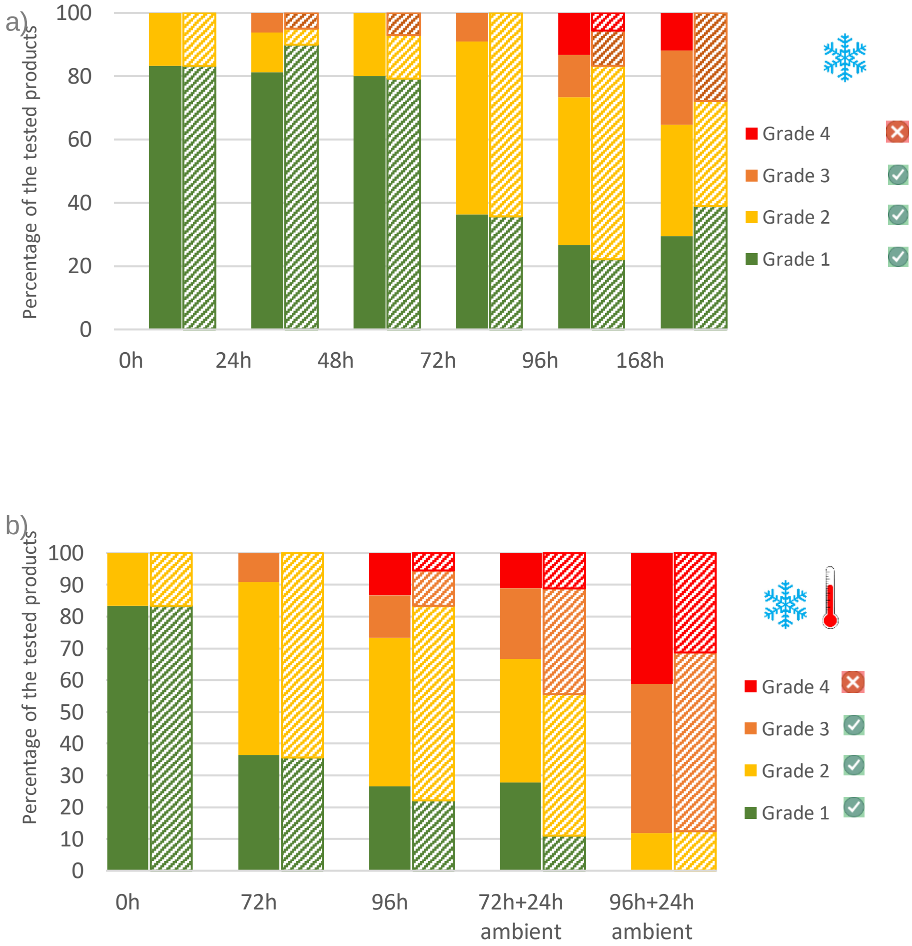


Figure 15 a & b: Visual quality assessment of Ciflorette strawberries (Environment 2 – Duplicate 1) - Figure 15a: Evolution in cold storage conditions (4°C) / Figure 15b : Evolution in cold storage conditions until 72h, followed by ambient storage conditions (21°C and low RH) – *Plain color: prototype samples / Color with patterns: control samples*

Strawberries – Gariguette variety (Duplicate 2)

Comparable results to duplicate 1 were observed for Gariguette strawberries, with no noticeable difference between prototype and control samples' grade distribution, and a decrease of quality over time that is accelerated in ambient conditions (Figure 16). This supported the results and interpretations of duplicate 1. Hence, if both batches had been stored at the same RH, a better quality over time would have been expected for the prototype samples.

Also, after 144h of cold storage, the overall quality of Gariguette strawberries was better than for Ciflorette strawberries, with 50% of grade 1 compared to only 20%. This showed the importance of initial maturity and variety on quality assessment by visual evaluation. No absolute results could be obtained and only comparison within a same experiment could be done.

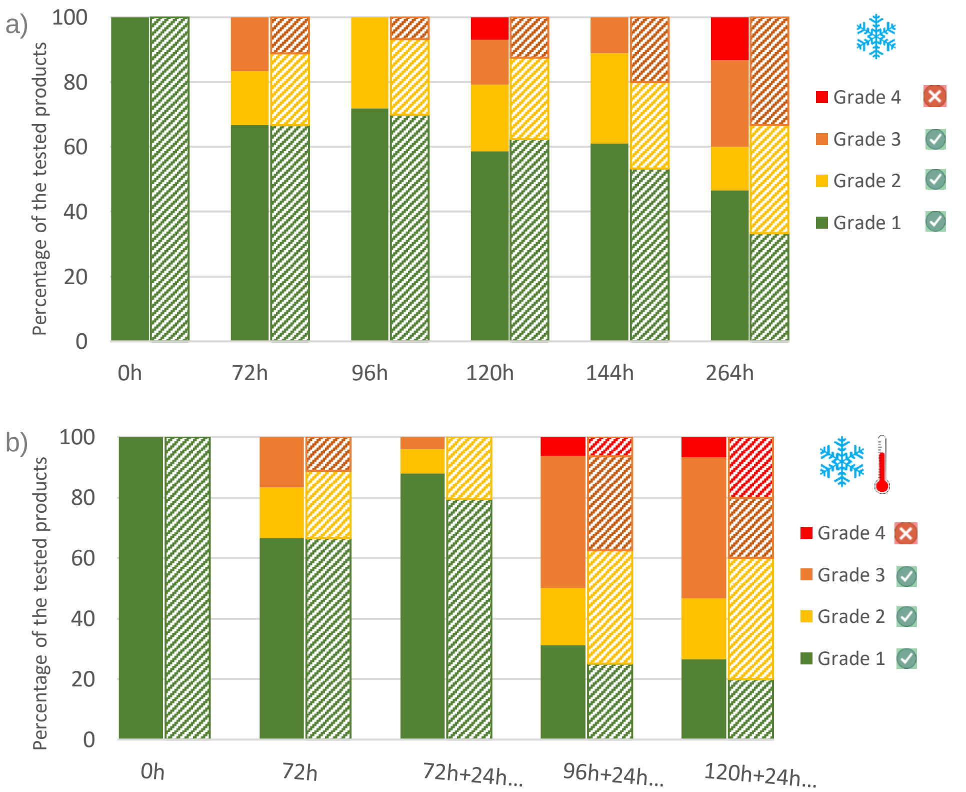


Figure 16 a & b: Visual quality assessment of Gariguette strawberries (Environment 2 – Duplicate 2) - Figure 16a: Evolution in cold storage conditions (4°C) / Figure 16b : Evolution in cold storage conditions until 72h, followed by ambient storage conditions (21°C & low RH) - *Plain color: prototype samples / Color with patterns: control samples*

Raspberries

The evolution of the overall grade of raspberries stored in the prototype decreased over time, due to normal fruit deterioration. A higher number of grade 1 raspberries at 96h in cold storage under the prototype could be observed. It might be due to the heterogeneity between the samples collected every day (Figure 17a).

When comparing to the control samples, no noticeable difference could be seen during cold storage over time. A balance between positive effect of CA and negative impact of lower RH as discussed previously for the strawberries could explain these results. However, during ambient storage after 4 and 5 days of cold storage, prototype samples had a lower visual quality than control samples (Figure 17b). This could be due to the lower RH in the prototype, which might have weakened the raspberries more than it weakened the strawberries.

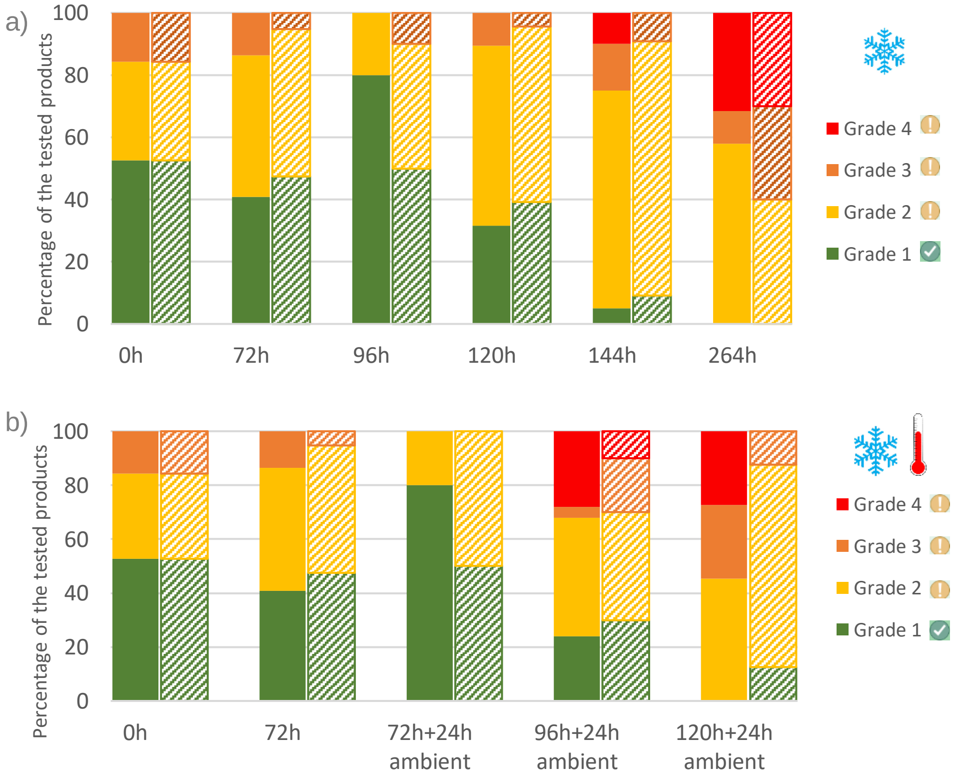


Figure 17 a & b: Visual quality assessment of raspberries – Figure 17a: Evolution in cold storage conditions (4°C) / Figure 17**Figure 17**b: Evolution in cold storage conditions until 72h, followed by ambient storage conditions (21°C and low RH) - *Plain color: prototype samples / Color with patterns: control samples*

Grapes Duplicate 1 (Origin: South Africa)

The evolution of visual quality for grapes over time was not coherent, with for instance only grade 3 grapes after 72h of storage and only grade 2 grapes after 96h of storage (Figure 18a). This was caused by a high variability between samples, which was most likely the main reason explaining difference in grades. Moreover, the grades observed at the start and end of the experiment were not noticeably different, thus showing that the grapes quality overall did not evolve significantly in a week.

Consumer's perception of visual differences between samples collected at a same time also gave conflicting results, with almost 50% of the consumers preferring control samples at 48H for their greener color, and prototype samples at 72h + 24h of ambient storage for similar reasons (Appendix J). This confirmed the high intrinsic heterogeneity between samples.

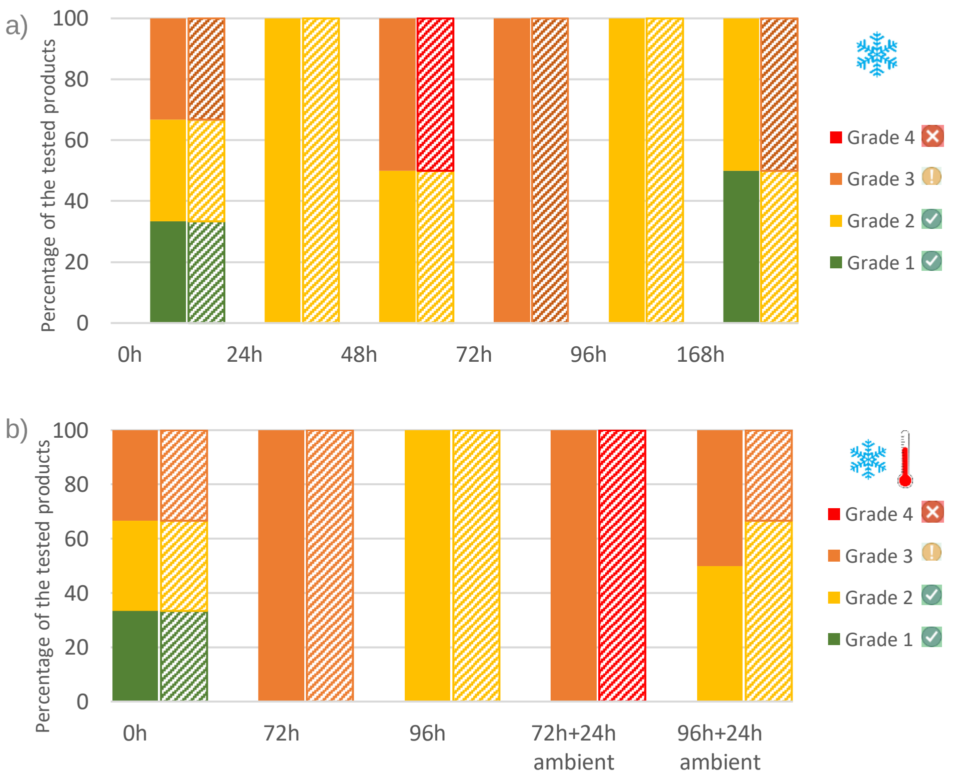


Figure 18 a & b: Visual quality assessment of grapes - Duplicate 1 - Figure 18a: Evolution in cold storage conditions (4°C) / Figure 18b: Evolution in cold storage conditions until 72h, followed by ambient storage conditions (21°C and low RH) - *Plain color: prototype samples / Color with patterns: control samples*

Grapes Duplicate 2 (Origin: India)

No difference of quality over two weeks of experiments and between batches were observed, with only fruits of an acceptable quality. The overall quality of these grapes was better than the grapes of duplicate 1, due to different maturity level of the initial samples and different varieties. These results comforted the findings of duplicate 1, confirming that grapes were not degrading significantly over short periods of time. This is coherent with previous works were impact of CA on grapes quality could only be observed over 3 weeks of storage (Martinez-Romero *et al*, 2003). Finally, the lower RH in the prototype had no visible effect on the quality of the grapes. This was expected as on the contrary high RH level (above 90%) have more impact on the quality of grapes by enhancing moulds development (Pardo *et al*, 2005).

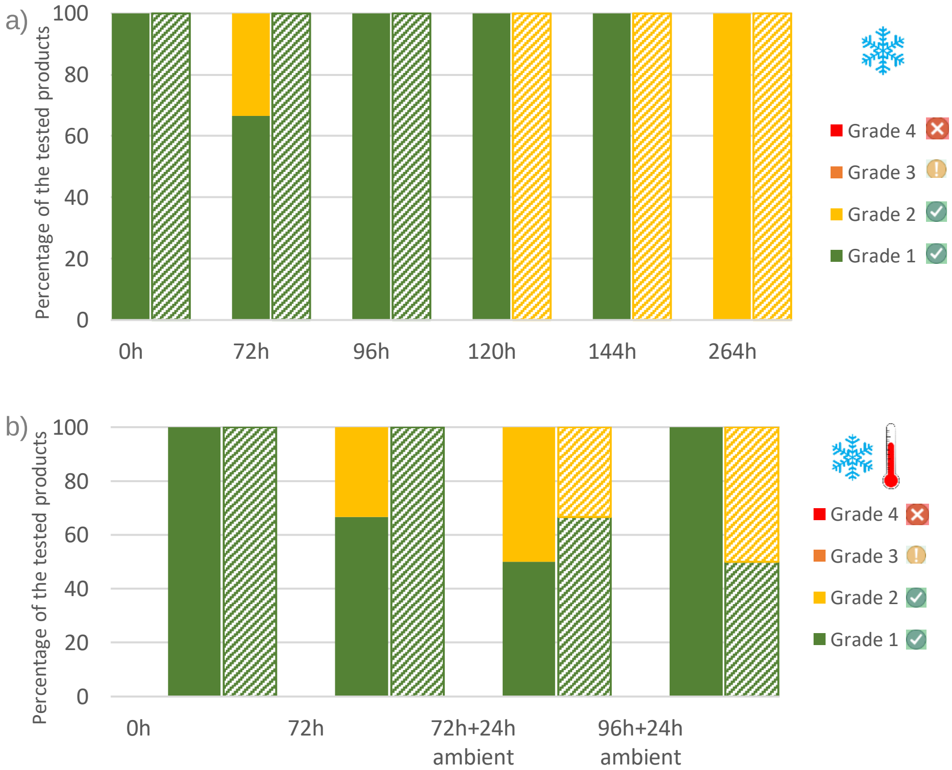


Figure 19 a & b: Visual quality assessment of grapes - Duplicate 2 - Figure 19a: Evolution in cold storage conditions (4°C) Figure 19b: Evolution in cold storage conditions until 72h, followed by ambient storage conditions (21°C and low RH) - *Plain color: prototype samples / Color with patterns: control samples*

Chicory

For chicory, prototype samples presented a better quality than control samples after 72h of cold storage in duplicate 1, as well as a better quality in ambient conditions for both duplicates (Figure 20a). When shown samples from both batches at 72 hours of cold storage in duplicate 1, more than 80% of the consumers noticed a difference between samples in favor of the prototype samples, which presented less browning on the leaves and the basal part of the leaves than the control ones. Delayed browning of the leaves could be explained by a slow-down of the senescence phenomena in CA storage (Charles *et al.*, 2008; Vanstreels *et al.*, 2002). Duplicate 2 results were less pronounced, with only an impact observed after storage in ambient conditions (Figure 20c).

Looking at consumer acceptability, CAS allowed to save 60% of the volume stored in the prototype after 72 hours of cold storage and up to 100% after 96 hours. CAS thus allowed to extend noticeably shelf-life of chicories after 3 days of cold storage. In ambient conditions, all samples for duplicate 1 were unmarketable due to a partial greening of the leaves and red discoloration of the basal part of the leaves, more important in the control samples, and that can be explained by the increase in temperature. For duplicate 2, CA storage seemed to allow saving 30% of the samples after 48h of cold storage and 24h at ambient conditions.

Mushrooms

There was a visible effect of CA storage on mushrooms' visual quality for duplicate 1 from 72h of cold storage, allowing to save respectively 40%, 60% and 40% of the volume stored under the prototype after 72h, 96h of cold storage and 48h of cold storage + 24h in ambient conditions (Figure 21a & b). This difference between prototype and control samples was due to a lesser browning of the mushrooms cap under CA storage, with 42%, 68% and 88% of the consumers noticing a difference in favor of the prototype samples respectively after 48h, 72h and 96h of cold storage. Slower browning could be due to a reduction of the polyphenol oxidase activity under CA conditions (Ye *et al.*, 2012). Under ambient storage conditions after 72h of storage, visible shriveling and wrinkling of the mushrooms explained the low quality for both batches, with a darker color for the control samples.

Different results were obtained for duplicate 2, where differences between prototype and control samples were not noticeable and consistent (Figure 21c). A difference in initial quality of the mushrooms could explain these results and showed that the noticeable effects of CA storage in duplicate 1 might not be reproducible.

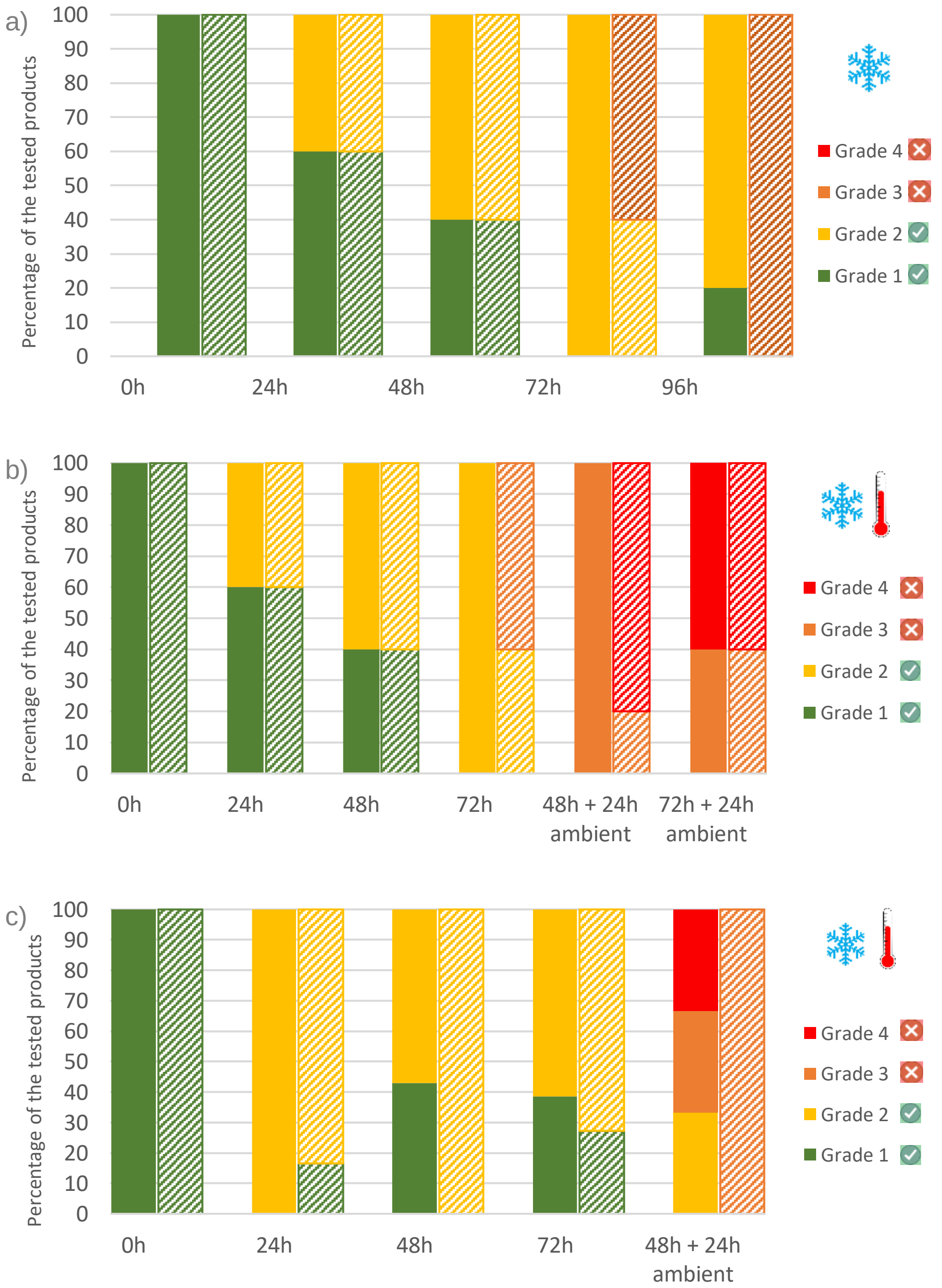


Figure 20 a, b & c: Visual quality assessment of chicories - Figure 20a: Evolution in cold storage conditions (4°C) Duplicate 1 / Figure 20b: Evolution in cold storage conditions until 48h, followed by ambient storage conditions (21°C and low RH) - Duplicate 1 / Figure 20c : Evolution in cold storage conditions (4°C) followed by ambient storage conditions (21°C and low RH) -Duplicate 2 - *Plain color: prototype samples / Color with patterns: control samples*

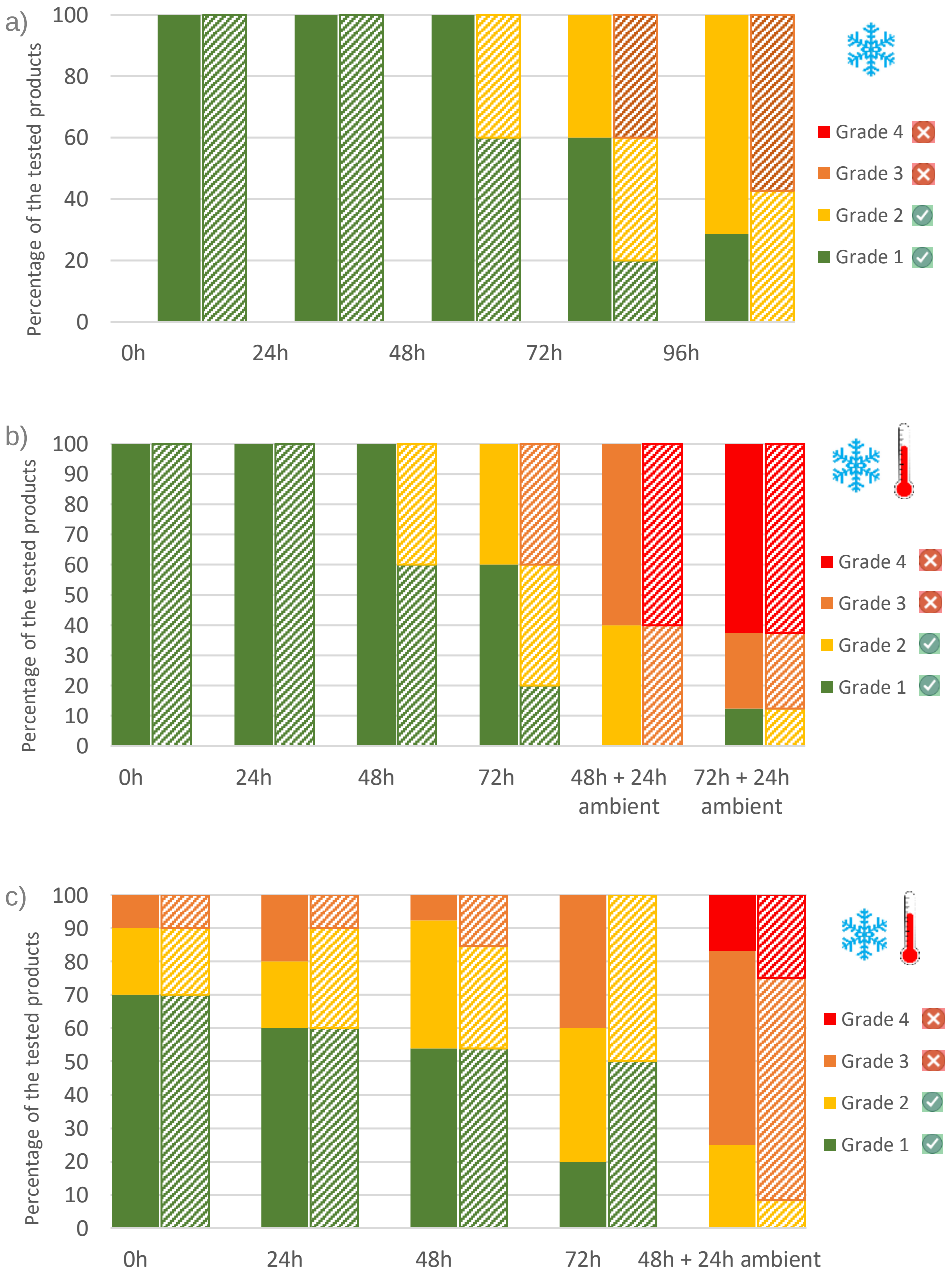


Figure 21 a, b & c: Visual quality assessment of mushrooms - Figure 21a: Evolution in cold storage conditions (4°C) Duplicate 1 / Figure 21b: Evolution in cold storage conditions until 48h, followed by ambient storage conditions (21°C and low RH) - Duplicate 11 / Figure 21c: Evolution in cold storage conditions until 48h, followed by ambient storage conditions (21°C and low RH)-Duplicate 2 - *Plain color: prototype samples / Color with patterns: control samples*

Lettuce

No significant difference between prototype and control samples were observed in duplicate 1 and 2 for organic lettuce, with all samples remaining partially acceptable in cold storage conditions (Figure 22). While grades of prototype samples seemed to be better than control samples in duplicate 1 after 72h and 96h of storage, less than 25% of the consumers interviewed were able to notice a difference between samples. Finally, lettuce were particularly sensitive to the change of storage conditions, with visible wilting and loss of turgidity when stored at ambient conditions.

White asparagus

No significant difference between prototype and control samples were observed in duplicate 1 and 2 white asparagus. Results were not coherent over time for duplicate 1, with worse grades for prototype samples after 72h of storage, but similar grades than control samples after 96h (Figure 23). This showed an important intrinsic heterogeneity between samples.

Storage under ambient conditions proved to have negative effects on asparagus' quality in both batches after 24h of ambient storage, leading to unmarketable shriveled asparagus. This might have been caused by a low RH below 50%, greatly impacting weight loss and appearance.

Finally, CA storage seemed to have had neither a positive nor negative effect on asparagus visual quality, in agreement with previous findings (Siomos *et al.*, 2000).

Conclusions on visual quality evaluation

Overall, CA storage for a limited period of time allowed to extend shelf-life of chicory and mushrooms after 72h of cold storage, saving up to 100% of the samples for chicory and 60% of the samples for mushrooms after 96h of cold storage. This was due to a delayed browning of the prototype samples, explained by a slow-down of the senescence phenomena and a reduction of the polyphenol oxidase activity in CA storage.

For strawberries, no noticeable difference in quality was observed. However, this could be due to a negative impact of lower RH in the prototype balanced by a positive impact CA storage. Hence, if both batches were to be stored at the same RH, the shelf-life of prototype samples would potentially be extended, with a slower decrease in quality over time.

For other products, like grapes or white asparagus, no noticeable difference was observed.

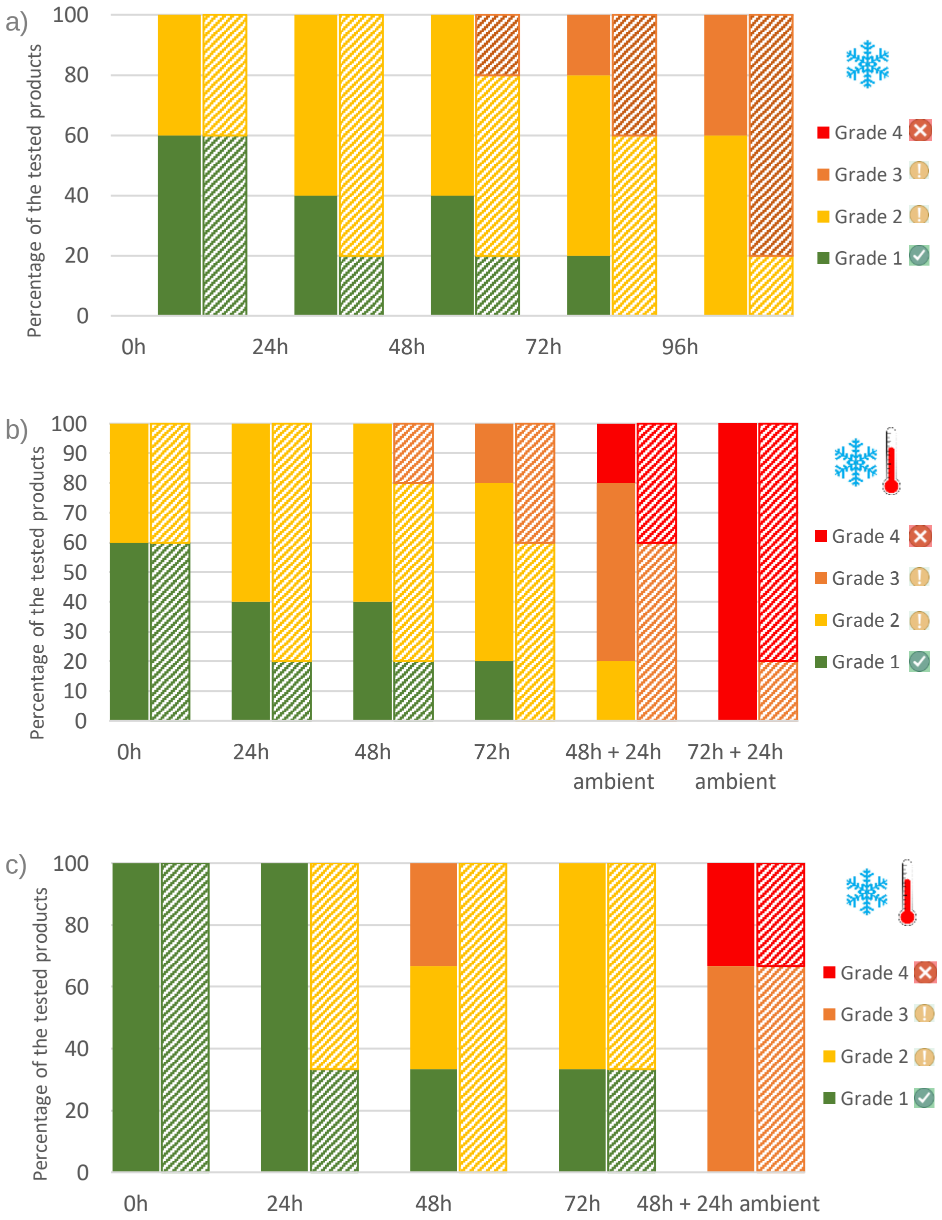


Figure 22 a, b & c: Visual quality assessment of lettuce – Figure 22a: Evolution in cold storage conditions (4°C) Duplicate 1 / Figure 22b: Evolution in cold storage conditions until 48h, followed by ambient storage conditions (21°C and low RH) - Duplicate 1 / Figure 22c: Evolution in cold storage conditions until 48h, followed by ambient storage conditions (21°C and low RH)-Duplicate 2 - *Plain color: prototype samples / Color with patterns: control samples*

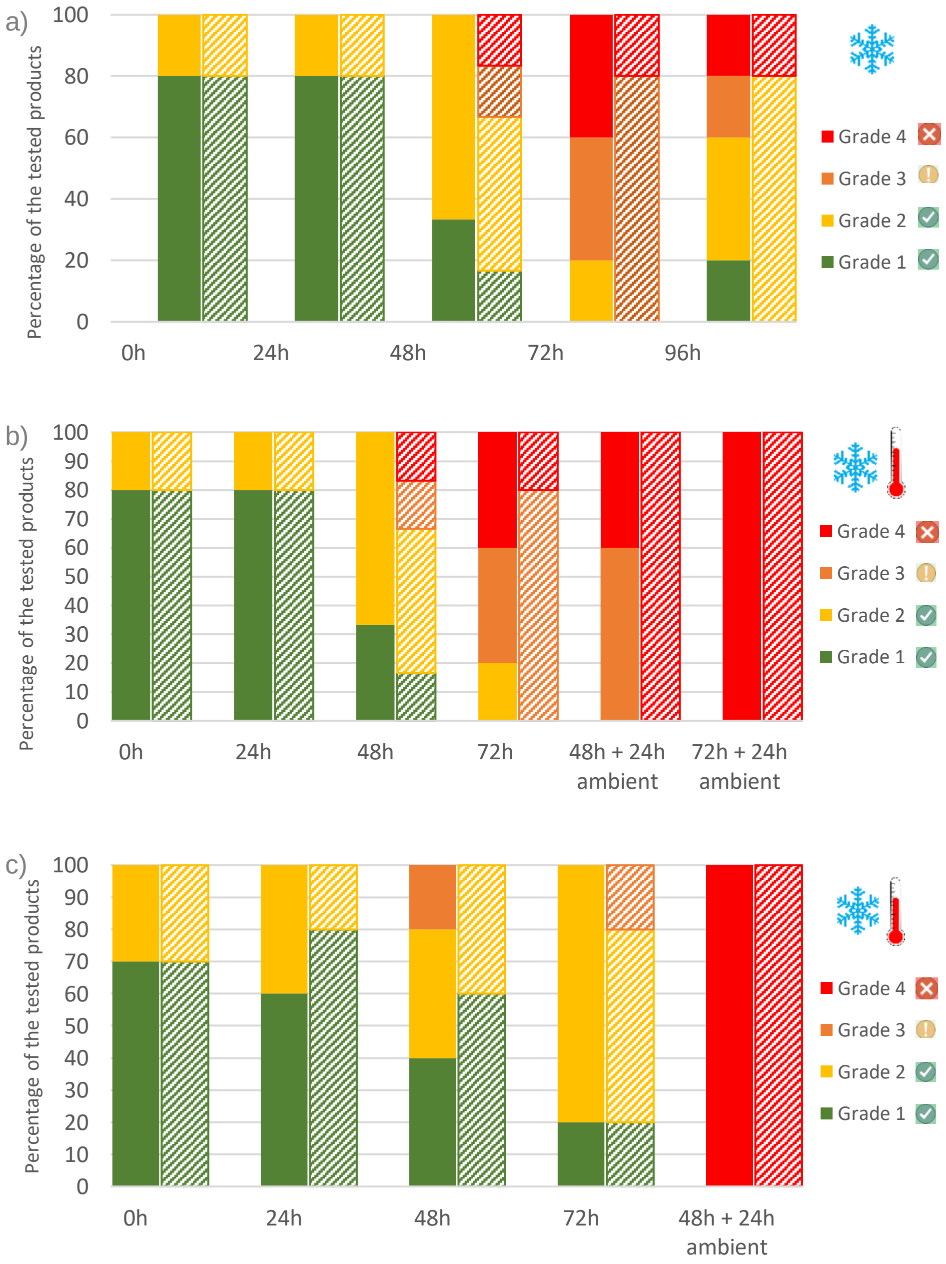


Figure 23 a, b & c: Visual quality assessment of asparagus - Figure 23a: Evolution in cold storage conditions (4°C) Duplicate 1 / Figure 23 b: Evolution in cold storage conditions until 48h, followed by ambient storage conditions (21°C and low RH) - Duplicate 1 / Figure 23 c: Evolution in cold storage conditions until 48h, followed by ambient storage conditions (21°C and low RH)-Duplicate 2 - *Plain color: prototype samples / Color with patterns: control samples*

4.2.3 Quantitative assessment of F&V quality

4.2.3.1 Weight loss

Leafy greens & mushrooms

There was a noticeable difference in weight loss between control and prototype samples for all leafy greens and mushrooms (Figure 24). From 24h until 72h of storage, the weight loss rates of the prototype samples were everyday lower than the one of the control samples, even if they were stored at a lower humidity (80% for the control vs 90% for the prototype).

For the leafy greens, this trend was supported by the error bars based on the standard deviations obtained, which did not cross between prototype and control samples (Figure 24 a & b). For the mushrooms, while measurements were performed on two packs of 5 mushrooms, both packs measured for each batch had a similar behavior and relatively close values. Thus the same trend than for the leafy greens applied (Figure 24c). For the white asparagus, the differences in weight loss were less obvious, even if they seemed to follow the same trend than the other products (Figure 24d).

Due to the lower RH around the prototype samples, opposite results were expected. Such a trend could be explained by a reduction of the respiration and transpiration mechanisms with CAS, leading to lower weight losses. This trend would be expected to be even more pronounced if products were to be tested at a similar RH. Hence, CA on the short-term seemed to have a consequent impact on water loss, an important quality attribute for leafy greens (Jung *et al*, 2012). This could explain the better visual quality of prototype samples after 72h for chicories and mushrooms, as weight loss is strongly linked to senescence phenomena like browning of the leaves (Nunes & Emond, 2007).

Moreover, when looking more closely at the evolution of the weight loss rate, daily weight losses decreased for control samples over time, while they remained lower and constant for prototype samples. This trend was observed for all leafy greens and mushrooms. Following this trend, if the experiments were to be continued for longer periods, weight loss rate could become similar between prototype and control samples. This means that the solution might be particularly adapted to short storage periods. One possible explanation for the higher weight loss rate of control samples in the first 24 hours of storage could be due to an important respiration peak.

Finally, organic lettuce and mushrooms weight losses, around 8% of the initial weight after 72h, were noticeably more important compared to other products' losses. For the mushrooms, storing the samples under the prototype allowed to reduce total loss of 5% in 3 days. This could have a great financial impact for the consumers and retailers.

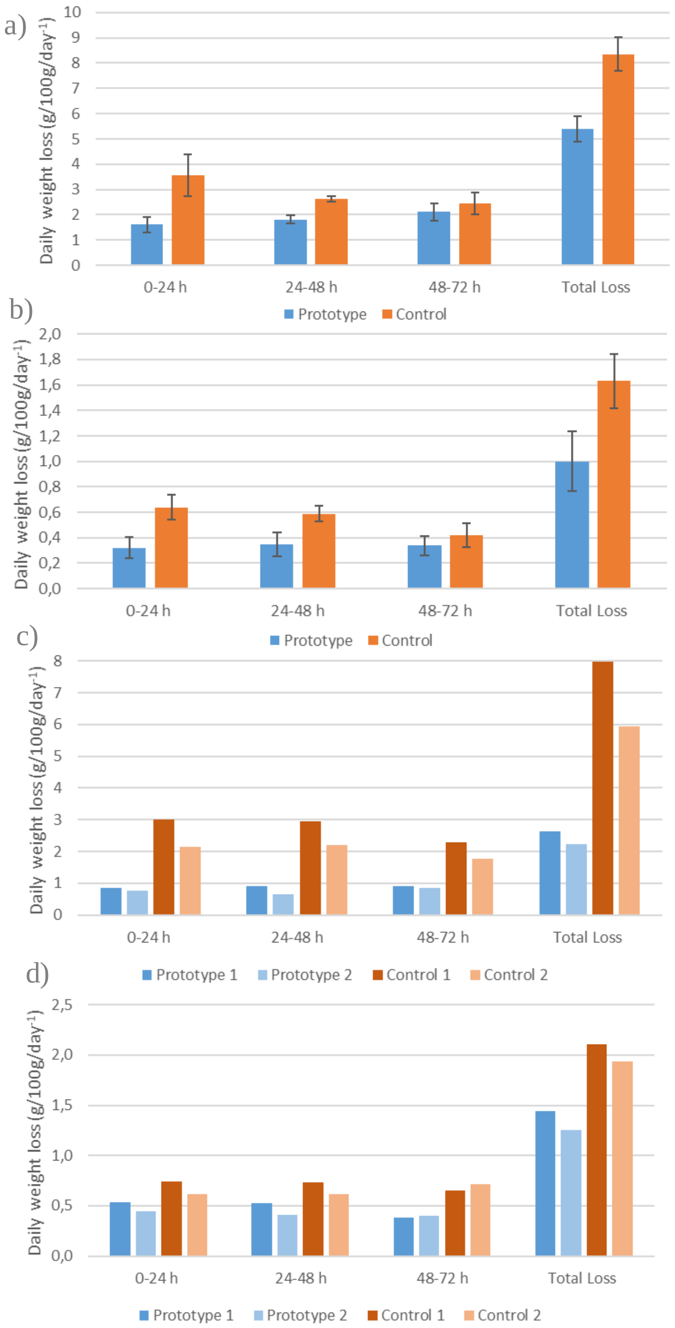


Figure 24: Organic lettuce (a), chicory (b), mushrooms (c) and white asparagus (d) daily weight loss rate evolution over 3 days of storage – *Weight loss is calculated on the same samples over time. A different number of samples are considered for each F&V per batch: 5 lettuces (a), 7 chicories (b), 2 containers of 5 mushrooms (c) & 2 containers of 5 asparagus.*

Strawberries

For strawberries, while there seemed to be no influence of the modified atmosphere on weight loss of the Ciflorette strawberries, tested in duplicate 1, a negative impact of the prototype on weight loss rate could be observed for the Gariguette variety, with 1% more weight loss on the prototype samples after one week of storage (Figure 25). This could be due to the lower RH in the prototype compared to the RH of the control sample.

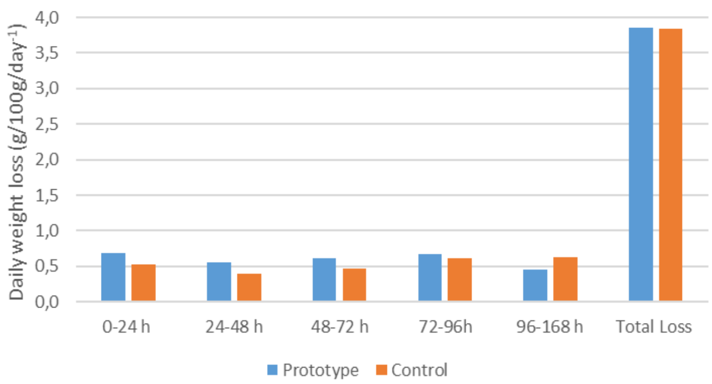
Grapes

No trend could be drawn from the weight loss evolution of grapes, as only two bags of grapes per batch were analyzed and the results between both bags of a same batch were not comparable. Differences between samples from a same batch were as important as difference between batches (Appendix K).

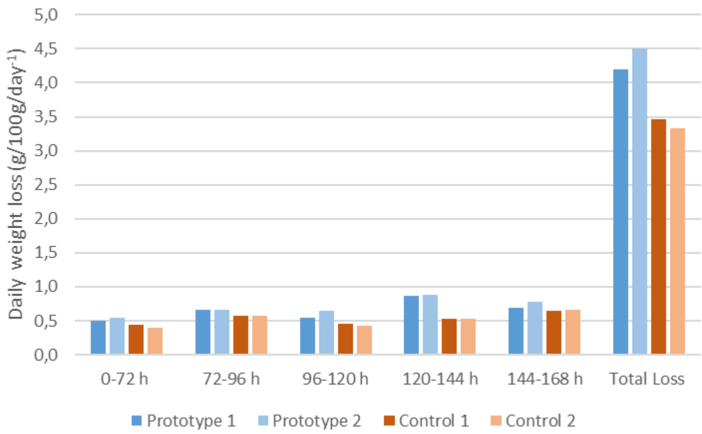
Raspberries

No noticeable difference could be observed between prototype and control samples over time (Appendix L).

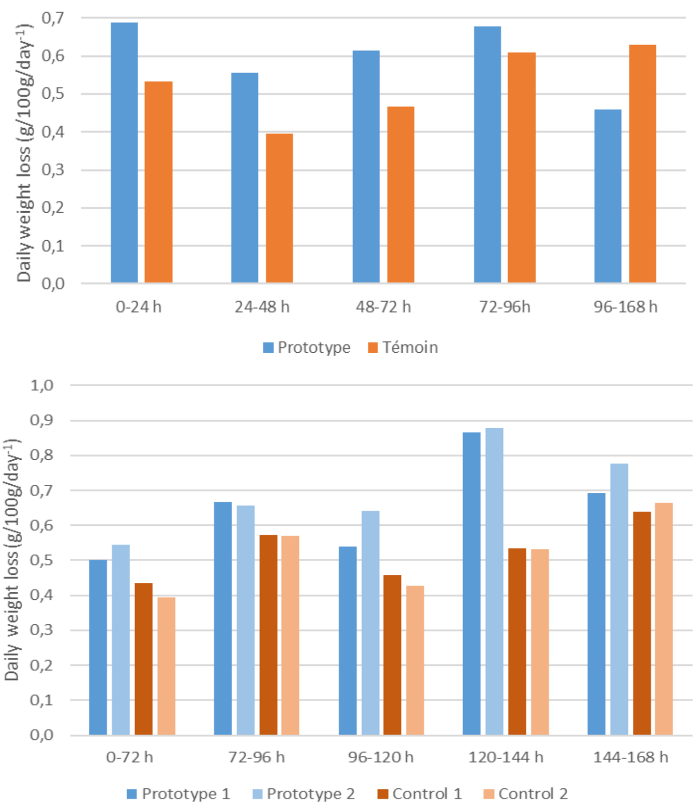
a)



b)



c)



d)

Figure 25 : Ciflorette strawberries (a), Gariguette strawberries (b) weight loss rate evolution over 7 days of storage (zoom of Figure 25a (c) and zoom of Figure 25b (d)) – *Weight loss is calculated on the same samples over time. A different number of samples are considered for each duplicate per batch: 1 container with 15 strawberries (a), 2 containers with 10 strawberries (b).*

4.2.3.2 Firmness

No noticeable trends were observed concerning firmness of most F&V, most likely due to the high intrinsic variability of samples and experimental errors due to the texture analyzer. However, storage under the prototype seemed to have had a positive effect on strawberries' texture, which could also be observed manually (Figure 26). A harder texture for prototype samples could be due to a delayed ripening of the fruit thanks to high CO_2 concentrations, causing a slower hydrolysis of the cell walls of the fruits (Larsen & Watkins, 1995). A harder texture would be an advantage for retailers, as it could prevent strawberries from being damaged under physical stress during manipulation in retail stores and help reduce food waste.

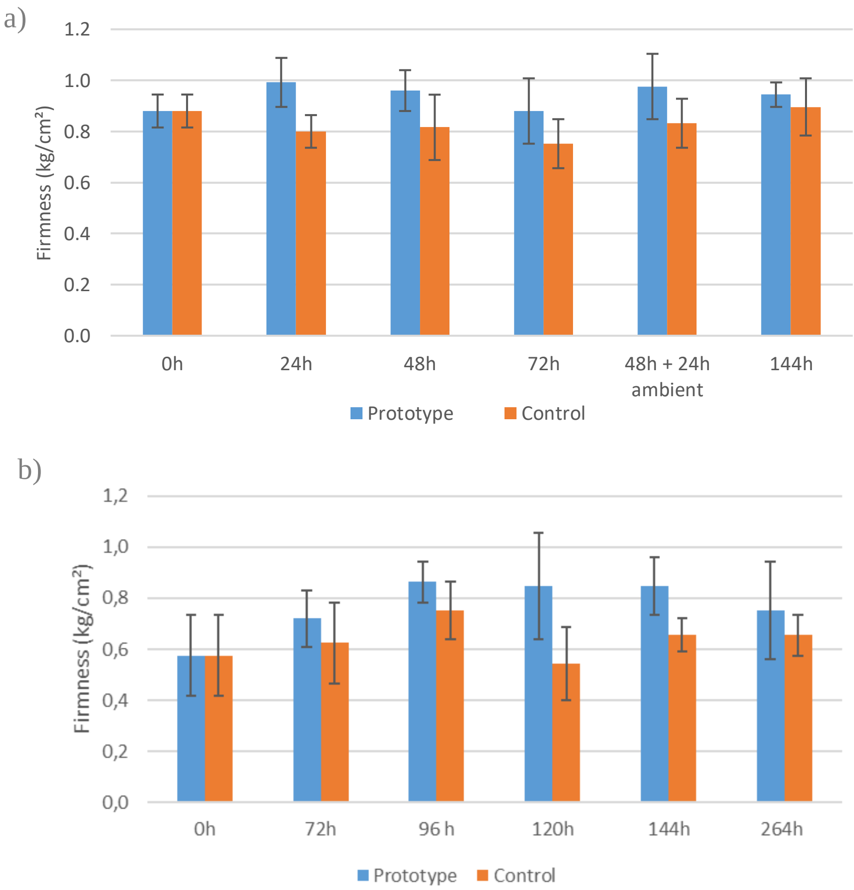


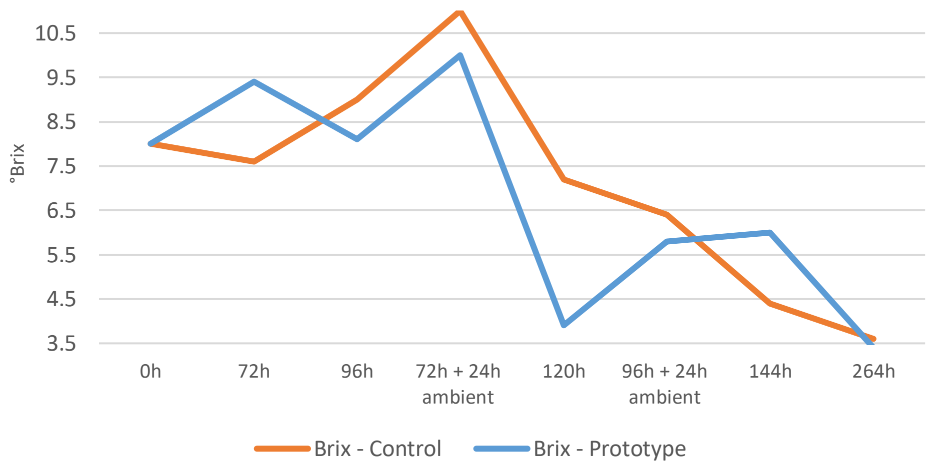
Figure 26: Strawberry texture analysis with Durofel equipment – Figure 26a: Duplicate 1 after cold storage / Figure 26b: Duplicate 2 after cold storage - *Firmness measurement weredone on 10 strawberries per batch and per time*

4.2.3.3 Brix level and pH

For the grapes and Ciflorette strawberries, no difference was noticed in term of Brix level between the prototype and control samples, and values remained constant with time (Appendix M).

Concerning the raspberries, no difference between prototype and control samples was noticed, however a noticeable decrease in sugar level could be observed over time, from 7,5 to 3,5°Brix (Figure 27). This could be due to important ripening reactions, consuming the available sucrose and decreasing the overall raspberry quality as seen previously.

Concerning the Gariguette strawberries, there seemed to be an increase in °Brix for the control samples with time. This does not necessarily mean that the total sugar level increased, but could be due to an apparent increase in sugar concentration in the fruit caused by a consequent weight loss (5% in 11 days).



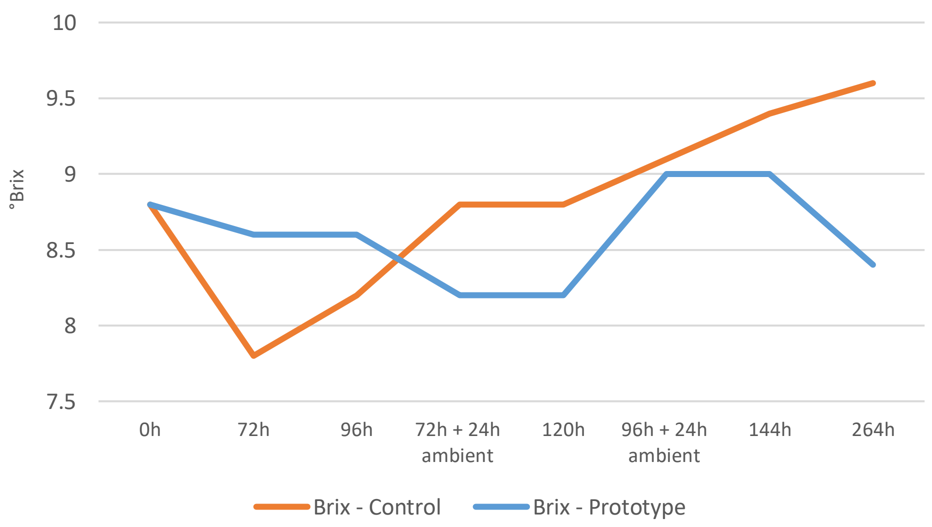


Figure 27: Total sugar level evolution – Figure 27a: Raspberries / Figure 27b: Gariguette strawberries (Duplicate 2)

4.2.3.4 Nutrient analysis

There was no consistent difference between samples in time and between prototype and control batches regarding total sugar content and vitamin C concentration (Figure 28). The overall total sugar content, around 7g/100 mL was coherent with normal values found in strawberries, between 5.5 and 11g/100 mL (Kallio *et al*, 2000). This was slightly lower than the values found with the refractometer which were approximatively 2 degrees Brix higher. As HPLC is a more reliable and precise measurement, this indicated that Brix values determined with the refractometer were slightly overestimated. The concentration of vitamin C, around 60mg/100mL, fitted with usual vitamin C content in strawberries ranging from 50 to 100mg/100mL (Hägg *et al.*, 1995).

These results were contradictory with what was found in the literature review, as maturation and respiration of fruits was supposed to degrade partially the available sugars and vitamin C. No difference over time could mean either the respiration reactions were not significant, or the decrease in sugars and vitamin C already occurred before reception of the products during the post-harvest phase. It could also be an apparent value, showing similar concentrations over time due to a joint effect of decrease in nutrient with decrease of weight, while the absolute content in nutrients would have decreased.

	Témoin		72 heures				96 heures				*p*
	Récolte		Témoin		Proto		Témoin		Proto		
Matière sèche (%)	10.0 (0.4)		10.3 (0.1)		10.1 (0.1)		10.6 (0.1)		10.7 (0.2)		0.1329
Sucres (g/100g)											
Saccharose	2.2 (0.1)	a	1.8 (0.1)	c	2.0 (0.1)	bc	2.1 (0.1)	ab	2.1 (0.1)	ab	0.0117
Glucose	2.0 (0.1)	c	2.1 (0.1)	b	2.2 (0.1)	b	2.2 (0.1)	b	2.3 (0.1)	a	0.0238
Fructose	2.4 (0.1)	d	2.6 (0.1)	bc	2.6 (0.1)	c	2.7 (0.1)	ab	2.7 (0.1)	a	0.0277
Total	**6.5 (0.2)**	**c**	**6.6 (0.1)**	**c**	**6.7 (0.2)**	**bc**	**7.0 (0.1)**	**ab**	**7.2 (0.1)**	**a**	**0.0311**
Vitamine C (mg/100g)											
Acide ascorbique	54.7 (2.7)		57.5 (0.7)		53.6 (0.3)		58.6 (2.9)		57.4 (1.5)		0.0931
Acide déhydroascorbique	2.4 (0.2)		2.1 (0.2)		2.2 (0.1)		2.4 (0.2)		2.6 (0.1)		0.3365
Total	**57.1 (2.5)**		**59.6 (0.9)**		**55.8 (0.4)**		**61.0 (2.7)**		**60.0 (1.3)**		**0.1192**

Moyenne (n=2) et écart-type entre parenthèses. Les valeurs avec des lettres différentes sont significativement différentes (Duncan test, p<0.05)

Figure 28: Dry matter, total sugar content and vitamin C concentration of Gariguette strawberries - Samples stored for 0, 72, and 96h at cold storage (4°C), chemical analysis done by HPLC **-** *In the table, "Témoin" refers to control samples and "Proto" to prototype samples. 3Matière sèche" stands for "dry matter" and "saccharose" for sucrose. Between parenthesis are indicated the standard deviations, and values with different letters (a,b or c) are significantly different using a Duncan test, p<0.05.*

4.2.4 **Conclusions**

Overall, CA storage for short periods of time had a positive effect on quality for leafy greens and mushrooms, allowing to extend shelf-life after 72h of cold storage for chicories and mushrooms by saving up to 100% of the products for chicories after 96h of cold storage. The differences in visual quality between batches could be explained by higher respiration rate for control samples, leading to a more important weight loss causing increased browning and higher deterioration. (Nunes & Emond, 2007)

For strawberries, a better firmness of the prototype samples indicated a slower ripening under CA storage conditions. This was confirmed by the visual quality evaluation, where no difference between control and prototype samples could be explained by a negative impact of lower RH for prototype samples compensated by a positive impact of CA slowing down maturation. Finally, the more important weight loss for prototype samples was explained by lower RH storage conditions. Hence, if both batches were to be stored at the same RH, the shelf-life of prototype samples would potentially be extended, with a slower decrease in quality over time for prototype samples.

Eventually, CA storage for short periods of time was not adapted for grapes, which presented a high heterogeneity between samples and did not present any decrease in quality over 10 days of experiments.

4.3 Eco-efficiency analysis

From a business perspective, while efficacy of the solution is a pre-requisite, financial viability is essential to be able to both generate profit for the company and value for the consumers. Moreover, in the current context, a solution will be viable on the long-term only if its impact on the environment is limited and positive. This section focuses only on the financially viability of the current prototype for the consumers, and the impact of its production and implementation on several environmental indicators.

4.3.1 **Cost analysis**

It was considered that avoiding food waste would prevent retailers from losing their investment to buy the products and allow them on the contrary to make a margin they would not have made if the products had been wasted. Hence, the positive financial impact of avoiding food waste for the retailers was equal to the selling price of the products in retail stores (investments + margin).

The quantities to be saved daily to compensate the cost of the daily gas consumption were overall important, ranging from 4% of the volume capacity of the prototype to be saved per day for strawberries to 125% for lettuces (Figure 29). These high values were due to an important gas consumption during the day, both during initial injections and intermittent gas flushing.

The values were compared to the amount of F&V that could be saved by the prototype as described in part 4.2. For chicory, CA storage had the capacity to save 60% of the volume contained in the prototype in 72h and 100% in 96h, while respectively 100% and 150% of the volume contained in the prototype needed to be saved in 72h and 96h to compensate costs-in-use when considering conventional chicory, and respectively 30% and 40% when considering organic chicories. Hence, the current solution would be financially viable only for organic chicories.

In a similar way, for mushrooms, CA storage had the capacity to save 40% of the volume contained in the prototype in 72h and 60% in 96h, while respectively 160% and 220% of the volume contained in the prototype needed to be saved in 72h and 96h to compensate costs-in-use when considering conventional mushrooms, and respectively 50% and 70% when considering organic mushrooms. Hence, the prototype seemed not to be financially viable for mushrooms with the current daily gas consumption.

Finally, for high margin products like strawberries and raspberries, whose shelf-life could be potentially extended by using CA storage with an appropriate level of RH, values around 15% of the volume capacity of the prototype needed to be saved in 72h were found. These values could realistically be achieved, and represent an encouraging result for the future.

Fruits & Vegetables	*% of prototype's volume capacity to be saved per day*	*Quantity that can be stored in the prototype (in kg or units for salad)*
Lettuce (France)	126,3	120
Organic lettuce (France)	72,7	120
Mushrooms (Champignons de Paris)	54,5	72
Organic mushrooms (Champignons de Paris)	17,2	80
Chicory (France)	36,9	165
Organic chicory (France)	9,2	165
White asparagus (France)	9,7	150
White asparagus – Low quality (France)	26,6	150
Strawberries Gariguette	5,2	162
Organic strawberries	3,9	162
Strawberries Ciflorette	5,6	162
White grapes (export)	11,0	172
Raspberries	5,8	113
Organic raspberries	3,5	113

Figure 29: Quantity of F&V to be saved per day to compensate financially the daily gas consumption- *Results were calculated using the cost of the daily gas consumption using Air Liquide L50 cylinders and the average cost for each F&V based on the prices in 5 French retail stores (Appendix D) To convert in % of prototype's volume capacity, a prototype filled with only one kind of F&V was considered (Appendix E). Products whose shelf-life could be extended by the prototype (see Part 4.2) were circled in orange.*

Overall, CA storage using the prototype was financially viable only for organic chicories and potentially strawberries. These results were totally dependent on the current size and gas consumption of the prototype. Hence, these results are only valid for the current experiment, and are subject to change at the industrial scale with different sizes and different airtightness solutions.

4.3.2 Environmental analysis

The environmental impact of several F&V production (strawberries, lettuce and white asparagus) and of the daily gas consumption by the prototype were calculated for four different indicators (Appendix N & O). It appeared that daily gas consumption under environment 1 conditions had an overall more important environmental impact than under environment 2, due to the difference in gas composition between both environments. From these values, the minimal quantity (in % of the total amount of F&V that can be stored under the prototype) of F&V that must be saved per day by the prototype to compensate the impact of its daily gas consumption was determined (Figure 30).

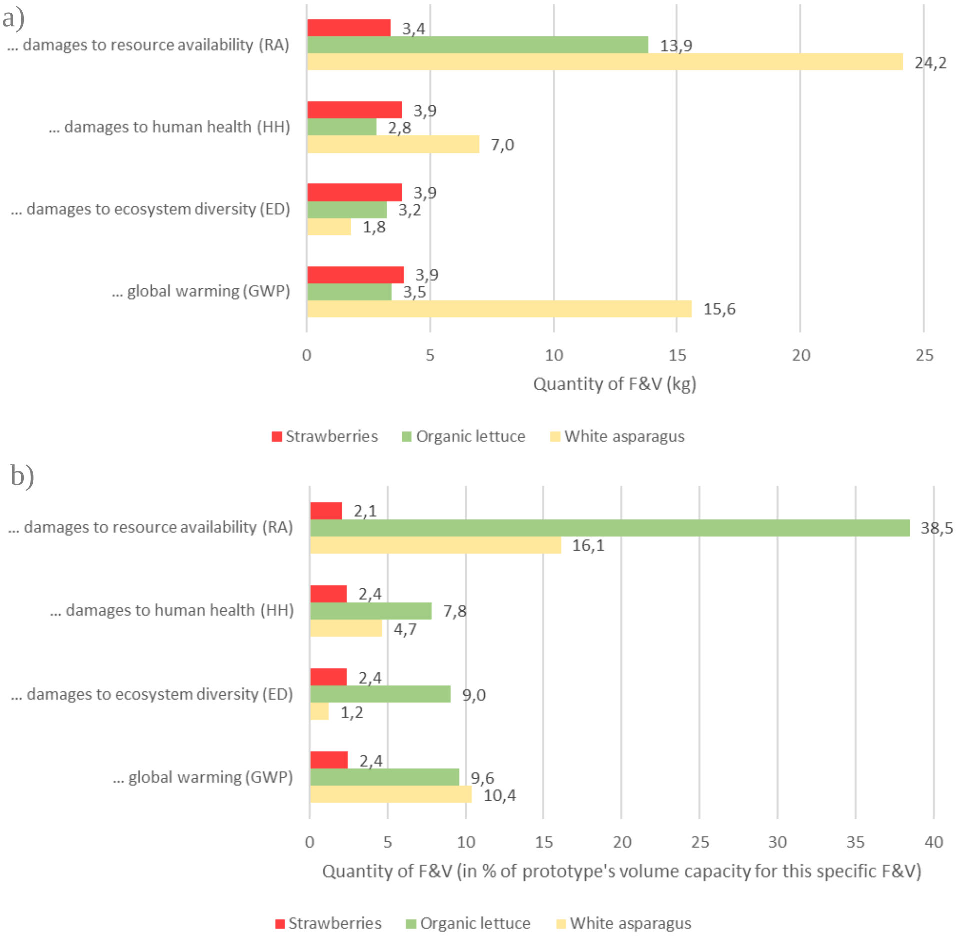


Figure 30 a & b: Food waste to be avoided per day for different F&V to compensate the environmental impacts of the prototype's daily gas consumption – Figure 30a: Quantity in kg/ Figure 30b: Quantity in % of volume capacity of the prototype - *A higher quantity in kg for a product indicates a lower impact of this product on this specific indicator compared to the other products. Impact category should not be compared between themselves.*

White asparagus presented noticeably higher values in kg than the other products for RA, HH and GWP (Figure 30a). This indicated that other fruits' production were more impactful than white asparagus production for these indicators. This could be explained by the important impact of heating in the greenhouse for strawberries and cooled storage for lettuce. On the contrary, all F&V considered here presented a similar impact on ED. This was due to land occupation and use of fertilizers and pesticides, which impact greatly soil and water quality. This impact might vary depending on the type of agricultural practice used, organic farming being for instance as impactful on GWP than conventional agriculture but requiring more land and causing higher water eutrophication (Clark & Tilman, 2017).

The quantity of products needed to compensate the daily gas consumption varied greatly depending on the impact category considered. This was due to the relative difference between the impact of daily gas consumption on this category and the impact of this F&V production. The quantities found for one F&V for different impact categories were not comparable, as the impact categories are using different units and are considering different environmental issues.

To conclude on the actual environmental impact of the prototype, it was important to relate the quantities to be saved to their share in volume in the prototype and thus express them in % of volume capacity (Figure 30b). In order to have an overall positive impact on all four impact categories considered, different minimal amounts must be saved daily for strawberries, asparagus and lettuce, respectively 2,4% of the prototype capacity, 16,1% and 38,5%. For strawberries, the quantity to be saved seemed achievable (15% for 72h of storage) and could potentially be reached if CA storage was done in optimal RH conditions. For asparagus and salad, for which no shelf-life extension potential was identified, the quantities to be saved were more important, and unreachable for lettuce after 72h of storage, with more than 100% of the quantity stored under the prototype that should be saved to achieve a positive environmental impact.

When considering only GWP, which is often the first impact category considered when evaluating environmental impact, lower quantities of products must be saved daily by the prototype to achieve a positive impact, with only 30% of the volume capacity needed to be saved in 72h for lettuce and asparagus.

Environmental impact on mushrooms and chicories were not performed due to a lack of data concerning these products in the Ecoinvent 3.4 database.

5 Conclusions and further research

5.1 Conclusions

This study was motivated by the F&V waste in European retails, representing around 10% of the overall F&V production and caused by a dissatisfaction of consumers with the freshness and visual quality of the F&V. In answer to this problem, this study served as an exploratory work on the influence of CAS combined with optimal temperature and relative humidity on F&V quality and its potential to extend F&V shelf-life for short-term preservation periods. This study was based on the use of an innovative prototype that was developed by Air Liquide to tackle food waste in retail stores' cold rooms. Different materials were investigated to ensure the prototype's ability to reach the desired gas composition, qualitative and quantitative evaluations were performed on seven different F&V to assess the impact of the prototype on F&V quality and shelf-life extension compared to current storage conditions, and financial and environmental impacts of the prototype were established.

Results pointed out that PP016 material, plastic laminate made of PET/Aluminium/PA/LDPE, was the best suited material from the three preselected materials by Air Liquide for use on the long term. It presented excellent barrier properties, good puncture strength and good folding endurance. For this specific application, folding endurance was the most crucial parameter. Considering water vapor and gas barrier properties was not sufficient, as some materials like PPCC1 were found not to be adapted for long periods of use due to formation of micro-leaks and perforations after repeated folding while they had satisfying barrier properties.

Concerning the efficacy of the solution, CAS positively impacted the quality of certain F&V and was able to extend their shelf-life after three days of storage. CAS allowed to extend the shelf-life of chicories and mushrooms by saving up to 100% of the products that could be stored in the prototype for chicories after 96h of cold storage, and up to 60% for mushrooms after 96h of cold storage. Differences in visual quality compared to control samples could be explained by a higher respiration rate for control samples, responsible for the more important weight loss and increased browning observed.

Moreover, CAS could potentially affect the quality of strawberries positively, with a better firmness of the prototype samples indicating a slower ripening. This was confirmed by the visual quality evaluation, where no difference between control and prototype samples was explained by a negative impact of lower RH for prototype samples compensated by a positive impact of slower maturation. In optimal RH conditions, shelf-life of strawberries is expected to be extended.

For salads and asparagus, CAS allowed to reduce weight loss but did not significantly affect visual quality. Finally, CAS for short periods of time was not adapted for grapes, which did not present any decrease in quality in 10 days.

Last but not least, with the current gas consumption, CAS using the prototype developed by Air Liquide proved to be financially viable for organic chicories and high-value added product like berries. For organic chicories, the quantity of products to be saved to compensate the cost of daily gas consumption was lower than the amount of chicories that had been saved by the prototype after 72h during the experiments. This was not the case for mushrooms, for which the viable amount of product to save to compensate the current daily gas consumption was too important. For strawberries, whose shelf-life could be potentially extended by using CA storage with an appropriate level of RH, values around 15% of the volume capacity of prototype needed to be saved in 72h were found, which could realistically be achieved. This represents an encouraging result for the future.

Similar conclusions were drawn for the environmental analysis, with a positive environmental impact of the prototype potentially achievable for strawberries with the current gas consumption, while negative impacts were observed for asparagus and lettuce when considering four different environmental indicators based on GHG emissions, human health, resource availability and ecosystem diversity. When considering only GWP, realistic amounts of products to be saved daily by the prototype to achieve a positive environmental impact were found, with only 30% of the volume capacity of the prototype to be saved in 72h for asparagus and lettuce.

In conclusion, this study confirmed that CAS combined with optimal temperature and humidity conditions had a positive impact on the quality of vegetables sensitive to browning and berries for short-term preservation periods. The prototype was able to extend the shelf-life of chicories, mushrooms and potentially strawberries after 3 days of storage. With its current gas consumption, the prototype was only financially viable for small F&V with high-added value, like berries or organic products, and its environmental impact potentially negative for most of the F&V when considering four impact indicators except for strawberries.

5.2 Further research

Recommendations for improving the prototype

Materials

Firstly, new transparent materials with a high folding endurance could be investigated, as none of the three preselected materials combined both high folding endurance and transparency, which are required to resist repeating cycles of use and allow operators in supermarkets to directly see the products. Another solution would be to develop a digital interface to inform the operator of the content of the prototype and replace direct visual inspection of the products.

Gas consumption

One of the main observation of this study was the important gas consumption required to maintain a constant atmosphere composition in the prototype, which compromised the financial viability and positive environmental impact of the solution for storage of certain F&V. Reducing gas consumption is a challenge for further development, and could be achieved by modifying the gas composition, reducing the injection flow rate or combining CAS with passive MAP.

Relative humidity

This study suffered from the difference in RH between prototype and control samples, affecting the capacity to conclude on the impact of CA on F&V preservation. An embedded humidification system inside the prototype to monitor the humidity thoroughly could be implemented to tackle this issue.

Further research to overcome delimitations and constraints

Shelf-life assessment

For assessing shelf-life and determining the grades, a trained panel could be used to strengthen the results and avoid bias linked to a one-person evaluation.

Moreover, during the qualitative and quantitative evaluation of F&V quality, one essential quality attribute was omitted due to lack of resources: taste. It would be interesting to assess the impact of CAS on taste, as it could have a significant influence on consumer's retention for retailers.

Experimental constraints

During the experiment, duplicates could not be performed at the same time as there was only one prototype available. Comparable duplicates were compromised in this study due to differences in initial maturity, variety and origin of the products between experiments. Sourcing products directly from a farmer to ensure same variety and same maturity at the beginning of each experiment would help implement real duplicates and strengthen the results.

Finally, this study only allowed to identify the products that could potentially be impacted by CAS for short storage periods and define trends.A following study focusing solely on promising products like strawberries, chicories and mushrooms, would allow to confirm or disprove the trends observed in this thesis work and obtain results that could be statistically analyzed.

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Appendices

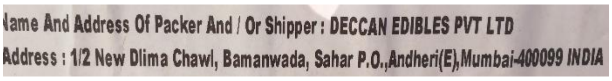
Appendix A: Varieties of F&V per environment and duplicate – Labels and information of origin

Environment 1	*Duplicate 1*	*Duplicate 2*
Organic lettuce - Category I 	✓	
Organic lettuce - Category II 		✓
Chicory 	✓	✓
White asparagus 	✓	✓
Mushrooms – Champignon de Paris	✓	✓

<table>
<tr><th>Environment 2</th><th>Duplicate 1</th><th>Duplicate 2</th></tr>
<tr><td>Strawberries - Ciflorette

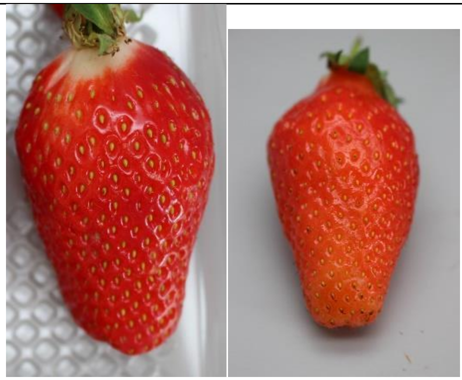
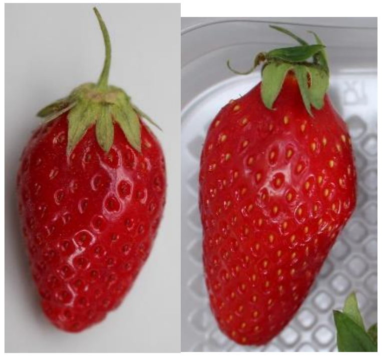
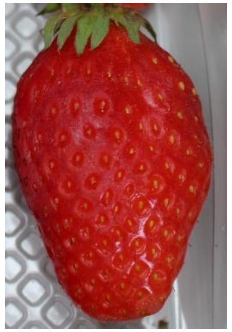


</td><td>✓</td><td></td></tr>
<tr><td>Strawberries-Gariguette

</td><td></td><td>✓</td></tr>
<tr><td>White grapes – South Africa</td><td>✓</td><td></td></tr>
<tr><td>White grapes – India

</td><td></td><td>✓</td></tr>
<tr><td>Raspberries</td><td></td><td>✓</td></tr>
</table>

Appendix B: Grading scales for F&V visual evaluation (*based on Nunes & Emond (2007)*)

RASPBERRIES		 		 
Description of the grade	Firm, juicy, round opening of the fruit	Soft in some parts, overall semi-soft, some drupelets with a light pink color round opening of the fruit	Overall soft, fragile when touched, flat opening of the fruit	Overall soft and not juicy, many drupelets with a light pink color, flat opening of the fruit
GRADE	**GRADE 1**	**GRADE 2**	**GRADE 3**	**GRADE 4**

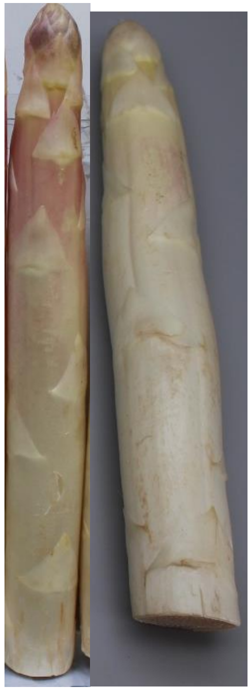
STRAWBERRIES				
Description of the grade	Bright color (from light orange-red to red), very firm and turgid, no appearing bruises and soft areas, shining surface	Light to dark red color, firm with rare softer areas visible, shining surface	Moderately firm with several softer areas, mat surface	Visibly deteriorated fruits, soft and leaky, mat surface
GRADE	**GRADE 1**	**GRADE 2**	**GRADE 3**	**GRADE 4**

GRAPES				
Description of the grade	Bright color (light green to green), shining surface, no decay	Warm color (green to yellow green), shining surface, no decay	Grapes with brown color, some grains start shriveling, mat surface, no decay	Presence of decay, brown color, shriveled grains, mat surface
GRADE	**GRADE 1**	**GRADE 2**	**GRADE 3**	**GRADE 4**

ORGANIC LETTUCE	 	 	 	
Description of the grade	Fresh cut appearance with light green color, leaves are very firm, turgid and brittle.	Overall firm and crunchy leaves, with some starting to lose turgidity	Leaves are limp and lost turgidity, moderate leaf discoloration with yellow-brown areas	Evident loss of turgidity, leaves are very soft, limp and bendy
GRADE	**GRADE 1**	**GRADE 2**	**GRADE 3**	**GRADE 4**

CHICORY				
Description of the grade	Fresh cut appearance with white leaf edges and no trace of green or reddish discoloration; very brittle, firm and turgid, leaves are tightly attached to each other and head is very compact	Slight discoloration, less white with some darker yellow spots and brown leaf edges; slight signs of head softness.	Moderate discoloration with brown leaf edges and yellow-green leaves or red discoloration ; loss of turgidity with some signs of softness	Important discoloration (visible browning or green leaves); clearly lose external leaves.
GRADE	**GRADE 1**	**GRADE 2**	**GRADE 3**	**GRADE 4**

MUSHROOMS				
Description of the grade	White and smooth glossy cap surface, stipe and gills, no sign or very slight signs of browning	Light brownish creamy surface, less glossy, slight browning, no appearing gills	Brownish surface, slight brown stipe, gills slightly exposed	Shriveled surface, gills exposed
GRADE	**GRADE 1**	**GRADE 2**	**GRADE 3**	**GRADE 4**

WHITE ASPARAGUS				
Description of the grade	Tender and firm, fresh, white stem and bracts	White stem, some browning on the bracts	Browning on the stem and the bracts	Visible wrinkles on the stem, browning on the stem and bracts
GRADE	**GRADE 1**	**GRADE 2**	**GRADE 3**	**GRADE 4**

Appendix C: Questionnaire for assessing consumer purchase intent and visual difference between samples

Link to the questionnaire:

https://docs.google.com/forms/d/e/1FAIpQLSc7C74FNT0IrerH40aHvAyRKgwgS0Y_-3NzXQsVjAhxpCxyCQ/viewform?usp=sf_link


Strawberries - Purchase Intent

You will first be presented several pictures of strawberries. For each picture, select Yes if you would buy it and No if you would not buy it.

P1 - Would you buy this product? *

YES

NO

If the answer is No, explain your choice

Purchase intent questionnaire – Sample question

Consumers were successively shown individual pictures of different grades for each product, reproducing a monadic sequential test. This setup allows to partially limit comparison between samples and be as close as possible as conditions of in retail stores.

Chicory - Visual Evaluation

You will now be presented pairs of pictures. Please tell if you see a difference between the two pictures, and if yes select the sample you prefer (A or B) and explain why.

P1 - Do you notice a difference in quality between the two set of products? *

A

B

YES

NO

If yes, which sample has the best quality?

A

Difference evaluation questionnaire – Sample question

Here, a comparative test of two sets of samples collected at the same time (prototype and control) was proposed to the consumers. This direct comparison allowed to exacerbate the differences and identify differences between products.

Appendix D: F&V price evaluation – *Based on the prices given by Auchan, Carrefour, Géant Casino, HyperU and ELeclerc for online grocery shopping in May 2019. First the corresponding product reference are presented, followed by their prices.*

Product reference on the retailer website	***Auchan***	***Carrefour***	***Géant Casino***	***HyperU***	***ELeclerc***
Lettuce (France)	Laitue pièce	Laitue pièce			Laitue pièce
Organic lettuce (France)		Laitue BIO	Salade Laitue		
Mushrooms (Champignons de Paris)	Champignons blancs pied entiers - 300g	Champignons Blanc pieds coupés au kg	Champignons de Paris Cat 1 Sans résidus 200g	Champignons blonds pied coupés France	Champignons de Paris au kg
Organic mushrooms (Champignons de Paris)		Champignons blancs Bio Barquette 250g	Champignons blancs Bio Hollande Cat 1 200g		
Chicory (France)	Endives sachet 1kg	Endives sachet 1kg	Endives Cat 1 France	Endives du Nord France à la pièce	Endive kg
Organic chicory (France)	Endives BIO Sachet 300g	Endives BIO Sachet 300g	Endives BIO France Sachet 300g		
White asparagus (France)	Asperges violettes 500g	Asperges blanches REFLETS DE France			
White asparagus low quality (France)		Asperges blanches botte 1kg	Asperges blanches/violettes calibre 12/16 Cat 1 Botte 500 kg		

Price in EURO per kg or unit for salad	***Auchan***	***Carrefour***	***Géant Casino***	***HyperU***	***ELeclerc***	***AVERAGE PRICE in Euro***
Lettuce (France)	0,99	0,99	0,99		1,2	***1,04***
Organic lettuce (France)		1,81				***1,81***
Mushrooms (Champignons de Paris)	3,3	3	4,95	4,9	3,99	***4,03***
Organic Mushrooms (Champignons de Paris)		11,45	11,45			***11,45***
Chicory (France)	2,49	2,49	2,4	3,3	2,29	***2,59***
Organic Chicory (France)	11,63	8	11,63			***10,42***
White asparagus (France)	9,98	11,8				***10,89***
White asparagus low quality (France)		2,95	4,98			***3,97***

Product references and average prices for the vegetables tested during the experimental phase

Product reference on the retailer website	***Auchan***	***Carrefour***	***Géant Casino***	***HyperU***	***ELeclerc***
Strawberries Gariguette	Fraises Gariguette Barquette 400g France	Gariguette Label Rouge Barquette 250g	Fraises Gariguette CAT 1 France Barquette 250 g		Fraises Gariguette France 250g
Organic strawberries	Fraises BIO Barquette 250g		Fraises BIO CAT 1 France Barquette 250 g		
Strawberries Ciflorette		Fraise Ciflorette Carrefour Barquette 250g			Fraises Ciflorette France 250g
White grapes (export)	Raisin mixte sans pépins barquette 500g - AFS	Raisins blancs sans pépin Danlas Barquette 500g	Raisins blancs sans pépinCat 1 Inde		
Raspberries	barquette 125g Espagne	Framboises france Barquette 125g			Framboises Barquette 125g
Organic raspberries	Barquette 65g Espagne	Framboises Bio Espagne Barquette 125g	Framboises Cat 2 Bio Espagne Barquette 125g		

Price in EURO per kg or unit for salad	***Auchan***	***Carrefour***	***Géant Casino***	***HyperU***	***ELeclerc***	***AVERAGE PRICE in Euro***
Strawberries Gariguette	11,22	16,8	13,96		11,8	13,44
Organic strawberries	19,96		15,96			17,96
Strawberries Ciflorette		13,56			11,2	12,38
White grapes (export)	5,98	5	7			5,99
Raspberries	14,32	15,28			22,4	17,33
Organic raspberries	38,31	23,92	23,92			28,71

Product references and average prices for the fruits tested during the experimental phase

Appendix E: Volume capacity of the prototype for each F&V – *Based on a total available volume of 0,48 m^{3}in the prototype and secondary packaging sizes used by wholesaler.*

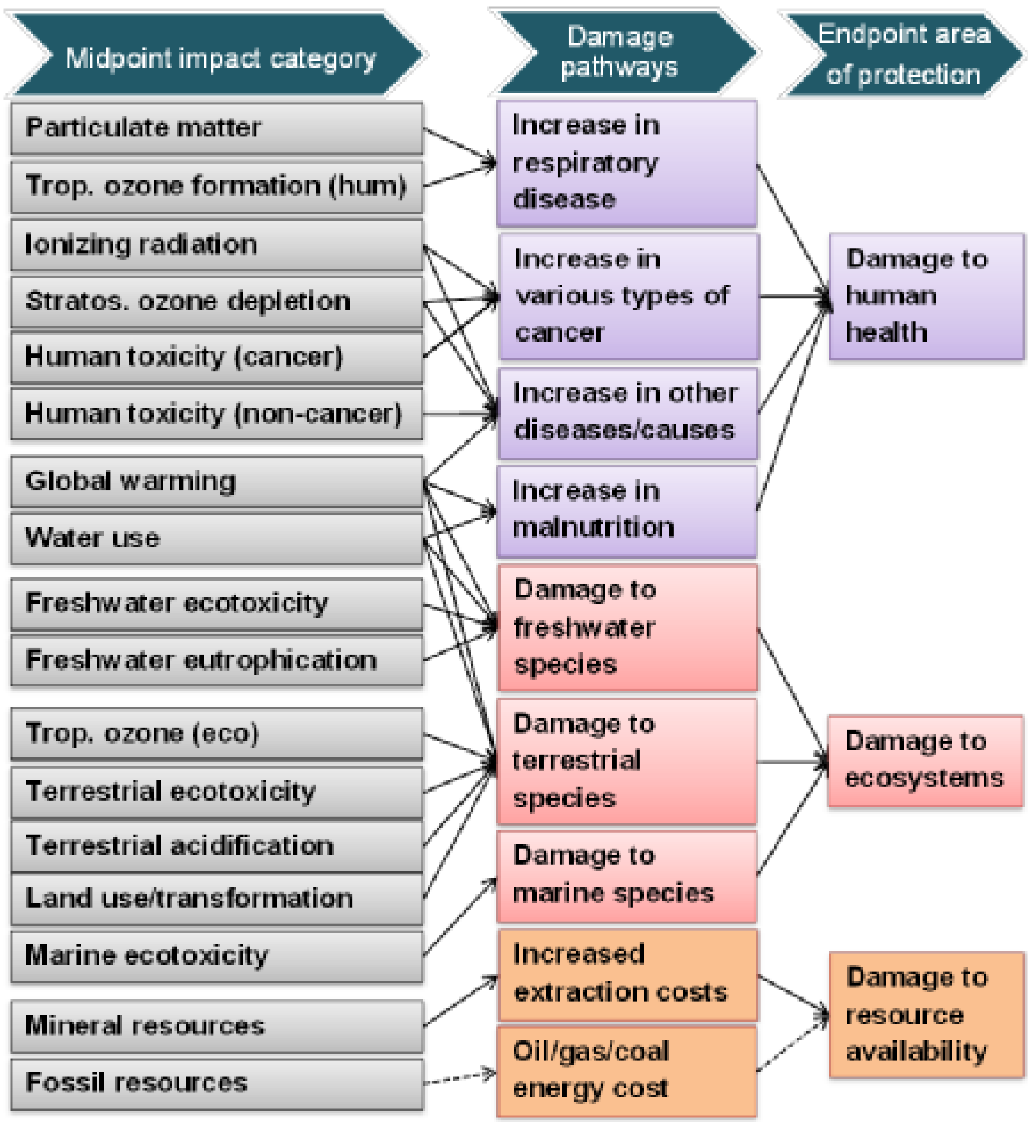
	Quantity (kg or unit)	***Corresponding volume in the prototype (% of total available volume)***
Strawberries (250g pack)	1 KG	0,62
Raspberries (125g pack)	1 KG	0,88
Grapes (500g pack)	1 KG	0,58
Salad (Wooden crate 60*40cm)	1 UNIT	0,83
Chicory (5kg cardboard box)	1 KG	0,61
Mushrooms (2kg cardboard box)	1 KG	1,39
White asparagus (5kg cardboard box)	1 KG	0,67

For the fruits, products were considered to be stored in PET trays of standard sizes with lids of 30 mm height. Those trays were considered to be stored under the prototype in crates E-6423 of dimension 600x400x240mm.

For vegetables, conventional sizes of secondary packages adapted to each product were considered, using Prince de Bretagne catalogue.

Appendix F: Overview of the ReCiPe indicators structure

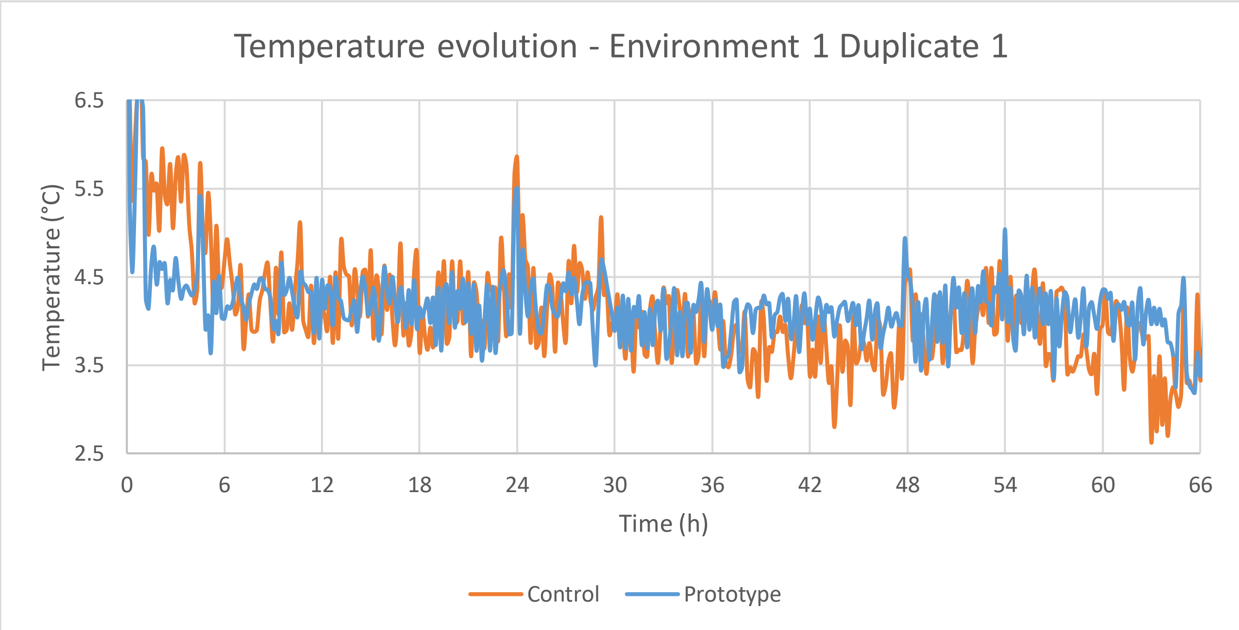
– *Midpoint impact category factors, usually used in LCIA, have been combined into three holistic endpoint indicators.*

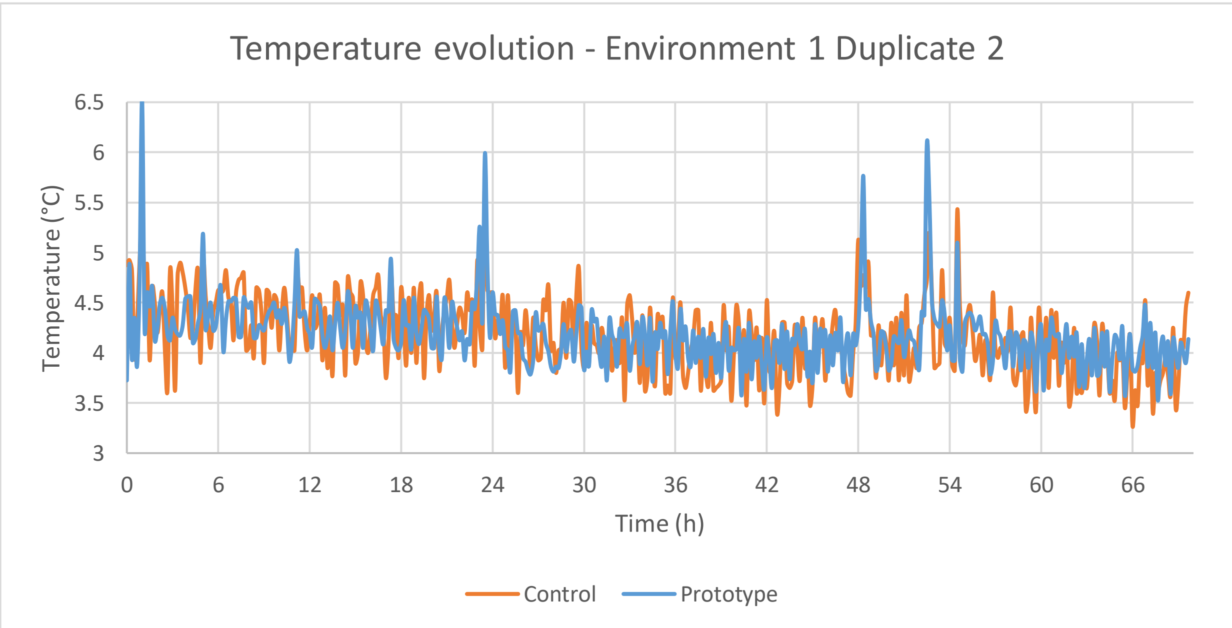


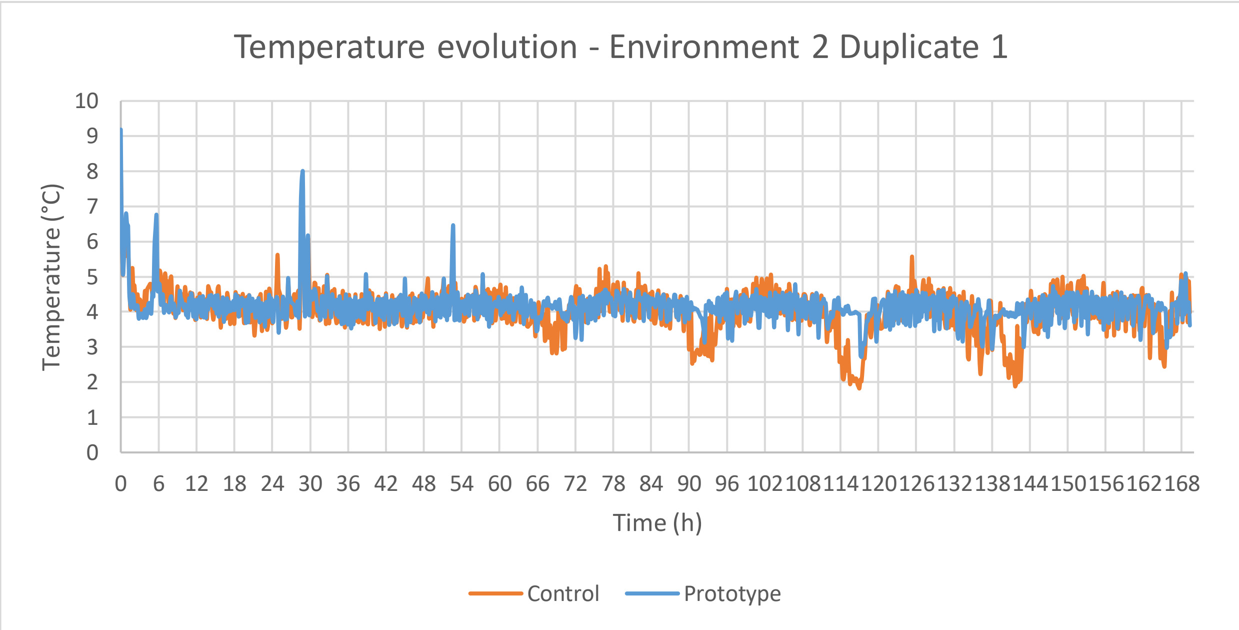
Appendix G: Plastic laminates' data sheet (ProtoPack, 2019)

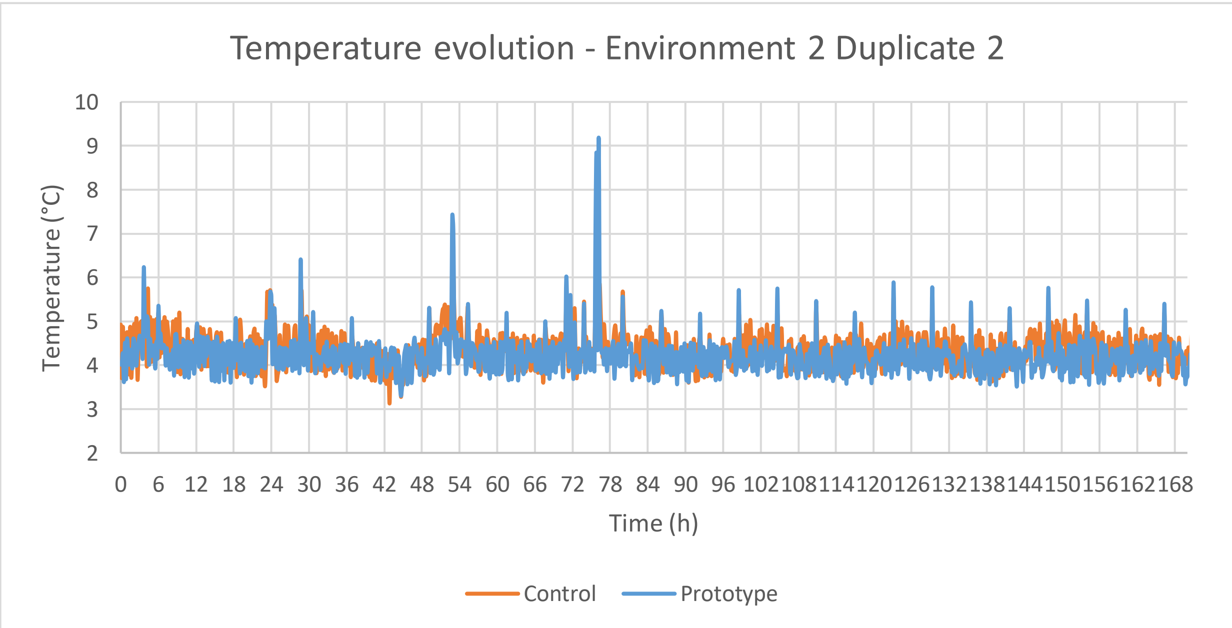
	Unit	**PP016**	**PP12110**	**PPCC1**
Composition		*PET/Alu/PA/ LDPE*	*Metalised PET/LDPE*	*CPET/PVDC/LLD PE*
Heat Seal Strength	N	>100-110/25mm	>65/25mm	>60/25mm
Tensile strength	N	160-175/25mm	116/25mm	>300/25mm
Tear strength - Machine direction	N	36/25mm	18/25mm	90/25mm
Puncture resistance	N	105	66	56
OTR (O2 Transmission rate)	g/m²/24hr	<0,006	<0,8	1
WVTR (Water vapour transmission rate)	g/m²/24hr	<0,05	<0,03	<0,5

Appendix H: Temperature evolution during experimental phase

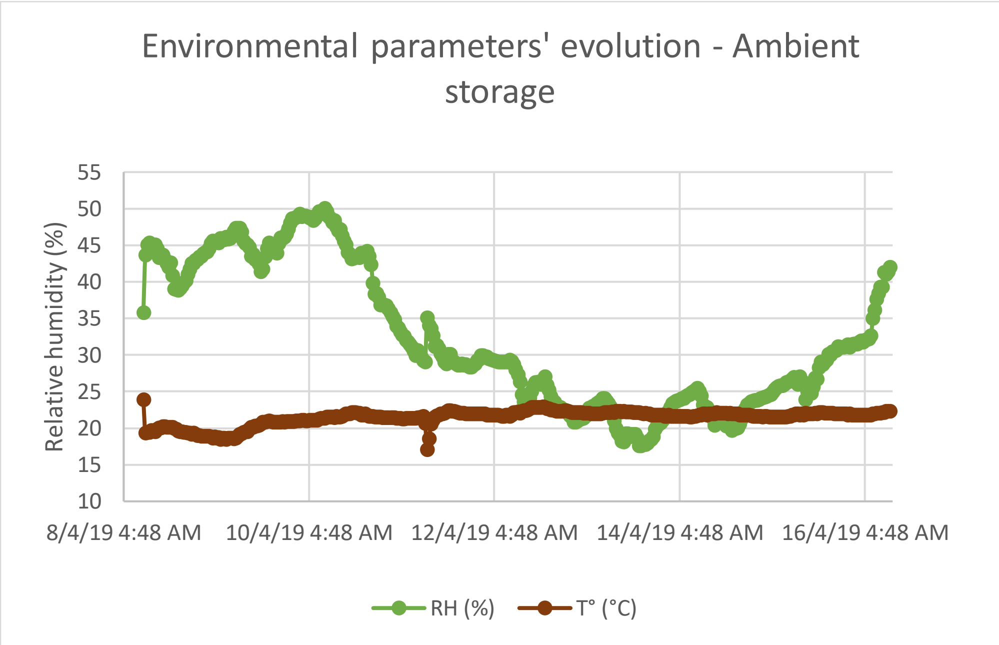





Temperature evolution - Environment 2 Duplicate 1
Temperature (°C)
10
9
8
7
6
5
4
3
2
1
0
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96 102 108 114 120 126 132 138 144 150 156 162 168
Time (h)
Control
Prototype


Temperature evolution - Environment 2 Duplicate 2
Temperature (°C)
10
9
8
7
6
5
4
3
2
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96 102 108 114 120 126 132 138 144 150 156 162 168
Time (h)
Control
Prototype

Appendix I: Environmental parameters' evolution during storage at ambient conditions



Appendix J: Difference observed by consumers for selected control and prototype samples – *Pictures of several samples of F&V from each batch (prototype & control) collected at the same time were presented to consumers via an online questionnaire*

Strawberries	*% of consumers noticing a difference*	*% of consumers preferring sample A*	*% of consumers preferring sample B*	*Preferred sample*
Duplicate 1 Ciflorette - 48H (A: Prototype / B: Control)	✗ 22,00	54,55	45,45	
Duplicate 1 Ciflorette - 72H+24H ambient (A: Prototype / B: Control)	✓ 60,00	66,67	33,33	*Prototype*
Duplicate 1 Ciflorette - 72H+24H ambient (A: Prototype / B: Control)	✗ 18,00	77,78	33,33	
Duplicate 1 Ciflorette - 96H (A: Prototype / B: Control)	✗ 6,00	33,33	66,67	
Duplicate 2 Gariguette - 72H (A: Prototype / B: Control)	! 42,00	42,86	57,14	*Control*

Chicory	*% of consumers noticing a difference*	*% of consumers preferring sample A*	*% of consumers preferring sample B*	*Preferred sample*
Duplicate 1 - 24H (A: Prototype B: Control)	✗ 16,00	75,00	25,00	
Duplicate 1 - 72H (A: Prototype / B: Control)	✓ 84,00	100,00	0,00	*Prototype*
Duplicate 1 - 72H+24H (A: Control / B: Prototype)	✓ 80,00	0,00	100,00	*Prototype*
Duplicate 1 - 96H (A: Control / B: Prototype)	✗ 28,00	78,57	21,43	
Duplicate 2 - 72H (A: Control / B: Prototype)	✗ 14,00	100,00	0,00	

Raspberries	*% of consumers noticing a difference*	*% of consumers preferring sample A*	*% of consumers preferring sample B*	*Preferred sample*
72H (A: Control/ B: Prototype)	✗ 16,00	87,50	12,50	
144H (A: Prototype / B: Control)	✗ 18,00	88,89	11,11	

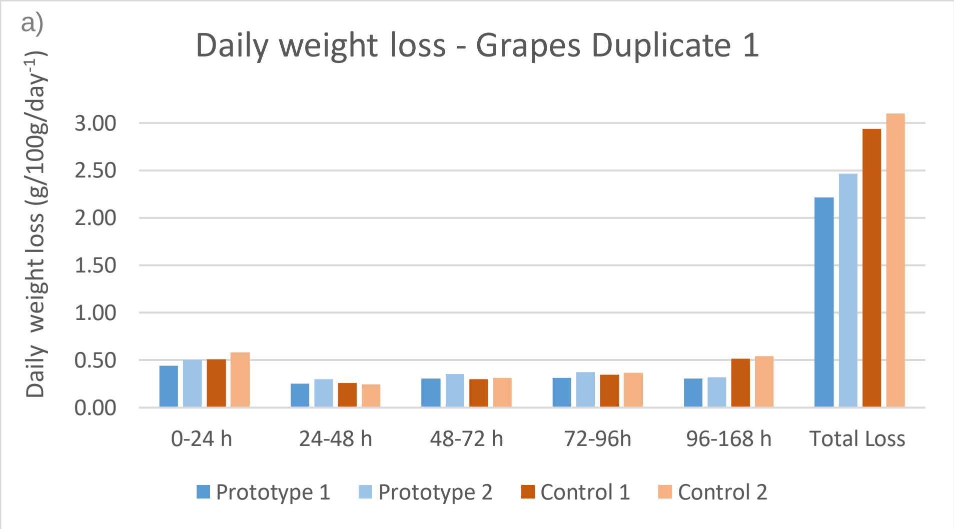
Grapes	*% of consumers noticing a difference*	*% of consumers preferring sample A*	*% of consumers preferring sample B*	*Preferred sample*
Duplicate 1 - 48H (A: Control/ B: Prototype)	! 48,00	91,67	12,50	*Control*
Duplicate 1 - 48H (A: Control/ B: Prototype)	✗ 26,00	61,54	38,46	
Duplicate 1 - 72H+24H ambient (A: Prototype / B: Control)	✓ 66,00	96,97	3,03	*Prototype*

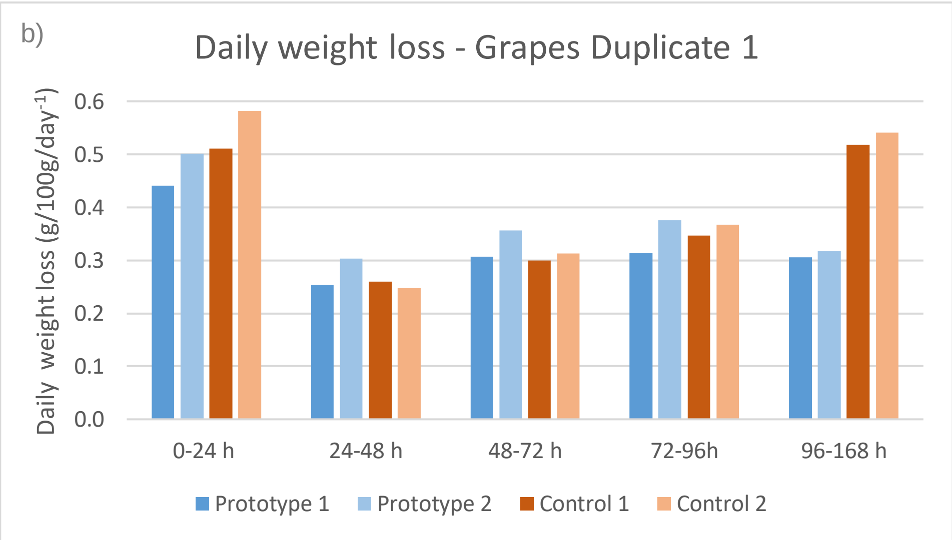
Mushrooms	*% of consumers noticing a difference*	*% of consumers preferring sample A*	*% of consumers preferring sample B*	*Preferred sample*
Duplicate 1 - 48H (A: Control / B: Prototype)	! 42,00	9,52	90,48	*Prototype*
Duplicate 1 - 72H (A: Prototype / B: Control)	✓ 68,00	100,00	0,00	*Prototype*
Duplicate 1 - 72H+24H (A: Control / B: Prototype)	! 42,00	9,52	95,24	*Prototype*
Duplicate 1 - 96H (A: Control / B: Prototype)	✓ 88,00	0,00	97,73	*Prototype*
Duplicate 2 - 72H (A: Prototype / B: Control)	✗ 20,00	80,00	20,00	
Duplicate 2 - 48H (A: Prototype / B: Control)	✗ 10,00	40,00	60,00	

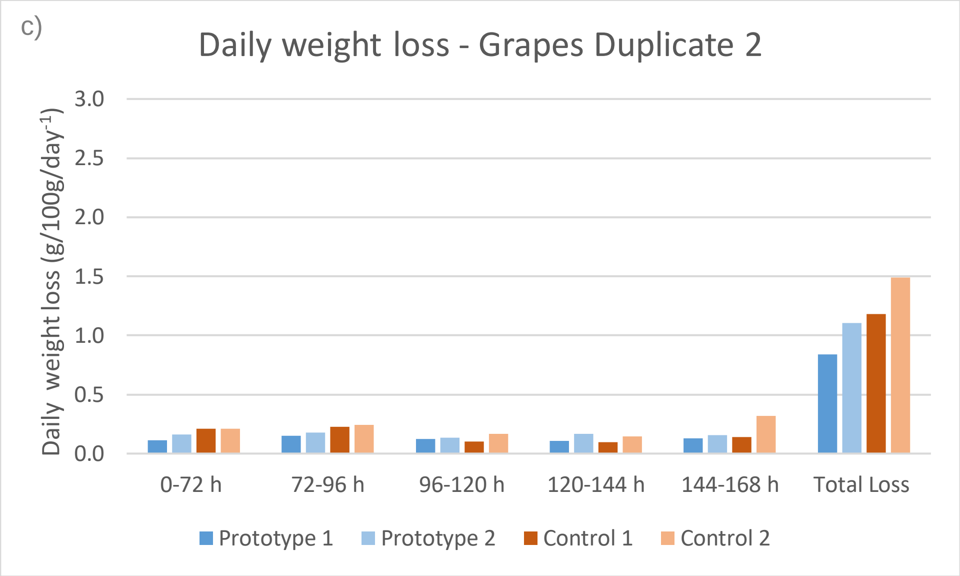
Salades	*% of consumers noticing a difference*	*% of consumers preferring sample A*	*% of consumers preferring sample B*	*Preferred sample*
Duplicate 1 - 72H (A: Prototype / B: Control)	✗ 24,00	83,33	8,33	
Duplicate 1 - 96H (A: Prototype / B: Control)	✗ 18,00	44,44	44,44	
Duplicate 2 - 72H (A: Prototype / B: Control)	✗ 20,00	40,00	50,00	

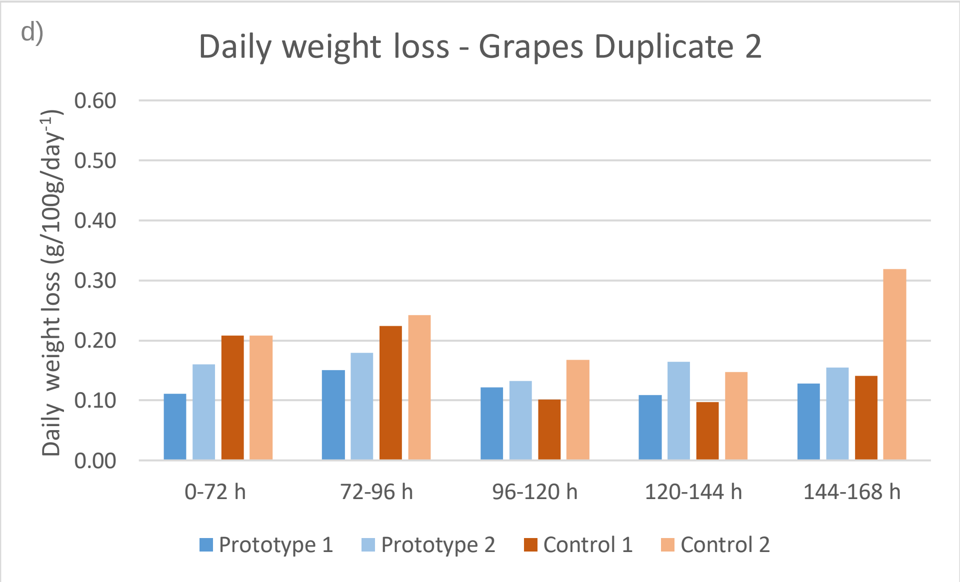
Asparagus	*% of consumers noticing a difference*	*% of consumers preferring sample A*	*% of consumers preferring sample B*	*Preferred sample*
Duplicate 1 - 48H (A: Prototype / B: Control)	✗ 2,00	100,00	0,00	
Duplicate 1 - 48H+24H (A: Prototype / B: Control)	✗ 30,00	80,00	13,33	
Duplicate 1 - 72H (A:Control / B: Prototype)	✗ 18,00	33,33	66,67	
Duplicate 1 - 72H+24H (A: Prototype / B: Control)	✗ 4,00	50,00	50,00	
Duplicate 2 - 48H (A:Control / B: Prototype)	✗ 0,00	/	/	
Duplicate 2 - 48H+24H (A: Prototype / B: Control)	✗ 10,00	20,00	80,00	
Duplicate 2 - 72H (A: Prototype / B: Control)	✗ 4,00	100,00	0,00	

Appendix K: Daily weight loss for grapes – *Appendix Ka & Kb for duplicate 1 (Kb is a zoom of Ka) and appendix Kc & Kd for duplicate 2 (Fc is a zoom of Fd)*

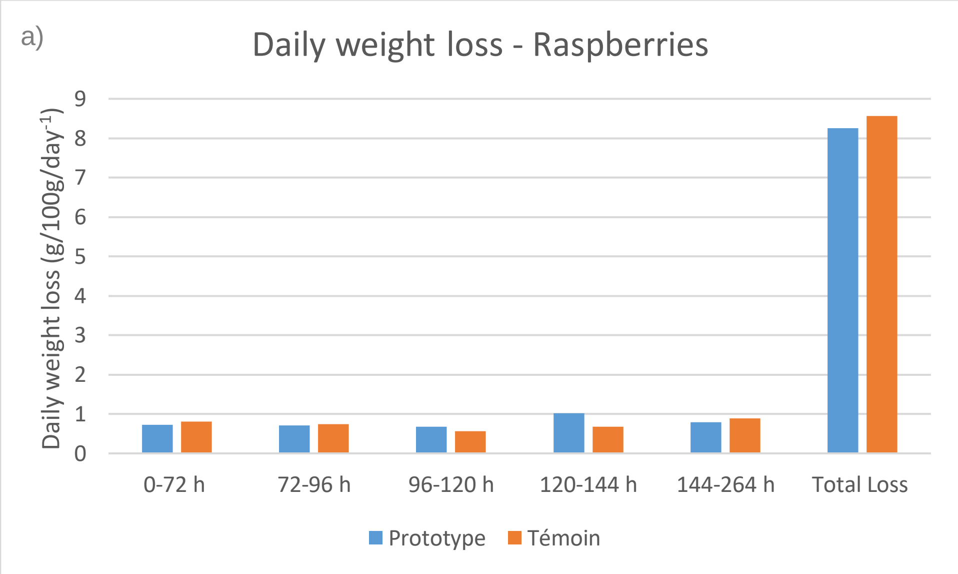


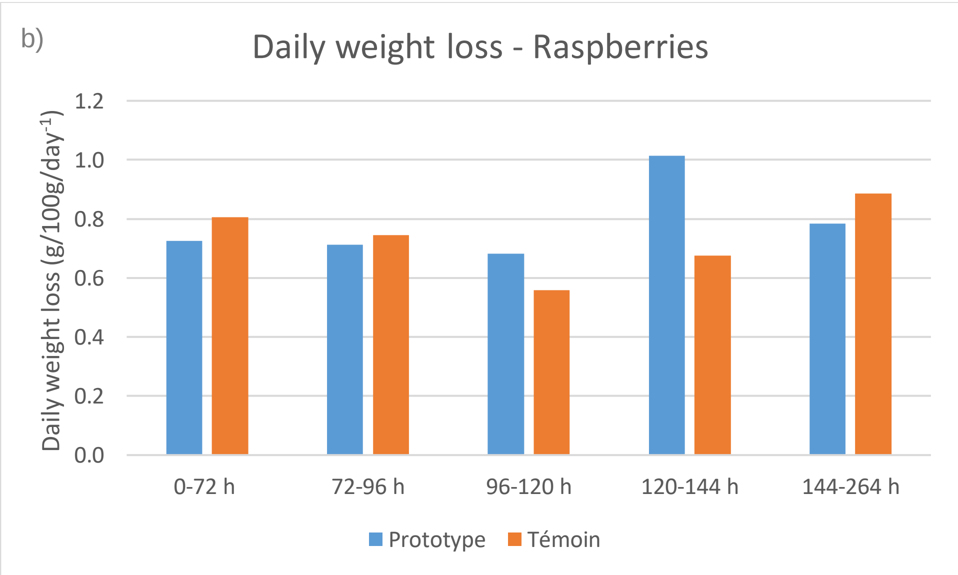



c)
Daily weight loss - Grapes Duplicate 2
Daily weight loss (g/100g/day-1)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0-72 h
72-96 h
96-120 h
120-144 h
144-168 h
Total Loss
Prototype 1
Prototype 2
Control 1
Control 2

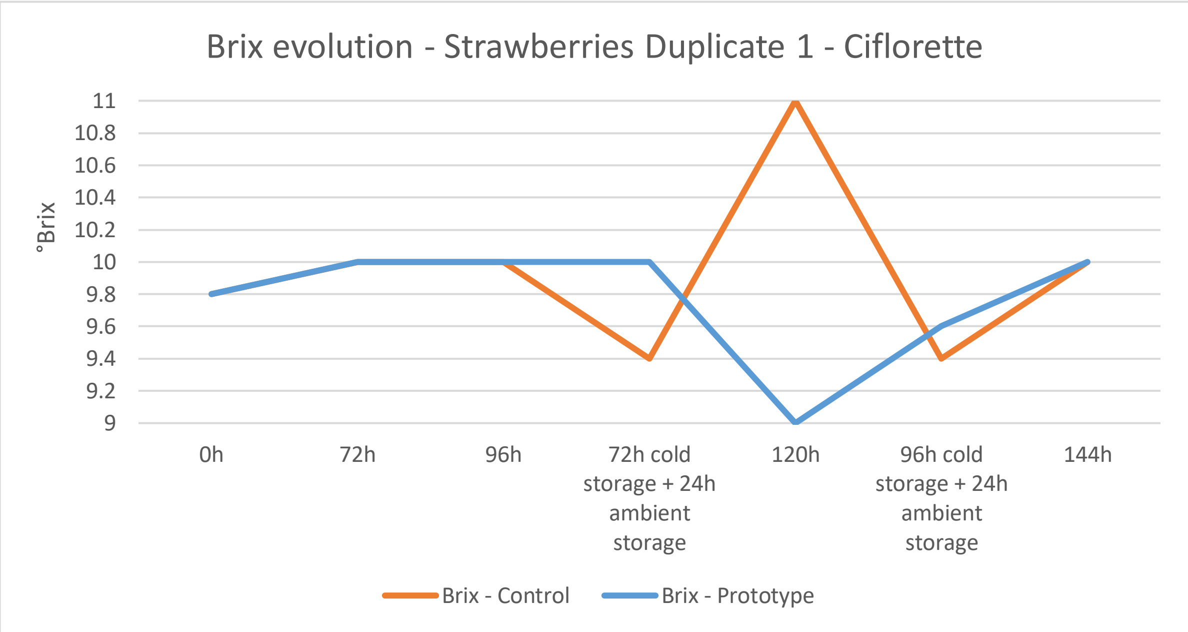

d)
Daily weight loss - Grapes Duplicate 2
Daily weight loss (g/100g/day-1)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0-72 h
72-96 h
96-120 h
120-144 h
144-168 h
Prototype 1
Prototype 2
Control 1
Control 2

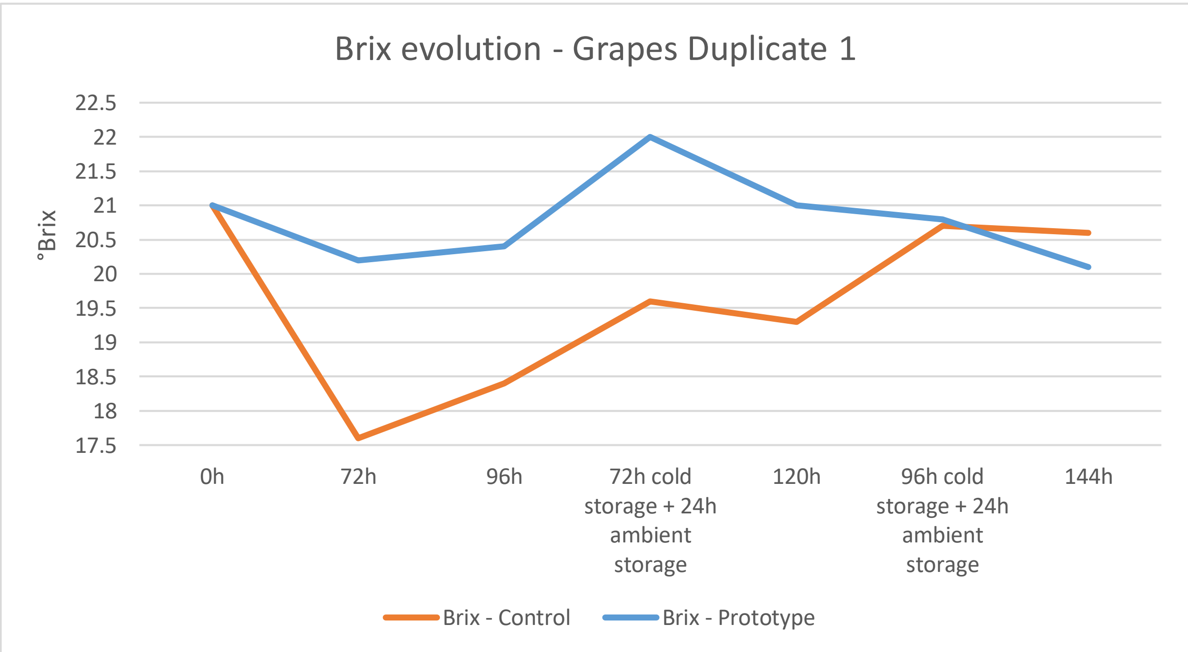
Appendix L: Daily weight loss for raspberries– *Weight loss was measured on only one pack of 100g of raspberries due to time and financial constraints – Results presented here are trends (Appendix Lb is a zoom of La)*

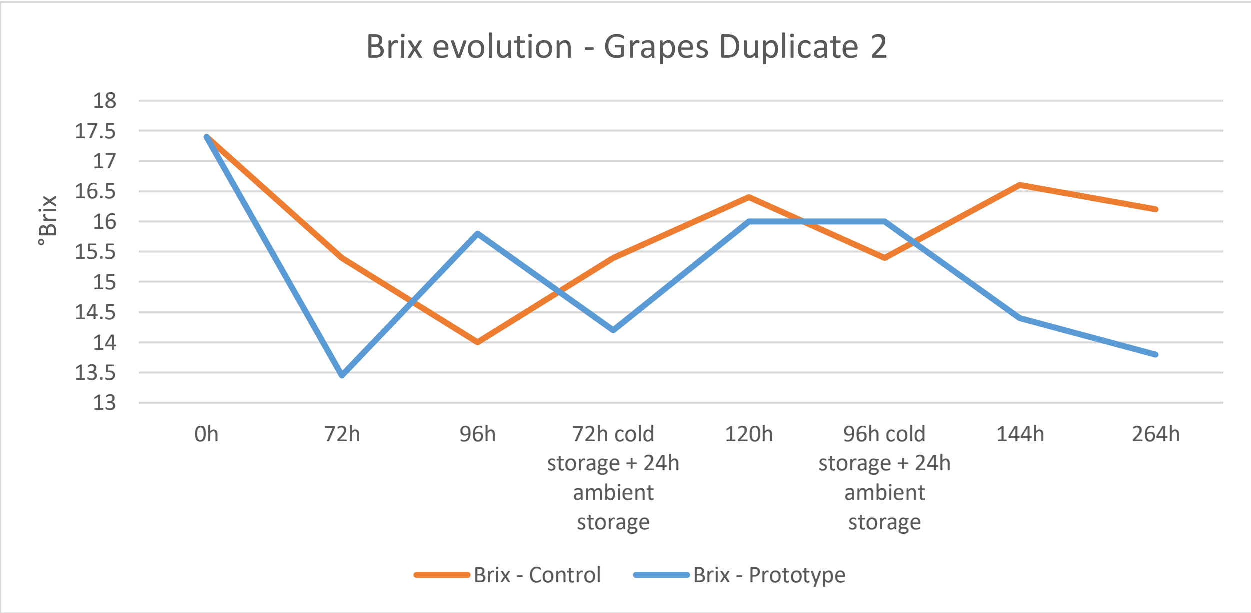




Appendix M: Brix level evolution – Strawberries & Raspberries






Brix evolution - Grapes Duplicate 2
°Brix
18
17.5
17
16.5
16
15.5
15
14.5
14
13.5
13
0h
72h
96h
72h cold storage + 24h ambient storage
120h
96h cold storage + 24h ambient storage
144h
264h
Brix - Control
Brix - Prototype

Appendix N: Environmental impact evaluation of the daily gas consumption by the prototype for environment 1 and 2 – *Four impact categories were considered: Global Warming Potential (GWP), Damage to Ecosystem Diversity (ED) measured in loss of species per yeardue to climate change, Damage to Human Health (HH) measured in years of life lost and disabled due to climate change, and Damage to Resource availability (RA) measured in increased cost for resources in USD.*

Environmental impact for 24h of use	***Environment 1***	***Environment 2***
GWP (in kg CO2eq)	1,30E+01	1,15E+01
ED (in species/year)	5,60E-08	4,59E-08
HH (in DALY)	2,21E-05	1,77E-05
RA (in USD)	1,66E+00	1,16E+00

Appendix O: Environmental impact evaluation of several fruits & vegetables

Environmental impact per kg of F&V	**White asparagus**	**Organic lettuce**	**Strawberries**
GWP (in kg CO2eq)	8,36E-01	3,78E+00	2,93E+00
ED (in species/year)	3,10E-08	1,72E-08	1,19E-08
HH (in DALY)	3,16E-06	7,83E-06	4,56E-06
RA (in USD)	6,87E-02	1,20E-01	3,40E-01