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Eco-conception du couple “ Emballage sous atmosphère modifiée Chaîne du froid ” pour minimiser l’impact post-récolte des fruits et légumes frais

Céline Matar

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THÈSE POUR OBTENIR LE GRADE DE DOCTEUR DE MONTPELLIER SUPAGRO

En Génie des Procédés

École doctorale : GAIA – Biodiversité, Agriculture, Alimentation, Environnement, Terre, Eau

Portée par l'Université de Montpellier

“Eco-design of Modified Atmosphere Packaging coupled with chilled chain system for minimizing the environmental impact of post-harvest chain of fresh fruit and vegetables”

“Eco-conception du couple emballage sous atmosphère modifiée chaîne du froid pour minimiser l'impact post-récolte des fruits et légumes frais”

Présentée par Céline MATAR

Le 21 Septembre 2018

Sous la direction de Valérie GUILLARD, Stéphane GUILBERT et Sébastien GAUCEL

Devant le jury composé de

M. Bruno DE MEULENAER	Full professor, Ghent University	Rapporteur
Mme. Rosalba LANCIOTTI	Associate professor, Bologna University	Rapporteur
Mme. Marie ALMINGER	Full professor, Chalmers University	Examineur
Mme. Christelle WISNIEWSKI	Full professor, Montpellier University	Présidente du Jury
Mme. Valérie GUILLARD	Associate Professor, Montpellier University	Directeur de thèse
M. Sébastien GAUCEL	Research Engineer, INRA Montpellier	Co-encadrant



UNIVERSITÉ
DE MONTPELLIER



PhD Title:

“Eco-design of Modified Atmosphere Packaging coupled with chilled chain system for minimizing the environmental impact of post-harvest stages of fresh fruit and vegetables”

Presented by: Céline MATAR

Joint Research Unit: eco-efficient Polymeric & Organic Packaging (ePOP)

UM - INRA- Supagro & CIRAD, 2 place Pierre Viala, Bat 31, 34060 Montpellier
cedex 01 France

PhD Director: GUILLARD Valérie – Associate Professor, Montpellier University

Co-director: GUILBERT Stéphane – Full Professor, Montpellier SupAgro

Co-supervisor: GAUCEL Sébastien – Research Engineer, INRA Montpellier

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Abstract

Health benefit of fresh fruit and vegetables remains hampered by their very short shelf life due to their high perishability responsible of considerable food waste and losses and consequently high environmental impact. Among innovative technologies, Modified Atmosphere Packaging (MAP) aims to maintain, in the close surrounding of the product, an atmosphere composition that prevents its decay. Existing models of mass transfers in the food/packaging system predict the evolution of gas concentrations (O_2 and CO_2) in MAP but without any estimation of food shelf life gain. A large part of food wastage is related to product's short shelf life, shelf life prediction is thus an indispensable prerequisite for quantifying the benefit of MAP on the reduction of food losses and the impact of these losses on our environment. In this context, the objective of this work is to propose an innovative approach to predict the gain of shelf life due to MAP and its positive effect on the reduction of food losses and environmental impact. MAP modelling tools simulating O_2 and CO_2 transfer were coupled to a food deterioration model. This latter predicts shelf life gain of fresh produce using MAP in realistic storage conditions. The model was validated on strawberries of the variety "*Charlotte*". A range of shelf life gain from 0.33 days in commercial MAP to 2.76 days in optimized MAP could be achieved compared to the conventional storage. This model was then used to predict a percentage of food losses at the consumer stage. To do this, a hypothesis was set assuming that food losses are proportional to the level of product deterioration. It was found that, if MAP packaging is established all along the postharvest chain and consumer are informed of the benefit of MAP, losses reduction may reach 40% in commercial MAP compared to macro-perforated packaging. These losses reduction leads to limited reduction of the environmental impact in commercial MAP as confirmed by LCA because they represent one small portion of the losses generated in the post-harvest chain, those linked to product deterioration. However, in optimized MAP, 20% of environmental impact reduction is recorded compared to current packaging.

Résumé

La très courte durée de vie des fruits et légumes limite leur consommation pourtant hautement recommandé pour son bénéfice sur la santé. Cette courte durée de vie est liée à leur caractère périssable responsable d'importantes quantités de pertes et gaspillages et par conséquent d'un impact environnemental élevé. Parmi toutes les technologies innovantes, L'emballage sous atmosphère modifiée (EAM) a pour but de maintenir dans l'environnement proche du produit, une composition d'atmosphère qui prévient sa détérioration. Jusqu'à présent, les modèles existants de transfert de matière dans le système 'produit emballé', prédisent l'évolution interne de gaz (O_2 et CO_2) sans aucune estimation du gain de durée de vie. Pourtant, une grande part des pertes est liée à la courte durée de vie du produit. C'est pourquoi, la prédiction de la durée de vie est un prérequis indispensable pour la quantification du bénéfice des EAM sur la réduction des pertes ainsi que sur l'impact environnemental dans la filière. L'objectif de ce travail est de proposer une approche innovante de prédiction de la durée de vie d'un produit en EAM, de la lier à la prédiction de la réduction de pertes et gaspillages et d'en évaluer le bénéfice environnemental. Un modèle de simulation de l'évolution de l' O_2 et du CO_2 a été couplé à un modèle de détérioration du produit. Ce dernier prédit le gain de durée de vie des produits frais en utilisant l'EAM en conditions réelles de temps et températures. Le modèle a été validé sur des fraises de la variété 'Charlotte'. Un gain de durée de vie allant de 0.33 jours en EAM commercial à 2.76 jours en EAM optimisé est obtenu par rapport au mode de conservation classique. Le modèle de détérioration a ensuite été utilisé pour estimer un pourcentage de pertes au niveau de la phase consommateur en faisant l'hypothèse que ces pertes sont proportionnelles au niveau de détérioration du produit. L'étude révèle que, dans le cas où l'EAM est établi tout au long de la chaîne post-récolte et si le consommateur conserve l'emballage intègre jusqu'à consommation, les pertes sont réduites de 40 % par rapport à l'emballage macro-perforé. Cette réduction de perte mène à une réduction limitée de l'impact environnemental de l'EAM commercial comme confirmé par l'Analyse de Cycle de Vie car ils ne représentent qu'une petite portion des pertes générées dans la chaîne post-récolte, celle liée à la détérioration du produit. Cependant, en considérant un EAM théorique, optimisé, 20% de réduction de l'impact environnemental est enregistré comparé à l'emballage macro perforé.

Valorization of PhD Thesis

Scientific papers

Published articles

Matar, C., Gaucel, S., Gontard, N., Guilbert, S., & Guillard, V. (2018). Predicting shelf life gain of fresh strawberries 'Charlotte cv' in modified atmosphere packaging. *Postharvest Biology and Technology*, 142(December 2017), 28–38. <https://doi.org/10.1016/j.postharvbio.2018.03.002>

Prepared articles

Matar, C., Gaucel, S., Gontard, N., Guilbert, S., & Guillard, V. (2018). Role of packaging in the sustainability of the food chain: Example of the post harvest chain of fresh fruit and vegetables.

Matar, C., Gaucel, S., Gontard, N., Guilbert, S., & Guillard, V. (2018). Quantifying/Modelling shelf life of fruit and vegetables in MAP: A multicriteria decision based on product's quality and postharvest actors' behavior.

Matar, C., Gaucel, S., Gontard, N., Guilbert, S., & Guillard, V. (2018). A global visual method for measuring the deterioration of strawberries in MAP.

Matar, C., Gaucel, S., Gontard, N., Guilbert, S., & Guillard, V. (2018). Considering consumer's behavior and practices in the prediction of postharvest losses reduction for fresh strawberries packed in Modified Atmosphere Packaging

Matar, C., Hélias, A., Gaucel, S., Gontard, N., Guilbert, S., & Guillard, V. (2018). Benefit of MAP at consumer's stage on the overall environmental impact of the postharvest chain of packed strawberries

Oral communications

Matar, C., Gaucel, S., Guillaume, C., Costa, S., Guillard, V., Guilbert, S. & Gontard, N. (2016). Predicting food wastes and losses reduction for fresh produce in Modified Atmosphere Packaging (MAP). EFFoST, Vienna (Austria), 28-30 November 2016.

Matar, C., Gaucel, S., Guillard, V., Guillaume, C., Costa, S., Guilbert, S. & Gontard, N. (2018). Predicting food waste and losses reduction for fresh produce in modified atmosphere packaging (MAP). Symposium of the doctoral school GAIA, branch APAB, Montpellier (France), 15 June 2018.

Posters

Matar C., Gaucel, S., Guillard, V., Gontard, N. & Guilbert, S. Decision Support Tool to predict food shelf life and optimize Modified Atmosphere Packaging of fresh fruits and vegetables, 2nd Euro-Mediterranean Symposium on Fruit and Vegetable Processing, Avignon (France), 4- 6 April 2016.

Matar C., Gaucel, S., Guillard, V., Gontard, N. & Guilbert, S. Decision Support Tool to predict food shelf life and optimize Modified Atmosphere Packaging of fresh fruits and vegetables, Symposium of the doctoral school GAIA, branch APAB, Montpellier (France), 15 June 2016.

Supervision activities

Romane NONIS, Master 1 in processing and quality of food, ESA (Ecole Supérieure d'Agriculture d'Angers), 3 months. Dimensionner un emballage sous atmosphère modifiée à partir de barquettes et films du commerce afin d'augmenter la durée de vie des fraises et diminuer les pertes de la filière mais aussi l'impact environnemental des systèmes de conservation actuels en couplant emballage et chaîne du froid. This internship led to a successful Master Thesis.

Aekkarun WORRADALUK (Bill), freshly graduated Food Engineer, Kasetsart university (Thailand), 6 months, environmental impact assessment of fresh fruits (strawberries) in modified atmosphere packaging by using life cycle assessment (LCA) approach. This internship led to a successful Master Thesis.

Marie PLAISANT, Bachelor student, IUT (Institut Universitaire de Technologie) Perpignan, department of biological engineering, department of environmental science, 2,5 months. Elaboration d'un emballage actif sous atmosphère modifiée qui soit adapté pour optimiser la conservation d'un produit frais de saison tel que la fraise

tout en diminuant les impacts sur l'environnement. This internship led to a successful Bachelor Thesis.

Teaching activities

Academic year: 2016-2017 et 2017-2018, 64h/year

Department of biological engineering, IUT (Institut Universitaire de Technologie) de Montpellier: biological engineering (2nd year) and Professional degree ALIPACK (3rd year). Courses, tutorial classes and practical exercises related to Modified atmosphere packaging, new packaging technologies, Mass transfer through packaging, physiology of fruits and vegetables and food spoilage.

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Abbreviations

The most frequent abbreviations in this work are listed here. However, due to the sectioning in the form of articles and the large number of parameters and units; tables of abbreviations were built at the beginning of each chapter for easier reading.

ADEME	Agence De l'Environnement et de la Maitrise d'Energie
CMAP	Commercial Modified Atmosphere Packaging, referring to a passive modified atmosphere created in the headspace of the product using a commercial film packaging : in our study LDPE (low density polyethylene) film was used
DST	Decision Support Tool
eMAP	equilibrium Modified Atmosphere Packaging
F&V	Fruit and Vegetables
FAO	Food and Agricultural Organization
FLW	Food Losses and Wastes
Fridge/ storage	Cold A storage of the product in the fridge or cold storage refers to a temperature of storage equal to 5°C
High T	High temperature
HPLC	High Performance Liquid Chromatography
Interfel	Inter-profession of fresh fruits and vegetables
Keep packaging	Keep packaging represents a consumer behavior toward the packaging. In this case, the consumer will keep the packaging closed until consumption of the product
LCA	Life Cycle Analysis
LCIA	Life Cycle Inventory Analysis
Long d	Long duration
Low T	Low temperature
MAP	Modified Atmosphere Packaging
no MAP/ Control/ Conventional packaging	no Modified Atmosphere Packaging also called Control or Conventional packaging refers to the macro perforated packaging used currently in the postharvest chain, to pack strawberries i.e. benchmark

OMAP	Optimized Modified Atmosphere Packaging, referring to a passive atmosphere created in the headspace using a film with ideal permeabilities to O ₂ and CO ₂ , not yet available or commercialized
Pre-Supermarket	Pre-supermarket refers to the postharvest stages from packing until the stage preceding the arrival to the supermarket, in our case: Transport 3
R	universal gas constant
Remove packaging	Remove packaging represents a consumer behavior toward the packaging. In this case, the consumer will remove the packaging after product purchase
RH	Relative humidity
RMSE	Root Mean Square Error
Short d	Short duration
USDA	United States Department of Agriculture
Ambient storage	A storage of the product at ambient temperature refers to a temperature of storage equal to 20°C
Current situation	Current situation refers to the current storage behavior of the French consumer i.e. current temperature and storage duration of strawberries at household

Preamble

The presented PhD project is conducted in the Joint Research Unit IATE (ePOP team). IATE (Montpellier, FR) is a joint research unit of INRA, CIRAD, SupAgro and University of Montpellier and is doing applied and fundamental research in the field of agro-polymers and emerging technologies.

ePOP team, led by the Full Professor Nathalie Gontard, is developing mathematical modelling tools in the field of food packaging based on a thorough analysis and characterization of the mass transfer in the whole food/packaging system and multi-criteria decision making tools for a better dimensioning of the packaging material. The team is focusing its effort on one hand, on the development of eco-efficient packaging solutions: passive, active and intelligent packaging using bio-sourced and biodegradable material for more sustainable food packaging solutions. On the other hand, its objective is to understand and model relationships between material mass transfer properties and food degradation in order to bring next generation of food packaging solutions by enabling customization of the packaging's properties to fit products', stakeholders' and environmental requirements.

The ePOP team was part of the national metaprogram 'GloFoodS' conducted by INRA-CIRAD (Transitions to the global food security) dedicated to the investigation pathways to worldwide food security in a context of competition for land and resources. In the context of GloFoodS, research project launched by IATE, 'Pack4fresh', was based on: "Eco-design of modified atmosphere packaging coupled with chilled chain system to minimize the environmental impact of post-harvest chain of fresh fruit and vegetables". This topic offers the unique opportunity for the team to understand the relationship between the adequate design of a food/packaging systems, the resulting food losses and wastes and the environmental impact of the whole packaging system.

In the framework of the 'Pack4fresh' project, a PhD thesis was launched, for a period of 3 years (October 2015/October 2018), co-financed by the INRA/CIRAD metaprogram 'GloFoodS' (half scholarship) and SupAgro school (half scholarship).

The PhD Student in charge of the Project was Céline MATAR, who held a degree in Agriculture engineering – specialisation: Food industry, with an academic research

experience on agriculture and food science. The student has been supervised by Associate Professor Valérie GUILLARD (Thesis Director), Full Professor Stéphane GUILBERT (co-director) and Research Engineer Sébastien GAUCEL (co-supervisors) of IATE. Partners of the metaprogram 'GloFoodS' who participated in this project are Dr, Sandrine COSTA and Dr, Karine GAUCHE from UMR MOISA (Market Organizations, Institutions & Actors' strategies).

Dr, Arnaud HELIAS (Montpellier SupAgro, Montpellier, France) and Dr, Catherine RENARD (INRA (National Institute of Agronomy research), Avignon, France) did accept to carry out the role of external experts for the PhD Project, because of their relevant knowledge in relation to the PhD Research topic. They were in charge of reviewing the work of the PhD Student during three yearly meetings.

Introduction

Introduction

Socio-economic context of the work

The multiple efforts done by the government to stress on the health benefit of fruits and vegetables (F&V) are constrained by the short shelf life of these fresh and perishable products. These food products degrade rapidly due to physiological aging and microbiological proliferation which reduces their consumption duration. Their high fragility is hardly compatible with the current storage, distribution and consumption modes and is responsible for **considerable food losses & wastes**. For example, F&V are responsible for 46% of total post-harvest losses and wastes. This represents 1.3 billion of tones of losses worldwide per year encompassing post-harvest storage, transport and distribution up to the consumer (Esnouf and Huyghe, 2015; Gustavsson et al., 2011). In addition, vegetables wastage counts for 21% of the total carbon footprint behind cereals at 34% (Scialabba, 2013a).

The current strategies used to reduce food losses is essentially based on the use of the **cold chain** which negative impacts on the environment are well known. In fact, the cold used in the industries, refrigerated transport and retailers all together represent 52% of total CO₂ emission related to refrigerant fluid which is equivalent to 7.69 million tons of CO₂ released per year in the air. More than 50% of food is retailed under refrigerated conditions (Garnett, 2006). 8% of the worldwide energy consumption is dedicated to the food chilled chain and 2.5% of the greenhouse gases are due to the production of this same cold.

In addition, when a food product is lost or wasted, its **packaging material** is also discarded creating additional wastes issues. Along their production cycle, packaging materials consume non-renewable resources such as oils, water, energy and produce greenhouse gases and pollutant accumulating in the marine environment. Since the beginning of the 2000s, significant efforts have been expended to reduce unnecessary packaging for food product as well as the use of biodegradable packaging materials made from non-food products, renewable resources, composting habits and energy recycling.

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Nowadays, the challenge relies on the reduction of environmental impact of the **food/packaging system**. Our objective is to be able to reduce post-harvest losses and wastes using an optimized packaging while paying attention to the environmental impact of the used packaging materials. Consequently, a reduction of environmental impact can be expected due to a reduction of postharvest food losses and wastes.

This PhD is taking part of the INRA-CIRAD 'Pack4Fresh' project. This latter is one of the multiple studies conducted by the metaprogram 'GloFoodS' through which scientists are working on improving worldwide food security by the reduction of food losses and wastes. Our role in the 'Pack4Fresh' project is to develop an eco-design approach of the fresh food post-harvest steps. This is done by deciphering the complex interrelationship between the positive impact on our environment of the food losses reduction and negative impact of the technologies used to reduce these losses (packaging, cold chain, etc.).

Scientific context of the work

One of the major causes of fresh F&V post-harvest losses and wastes are their **short shelf life**. Shelf life is defined as the time it takes for the product from harvest until it's no longer marketable because of undesired sensory, chemical, physical and microbiological characteristics. Many intrinsic factors can affect product's shelf life such as color, texture, water activity, natural microflora, pH as well as extrinsic factors such as storage temperature, atmosphere gases composition and environmental microbial counts (Kilcast and Subramaniam, 2000). These factors are measured to define the quality of a product knowing that it also depends on the satisfaction of consumer's demands (Valero et al., 2012). Many other definitions of shelf life also exist specifying a 'used by' and 'best before' date for a better control of products' life.

For fresh, highly perishable food, **cold** is the first technology used to preserve nutritional, organoleptic and microbiological characteristics. Because it slows down all the kinetic degradation reactions including oxidation, physiological reactions and microbiological proliferation. Even if the refrigeration equipment contributes to the reduction of the food losses by extending the shelf life of the product, they participate directly and indirectly to climatic upheaval by the electricity consumption and the use of refrigerants.

Modified Atmosphere Packaging (MAP) can be used as an alternative to cold (or at least, to decrease the use of cold) because it also prevents ripening and associated changes in fruit. The deceleration in the degradation of food reactions is done by the modification of gas concentration (essentially O₂ and CO₂), principally O₂ reduction and CO₂ moderate increase, in the headspace of the product. This technology particularly developed for fruit and vegetables and other fresh ready-to-use products can follow the product till its arrival to the food stores and consumer's house (Fonseca et al., 2002; Carole Guillaume et al., 2010). It consists in modifying the headspace atmosphere (the left volume at the top of a filled package) resulting in a natural equilibrium between the consumption and production of the gases by the respiring product (i.e. fruits and vegetables, cheeses, fermented products) and the gas permeation through the package film. This is called passive modified atmosphere packaging (MAP). Active components such as O₂ scavengers or CO₂ emitters can be added to the package or gas flushing can be performed to accelerate the gas equilibrium step in headspace. In that case we define it as an active modified atmosphere packaging (Guillaume et al., 2010). In all case, the objective is to reach an atmosphere close to the optimal one. In the case of passive MAP, the optimal atmosphere is strongly dependent on the packaging film material and its permeation properties and geometry and size that must be adapted to the respiration characteristics and mass of the product.

Nowadays **choice of a packaging material in MAP** application is based on empirical approach with a rare use of rational requirement driven approaches. Requirement driven approaches consist in characterizing the needs and requirements of the food and then translating them into mass transfer properties. Once known, they are considered as a constraint in the choice or conception of the packaging. This optimised approach is based on the use of mathematical modelling tools to avoid over-testing and inadequate sizing of the packaging material. A better food quality and safety is expected by adequately targeting the appropriate material and packaging dimensioning to the food requirements (Cagnon et al., 2013; Chaix et al., 2015). An example of this decision support tool (DST) is available at http://plasticnet.grignon.inra.fr/lateTools/TailorPack_

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To date, very few studies tried to quantify in days and **model food shelf life** under modified atmosphere packaging: only 13 studies were found in the WOS dealing with that topic. This might be due to the need of a unified clear definition of shelf life that will allow us to build a methodology for its characterization. Models for predicting and optimizing shelf life still need to be conceived.

- ☞ The link between shelf life gain and food losses reduction still need to be clearly state and quantified. These modelling approaches of shelf life and food losses are an indispensable prerequisite for the quantification of the benefit of MAP in the post-harvest chain.

Another important aspect to mention is the **environmental impact** of the technologies used to reduce food losses and wastes, e.g. MAP and cold chain. Wikstrom & William conducted a Life Cycle Analysis (LCA) trying to identify potential environmental gain from reducing food losses through the use of new packaging. In their study, William et al. concluded that reducing environmental impact from packaging is possible when the packaging design helps to reduce food losses (Williams and Wikström, 2011).

- ☞ In classical LCA approach, until now, there were no complete studies on the environmental impact of the food packaging, taking into consideration in addition to the production of the material and its end of life (i.e. recycling, biodegradability), its usage benefit including the impact of the package on the reduction of food losses due to the deceleration of product degradation. It is urgent to change the paradigm of evaluation of environmental impact of packaging materials by considering in addition to resources and waste issues their positive impact in term of decreasing food losses. In the particular case of MAP technology, it is also important to evaluate the positive impact that the reduction of the use of the chilled chain, thanks to MAP, may have for the whole post-harvest chain.

Aims of this PhD project

In this context and to address the main challenges listed above, going beyond state-of-the-art, this PhD work aims to clearly quantify the increase of product shelf life that

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can be achieved using MAP technology and the concomitant food losses reduction and environmental benefit achieved. A focus is made on building the link between product shelf life, losses generated and the role of stakeholders' behavior and especially consumers on these potential losses reduction. Moreover, this project aims to conduct a LCA beginning at post-harvest stages to evaluate environmental impact of food/packaging system as a whole to help to quantify if MAP technology could be an environmental-friendly technology, compensating the use of cold chain.

To achieve these objectives, the PhD must address the following, underlying scientific questions:

- How the shelf life of a product is defined? What are the major parameters taken into consideration to establish this definition?
- How shelf life could be characterized and predicted for a given product in MAP, considering the effect of modified atmosphere on this shelf-life?
- How to predict food losses reduction using shelf life models?
- How to consider stakeholders' behavior in the evaluation of shelf life and in the reduction of losses?

Thesis strategy and outline

The PhD strategy used in this three-year time frame to answer the questions listed above is synthesized by the following diagram:

Introduction

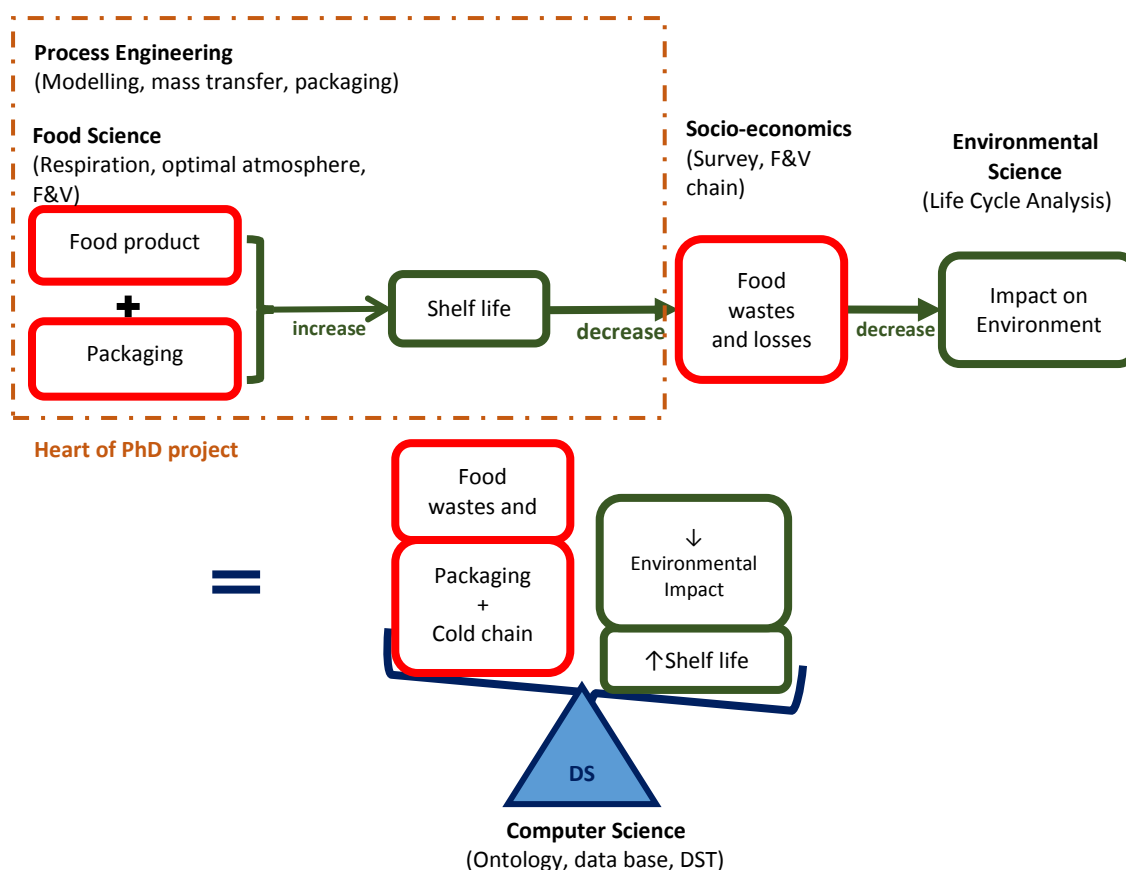


Figure 1: Summary outline of Pack4Fresh' project

Besides, my main work on the Food Engineering and Food Science as mentioned in Figure 1, I also worked on building the links between the following disciplines: social sciences and humanities (to identify the behavior of the stakeholders in the postharvest chain), Environmental Science and Computer Science.

This PhD Project was divided in four main tasks (four chapters within this document) carried out within a specific time frame during the PhD Project. The finalization of each task was followed by the writing of one or two scientific article.

Firstly, literature reviews were done to have a global knowledge of the already existing information concerning shelf life assessment of fresh fruit and vegetables in MAP and corresponding losses and wastes (**chapter 1**). For this end, an overview of the food losses and wastes recorded in the postharvest chain of fresh fruit and vegetables was carried out. Next, the effect of MAP on the increase of product shelf life and consequently reduction of losses and wastes and their environmental impact was investigated. This two research outlines constituted a first part of the state of art and was represented under the form of a review article named: 'Role of packaging in the

Introduction

sustainability of the food chain: Example of the post harvest chain of fresh fruit and vegetables' (**review 1**). In a second part of the state of art, the objective was to investigate into detailed the available shelf life assessments techniques and available models in MAP able to quantify product shelf life while taking into account actors' behaviour in the postharvest chain. This second review was named: 'Quantifying/Modelling shelf life of fruit and vegetables in MAP: A multicriteria decision based on product's quality and postharvest actors' behavior' (**review 2**). It was found that product shelf life was not yet quantified in MAP, consequently, we built an upgraded MAP mathematical model able to predict product deterioration in MAP (**chapter 2**). Strawberries were taken as model food because of their high perishability. In this chapter, we started by setting up an experimental visual method able to assess the quality of the product as a function of time (**article 1**). This experimental method was after used to develop and validate a predictive deterioration model that has been coupled with MAP modelling tool that predicts gases transfer and respiration in the packed food system. This upgraded model was validated in simplified and real conditions of use (**article 2**). The next step consist in linking the predictive deterioration model to a percentage of food losses recorded at the consumer stage (**chapter 3**). In this task, the upgarded MAP modeling tool was linked to a percentage of food losses and a serie of scenarios identified in the French strawberries postharvest chain were tested. French consumer behaviour were considered in the recorded percentages of losses (**article 3**). In order to insure a sustainable approach, the last step is to evaluate the environmental impact of the establishment of MAP in the postharvest chain at the consumer stage (**chapter 4**). The output of this task consist in measuring the possibilities of replacing the use of the cold chain by MAP used at ambient temperature at household level (**article 4**).

The **General Discussions** concerning shelf life prediction in MAP linked to food losses and the environmental impact of the food packaging system are included after chapter 4. Conclusions and perspectives concerning the outcome of the PhD Project and following research and applications is included in the last section of this manuscript (**Conclusions and Perspectives**).

A synthetized scheme of the thesis outline is proposed hereafter in Figure 2.

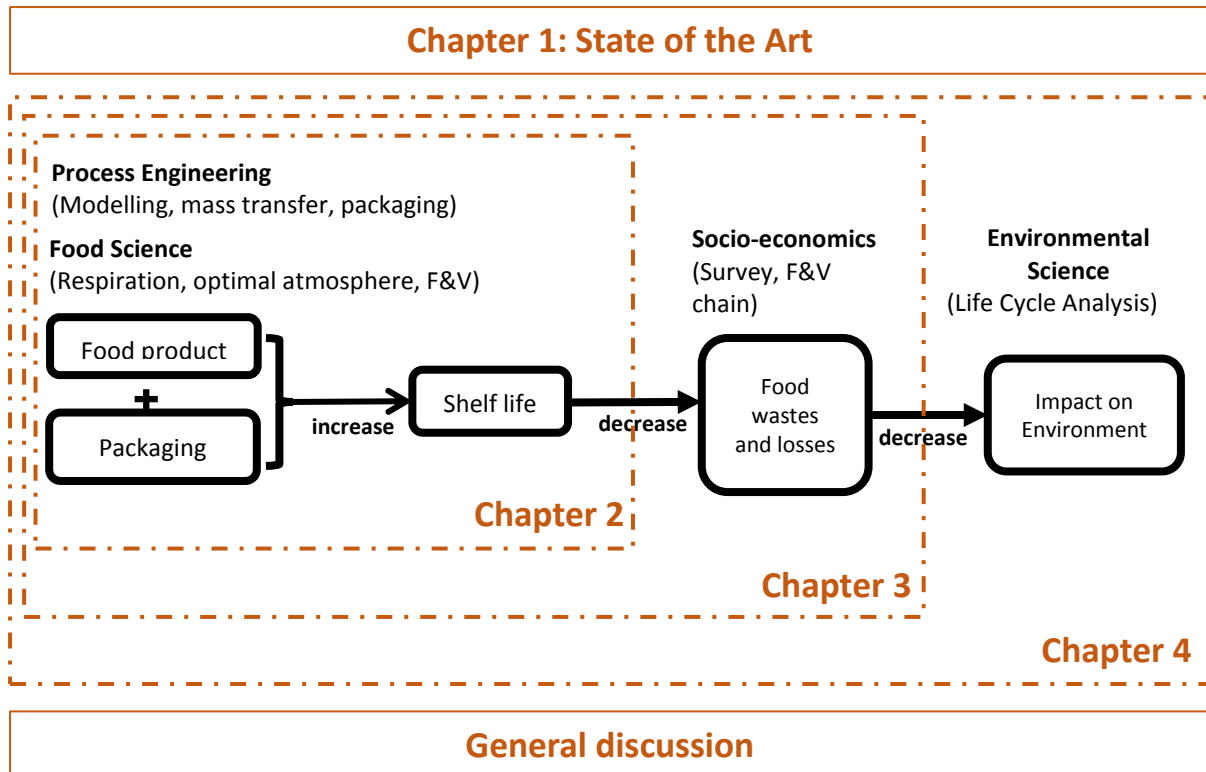
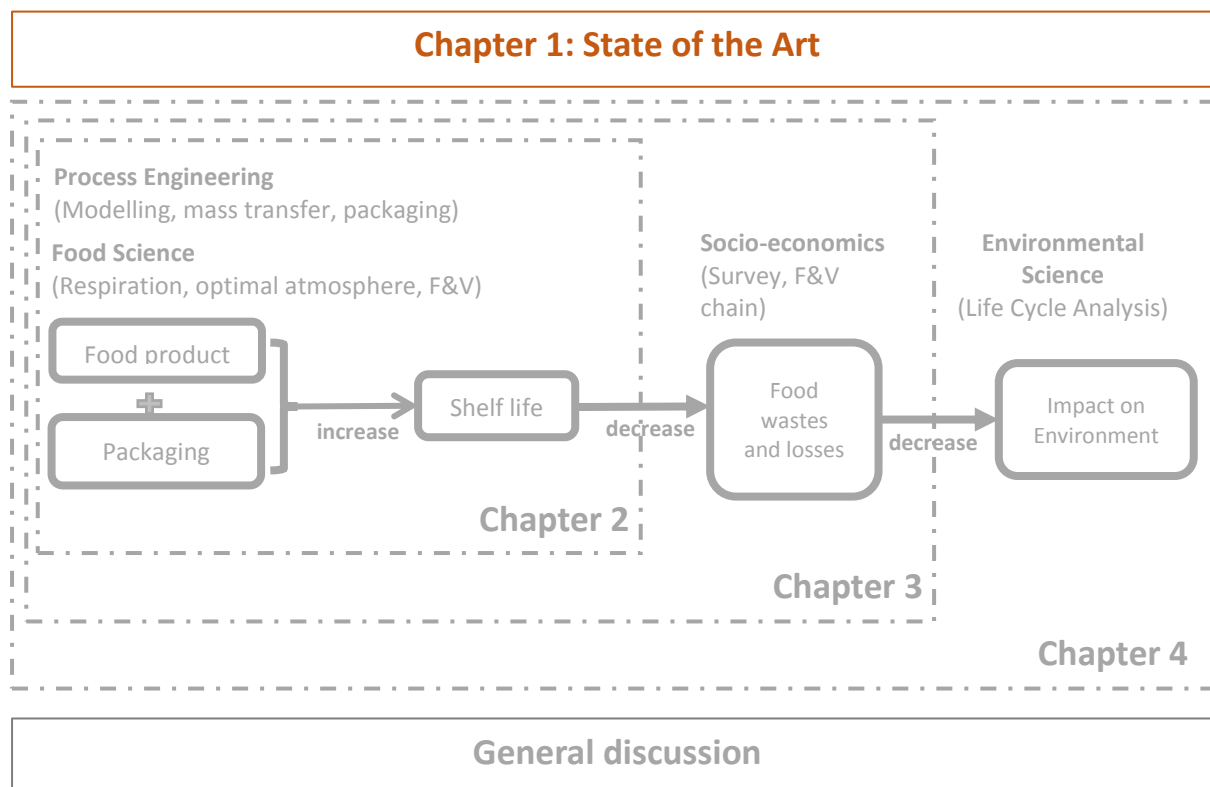


Figure 2 : Thesis outline summary

Chapter 1: State of Art

Chapter 1: State of Art

1.1 Introduction



In the last 20 years, scientists invested major efforts in studying the problematic of increasing food losses and wastes because they are leading to economic and environmental problems. To solve this issue of food wastage, a lot of effort has been paid food shelf life extension and technologies such as 'Modified Atmosphere Packaging' technology, were developed to increase fresh product shelf life. The increase of product shelf life will undoubtedly participate in the reduction of food losses and wastes. However, these two aforementioned fields 'food losses and wastes' and 'modified atmosphere packaging' were never studied and linked together. In fact, the direct quantification of the effect of MAP on the reduction of food losses and wastes will give a concrete impact of MAP technology on losses.

Furthermore, advances in the modelling and assessing the impact of MAP technology on product shelf life are also needed. So far, predictive models for product shelf life in MAP are mainly relying on environmental parameters (such as O₂ and CO₂) or

qualitative quality parameters. However, very few models predicted gases evolution and shelf life at the same time. Thus, what is needed for a shelf life assessment is the development of a predictive assessment model of food quality in MAP.

This chapter includes 2 review articles:

The first one explains how packaging contribute to the sustainability of the food chain. An example of postharvest chain of fresh fruit and vegetables was chosen because of the high percentage of losses (40%) generated by this supply chain.

The second review is a comprehensive overview of the existing shelf life modelling and quantification approaches highlighting their limits of application.

1.2 Role of packaging in the sustainability of the food chain: Example of the post harvest chain of fresh fruit and vegetables (Review 1)

Matar Céline, Gaucel Sébastien, Gontard Nathalie, Guilbert Stéphane & Guillard Valérie*

Joint Research Unit Agro polymers Engineering & Emerging Technology, UM -
INRA- Supagro & CIRAD, 2 place Pierre Viala, Bat 31, 34060 Montpellier cedex 01
France

*guillard@univ-montp2.fr

Abstract

By 2050, global food waste is estimated to rise over 200 million tons which leads to huge environmental impacts. In contrast, 20 000 children under the age of 5 die daily from hunger. Therefore, the issue of food losses and wastes prevention recently gained a worldwide interest to fight hunger by improving food availability and encourage environmental sustainability. Special focus will be addressed on fruit and vegetables losses since they represent around 40% of the total food losses and wastes. This review aims at showing how the packaging, although blamed for representing high environmental impact, is able to participate in the reduction of food losses and wastes. An overview of the heterogeneity of fruit and vegetables losses and consequent environmental impact is presented. Following that, the current scientific knowledge on the role of modified atmosphere packaging technology on shelf life extension, food losses and wastes reduction and environmental impact will be detailed. Deep analysis of the literature showed that on one hand, the impact of modified atmosphere packaging on shelf life increase is already very well-known but rarely quantified in days. Moreover, the amount of food losses and wastes reduction following shelf life increase was never quantified. On the other hand, environmental impact of the food and the packaging as a whole system including the influence of the packaging on the food losses and wastes reduction is rarely represented in a clear and simple manner. Further research is needed to facilitate the representation/quantification of the links between produce packed in modified

atmosphere packaging, shelf life increase and resulting food losses and wastes reduction.

Nomenclature

Symbols	Definition	Unit	Equation
$E_{a,k}$	Activation energy for parameter k	J mol^{-1}	(4)
$K_{m_{O_2}}$	Constant of Michaelis and Menten	Pa	(2),(3)
k_{ref}	Maximal respiration rate is the value of parameter k at reference temperature T_{ref}		(4)
n_{O_2} or n_{CO_2}	O_2 , CO_2 species in the headspace	mol	(2),(3)
P_{O_2} P_{CO_2}	Permeability of the film for gas O_2 or CO_2 respectively	$\text{mol m}^{-1} \text{Pa}^{-1} \text{s}^{-1}$	(2),(3)
$p_{O_2}^{in}$	Partial pressure of O_2 in the headspace	Pa	(2),(3)
$p_{O_2}^{out}$ $p_{CO_2}^{out}$	Atmospheric partial pressure of O_2 and CO_2 respectively	Pa	(2),(3)
R_{O_2max}	Maximum respiration rate per kg of food commodity	$\text{mol kg}^{-1} \text{s}^{-1}$	(2),(3)
$T_{ref,k}$	Reference temperature (K) for the parameter k	K	(4)
W_P^i	Waste handling of packaging	MJ, carbon dioxide equivalents, etc. per unit of lost food in the consumer phase	(6),(7)
A	Surface area of the film	m^2	(2),(3)
B	Purchased food	kg, L, nutrient, etc.	(5)
u	Thickness of the film	m	(2),(3)
e	eaten food	kg, L, nutrient, etc.	(5)
E^i	Overall energy use or environmental impact	MJ, carbon dioxide equivalent	(6)
F^i	Energy use or environmental impact to produce and distribute one unit of purchased food to the consumer, with the exception of packaging	MJ, carbon dioxide equivalents, etc. per unit of purchased food	(6),(7)
i	Environmental impact category, can be energy use, global warming potential, eutrophication potential		(6)
k	Temperature dependent parameter		(4)
L	Fraction of food lost at the consumer phase	dimensionless	(5)

	L = 0 means no losses, L = 1 means that all purchased food is lost		
m	Weight of the food product	kg	(2),(3)
P ⁱ	Energy use or environmental impact to produce the packaging for one unit of purchased food to the consumer	MJ, carbon dioxide equivalents, etc. per unit of purchased food	(6),(7)
q _{RQ}	respiratory quotient	dimensionless	(2),(3)
W ⁱ	Energy use or environmental impact of waste handling of the food lost at the consumer phase	MJ, carbon dioxide equivalents, etc. per unit of lost food in the consumer phase	(6),(7)

1.2.1 Introduction

Worldwide, 1 of every 7 person go to bed hungry and more than 20,000 children under the age of 5 die daily from hunger (Angellier-coussy et al., 2013a; Gustavsson et al., 2011). While the planet is struggling in supplying sufficient resources for human, around 100 million tons of foods are wasted annually in the European Union (EU), nearly 30% of the agri-food supply chain from initial agricultural production down to final household consumption. Even if the relation between food waste and shelf-life is not straightforward, a large part of food wastage is related to the short shelf-life of many fresh produce inherent to their biological origin. Moreover, inaccuracies in, or misunderstanding of food date labels are estimated to cause over 20% of the avoidable disposal of still-edible food (Stenmarck et al., 2016). By 2050, global food waste is estimated to rise over 200 million tons which leads to huge environmental impacts such as high carbon footprint, blue water footprint, vain land use, etc...

When one food is thrown, one packaging is also discarded leading to additional environmental burden. In our plastic based economy, packaging materials are principally oil-based. After an exclusively single and very-short use inherent as food packaging, 40% are landfilled corresponding to 9 million tons of plastic packaging waste that are fated to accumulate in soils. 32% leak out of collecting and sorting system that finally end into soil and ocean as well. These marine and soils litters first degrade into micro and then into nano-sized particles that could easily penetrate into living organisms such as fishes and then fed up the food chain, all the way to humans with dramatic deleterious long-term adverse effects (EU DG, 2011).

In this context, it is urgent to solve the environmental issues of the food/packaging system as a whole. A key action is to minimize, as much as possible, the losses of edible food all along the food value chain, to mitigate both burden of edible food losses and packaging waste on our environment.

One possible solution is the use of sustainable packaging solution which means increase its positive usage benefit, which is food losses and wastes reduction. This could be achieved by primarily fitting the packaging functionalities to food requirements to preserve food quality and safety all along the supply chain and mainly at distribution and consumption stages. Modified Atmosphere Packaging (MAP) system is a good example of an eco-packaging solution.

Packaging is usually wrongly considered as an additional economic and environmental cost rather than an added value. However, significant benefits in term of shelf life extension and then food losses reduction could be achieved using a well dimensioned packaging material, adapted to food needs in term of preservation. Indeed, packaging is a central element to food quality preservation by mainly, controlling gas and vapors exchanges with the external atmosphere. Even if the relation between shelf-life and waste is not simple, significant benefits are expected in term of reduction of food waste thanks to shelf life extension.

The reduction of food waste and losses achieved by using well-dimensioned packaging solutions still need to be quantified and disseminated to all stakeholders in an informative and easy-to-understand manner, and especially to consumers in order to increase their awareness and acceptance of such packaging as sustainable food packaging solutions.

This paper aims to demonstrate how packaging could be a key element of sustainable food consumption by decreasing food waste and losses. In a first part, the paper will provide a situational analysis of food waste and their environmental impact, by focusing on fresh fruit and vegetables (F&V) in the post harvest chain due to their high amount of losses (40% of total food losses) generating high environmental impact. The second part will discuss on one hand, why packaging is a central element to food quality preservation and how packaging, more especially MAP could contribute to food losses and waste reduction. On the other hand, the existing approaches used to link

shelf life increase, food losses reduction and resulting environmental impact assesment will be deciphered. Finally, future needed actions will be proposed for a sustainable food/packaging system.

1.2.2 Overview of data and environmental impact of food losses and wastes:

1.2.2.1 *Heterogeneity of definitions*

Food losses and wastes (FLW) can be tackled referring to two main approaches: on the one hand, FLW represents wasted edible and non-edible food parts. While on the other hand, FLW focuses only on edible wasted food parts (Gitz et al., 2014).

Besides this approach, in the literature, three main definitions of FLW are considered:

A first one relay on the differentiation between food losses and food wastes. Food and agricultural organization (FAO) used this definition to define lost edible food along a supply chain. Three terminologies are used. They mainly differ by the supply chain stages taken into consideration and in which edible food mass decreases:

‘Food losses’ refers to the food lost during the production till its transportation to the supermarket including harvesting, packing, transportation and storage at wholesalers.

‘Food waste’ refers to product losses from its arrival at the supermarket to the consumer’s fridge.

While ‘Food wastage’ is an expression used to cover food lost all along the supply chain from harvesting till its arrival at the household. Thus, food wastage includes food losses and food waste.

A second definition, link FLW to the nature or origin of the cause of loss or waste. Whether the cause is behavioral (waste) or not (loss), voluntary (waste) or not (loss), explicit choice (waste) or not (loss) (Gitz et al., 2014). But the problem here is the ability to accurately define a behavior as voluntary or not taking into account the economic, social context and moral meanings of every person who decided to discard or throw a food product (Adobati, 2015).

In a third definition, FLW is taken as a whole generic terminology encompassing food waste and food wastage. This can get often confusing because some of the ‘waste’

food is in fact a 'loss'. This definition becomes even more debatable when authors include non-edible parts in all of the food related wastes (Quested, 2009).

During this work, possibilities to reduce edible food losses and wastes related to the post-harvest stages of the product i.e. from harvesting until consumer's house will be studied. Only postharvest losses and wastes related to the shelf life of the product will be discussed for a possible reduction. i.e. all the losses due to preservation process along the chain without taking into account losses associated to other behavioral or disorganization problems such as producing larger quantities than needed, overloading of warehouse storage, mechanical damage due to loading and unloading of lorry at the distribution level, inadequate presentation mode in the supermarket and food not consumed on time at the consumer level.

Since F&V losses and wastes represents 40% of the total losses, this study will be focusing on this sector having a sizeable influence on the environment. The terminology 'Food losses and wastes (FLW)' will be employed referring to losses and wastes in the supply chain starting from harvest until the household level.

1.2.2.2 Heterogeneity of losses data: A focus on Fruit and vegetables supply chain

Worldwide, in 2007, the major contributors of total food wastage volumes are fruit and vegetables (40%), cereals (25%) and starchy roots (19%). The aforementioned food crops (i.e. vegetal products) account altogether for about 84% of total food wastage volumes, and the remaining 16% are coming from products of animal origin (Scialabba, 2013b). This percentage represent the losses encompassing post-harvest storage, transport and distribution up to the consumer excluding non-edible feed and parts that are planned for non-good uses (bioenergy).

Table 1: Percentages by weight of losses and wastes for fruit and vegetables (F&V) within the fruit and vegetables supply chain, ('-' corresponds to the absence of data)

Region/Country	Author	Year	Supply Chain stages (% By weight of losses and wastes for fruit and/or vegetables within F&V chain)					Definition of food losses and wastes	Method of calculation	
			Agricultural production	Postharvest handling and storage	Processing and storage	Distribution	Consumption			
Industrialized Asia	(Gustavsson et al., 2011)	2007	10%	8%	2%	8%	15%	All edible	Indirect Mass flow model	
Sub-Saharan Africa	(Gustavsson et al., 2011)	2007	10%	9%	25%	17%	5%	All edible	Indirect Mass flow model	
North Africa West and central Asia	(Gustavsson et al., 2011)	2007	17%	10%	20%	15%	12%	All edible	Indirect Mass flow model	
South and Southeast Asia	(Gustavsson et al., 2011)	2007	15%	9%	25%	10%	7%	All edible	Indirect Mass flow model	
Latin America	(Gustavsson et al., 2011)	2007	20%	10%	20%	12%	10%	All edible	Indirect Mass flow model	
North America and Oceania	(Gustavsson et al., 2011)	2007	20%	5%	2%	10%	19%	All edible	Indirect Mass flow model	
			Total: 37%							
			Total: 56%							
United States	(Buzby et al., 2009)	2005-2006	-	-	-	8.4% of Fruit 8.4% of Vegetables	-	Fresh edible	Indirect Difference between weight at Shipment data and point of sale data.	
	(Buzby et al., 2014)	2010	-	-	-	19 % of Vegetables 13.9 % of Fruit		All edible	Indirect ERS Loss-Adjusted Food Availability Data	
	(Dou et al., 2016)	2015	-	-	-	8% of Vegetables 9% of Fruit	19% of Vegetables 22% of Fruit	All edible	Indirect USDA ERS LAFA databases;2010 data	
			Total for Fruit: 61% Total for Vegetables: 47%							

Region/Country	Author	Year	Supply Chain stages (% By weight of losses and wastes for fruit and/or vegetables within F&V chain)					Definition of food losses and wastes	Method of calculation	
			Agricultural production	Postharvest handling and storage	Processing and storage	Distribution	Consumption			
Europe including Russia	(Gustavsson et al., 2011)	2011	20%	5%	2%	10%	19%	All edible	Indirect Mass flows model was used to account for food losses and waste in each step	
			37%							
			56%							
United Kingdom	(Curry, 2012) (Terry et al., 2011)	2009	Total: 5% - 25%				-	Edible and non-edible	Direct Interviews	
Norway	(Hanssen and Møller, 2013)	2012	14%	-	-	Wholesaler: 0.48% Retail: 4.7% Fruit + 4.5% Vegetables	16 – 21% % of respondent discarded F&V (consumer level)	Edible	Direct - Survey at consumer level - Quantification at all previous levels	
Sweden	(Eriksson et al., 2012)	2010	-	-	-	4.3% waste of F&V Unrecorded in-store waste: 23% of F&V	-	Edible and inedible	Direct/Indirect In 6 stores Database of product income and outcome (sold) + mass flow of unrecorded waste	
France	(Allain, 2015; Esnouf and Huyghe, 2015; Jeannequin et al., 2015)	2015	9%			3%	-	Fresh edible and non-edible	Direct Interviews	
			Total: 12.06 %							
	(ADEME, 2016)	2015-2016	11% of Vegetables 11% of Fruit	7% of Vegetables -	4% of Vegetables 6% of Fruit		8% of Vegetables 8% of Fruit	Edible	Direct Interviews	
			Total: 17-22%							
Total: 25-30%										

Table 1 gather different studies done on the estimation of the percentage of F&V losses from agriculture production till the consumption.

Firstly, FAO estimated the % of F&V losses within the supply chain by using an indirect method i.e. mass flow model (Gustavsson et al., 2011). Indirect method relies on indirect measurements, based on mass flow model used for a specific supply chain. Whereas, direct measurements are direct collection and sorting of waste samples at the consumer level and surveys or diary studies at the distribution level (van der Werf et al., 2016).

All over the continents estimation were generated using the indirect method. Percentages of losses at each step of the postharvest chain varied from 2 to 25% depending on the stage and continent under study. It was shown that underdeveloped countries generated less F&V wastes at the consumer level such as Sub Saharan and Africa with 5% of F&V losses and wastes, in contrast with developed countries such as North America, Oceania and Europe with 19% of F&V losses and wastes. This higher percentage of F&V losses at the consumer level in the developed countries is also applicable for all food losses as demonstrated by FUSIONS study. In fact, in 2013, estimates of European food waste level were equal to 65% of the losses at household and service level (Stenmarck et al., 2016).

Next step is to compare data generated from FAO to other local studies done in each continent.

Beginning with United States where studies were mainly conducted by the US department of Agriculture (USDA). It was found that at the distribution and consumer level in the US, 30 and 28% of fresh fruit and vegetables losses respectively occurred (Dou et al., 2016). While Gustavsson estimated a value of 29% for North America and Oceania (Gustavsson et al., 2011). Thus, an agreement of losses ranges between the two studies that could be due to the indirect methods used in both methodologies. A closer look on percentages of losses at the distribution level revealed similar estimations between 8.4 and 10% for Buzby et al., 2009 and Gustavsson et al., 2011 studies. Same tendency for the consumption level were values ranged from 19 to 22% (Dou et al., 2016; Gustavsson et al., 2011). Globally, it can be noted that estimation

done by FAO and studies conducted by USDA are in accordance in Oceania, North America, including United States.

This is not the case for the European continent where British, Norwegian, Swedish and French data are in disagreement with European FAO values.

In the United Kingdom, Terry et al 2011 showed that losses from production to the household ranged from 5-25% lower than the 37% estimate by FAO at the European level. This overestimation by FAO may come from the indirect method applied unlike Terry et al who relied on interviews to establish estimations (direct method).

In France, the inter-profession of fruit and vegetables (Interfel) and the agency of environment and energy control (ADEME) are the two available studies, based on FUSION study and recorded values between 12.06% and 17-23% of losses from production to distribution level respectively. Much higher estimations, around 37% of losses, were suggested by FAO. This gap in the estimation may come from different methodologies and samples size. The definition of food losses is also different in both cases. Interfel study did not consider the food redirected to animal feed as a loss which can explain lower losses found (Allain, 2015).

In Sweden, locally, 23% of waste were recorded through a database gathering 6 stores' income and outcome completed by a mass flow calculating the unrecorded waste data. This value is 2 times higher than the 10% of losses estimated by FAO.

In Norway, estimation done for distribution level vary around 4.5 - 4.7% much lower than the 10% provided by FAO (Gustavsson et al., 2011; Hanssen and Møller, 2013). Whereas, at the consumer level estimation done using the direct method by Hanssen et al are in the same range as FAO European indirect estimations between 19 and 21%.

In summary, data provided are not always in accordance which question the methodologies used to estimate the percentages of losses influenced mainly by the size of the samples, limits of the systems studied, definition of food losses and wastes and year of study. In other words, it is quite difficult to compare the studies because each one has different system boundaries in the post-harvest chain. This shows the need of a simple global methodology that could be applied by many actors such as

FAO, USDA, Interfel making the studies easier to compare and analyze. Whatever the exact amount of food losses and wastes recorded for F&V chain, its high perishability leads to important environmental impact.

1.2.2.3 Significant environmental impact of F&V losses

In order to highlight the important environmental and economic cost of losses and wastes, F&V losses are compared to meat, milks and eggs losses in [Figure 3](#)(Scialabba, 2013a).

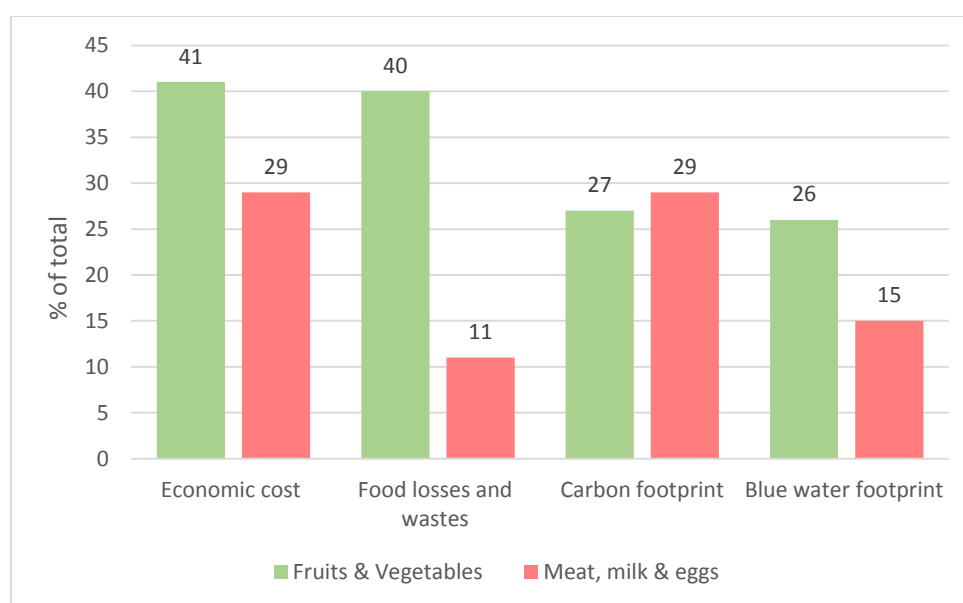


Figure 3: Economic cost, food losses and wastes and environmental impact of 2 food commodities expressed in % of total (data taken from FAO report (Scialabba, 2013b))

F&V representing 41% of total economic cost are the major contributors followed by 29% for meat, milk & eggs and 17% for cereals (Scialabba, 2013a). F&V economic cost is higher than meat even though the cost of a kilogram of meat is much higher than of F&V. This is because F&V has a much higher losses and wastes in volume (40%) compared to meat (11%).

F&V are responsible of 27% of carbon footprint. This is mainly due to the use of diesel and nitrogen fertilizers. Heated greenhouse for vegetables and more specifically the type of heated production used such as fossil fuel also impact carbon footprint values. Whereas, milk and eggs carbon footprint is higher than F&V values equal to 29%. In

fact, animals such as ruminants produce high quantities of methane and need food provision;

In addition, a large variety of F&V needs to be irrigated which lead to 26% of blue water footprint. A lower value (15%) is registered for meat and milk product compared to F&V. Thus, animals' feed composition, feed conversion and origin consume less water than F&V.

The average environmental impact between carbon footprint and blue water footprint impact is equal to 26,5 % for F&V and 22% for meat, milk and eggs. Thus environmental impact of meat & milk is close to that of fruit and vegetables despite the fact that the respective percentages of losses are very different (40% for fruits and 11% for meat).

Thus, it is possible to act on the volume of F&V losses in order to reduce their environmental impact in contrast with meat. For this end, an appropriate packaging design could be a way to reduce losses and wastes in the F&V supply chain (Conseil National de L'Emballage, 2011).

1.2.3 Role of packaging for sustainable food consumption

Packaging is an essential element of response to address key challenges of sustainable food consumption by tackling raw materials, usage and wastes issues (Licciardello, 2017). Innovative sustainable packaging goes far beyond recycling or bio-based products. It is clearly about minimizing the environmental footprint of packed food by addressing food waste and loss reduction and food safety issues (prevention of food-borne diseases and food chemical contamination), in addition to oil and food material resources savings as well as non-biodegradable plastic wastes management (Licciardello, 2017).

The primary fundamental role of food packaging is thus to preserve food quality and safety along the food supply chain until household. It is clearly related to the control of food degradation reaction during storage.

The degradation reactions rates of food is a function of temperature, which is controlled via the cold chain, light transmission and atmosphere composition around the food. Packaging plays a major role here by controlling the mass transfer i.e.

transfer of gases, water vapour between the external atmosphere and the packaging headspace. By defining around the food, a headspace atmosphere whose composition is suitable for the food preservation, by using the technology of Modified Atmosphere Packaging (MAP), packaging plays a key role in the smorgasbord of actions for a better food preservation (Angellier-coussy et al., 2013a).

1.2.3.1 Main role of food packaging, improve food preservation by controlling mass transfer

Modified atmosphere packaging (MAP) consists on changing gases composition in the headspace of the packed product (Belay et al., 2016; Chaix et al., 2015).

After being packed, the fresh produce continues to respire by taking oxygen from air and releasing carbon dioxide (Figure 4). In parallel, oxygen and carbon dioxide will diffuse through the film with a rate defined by the permeability of the film used. In consequence, in the headspace, gas partial pressure will first pass through a transient period followed by a steady state indicating that an equilibrium of gases was reached (Figure 5). This mean that the diffusive exchanges of gases through the film compensate the gas production or consumption by the respiring product. This steady state, called equilibrium modified atmosphere packaging (eMAP), should be reached as soon as possible and be close to the optimal recommended storage atmosphere for each product to preserve its quality and safety (Carole Guillaume et al., 2010).

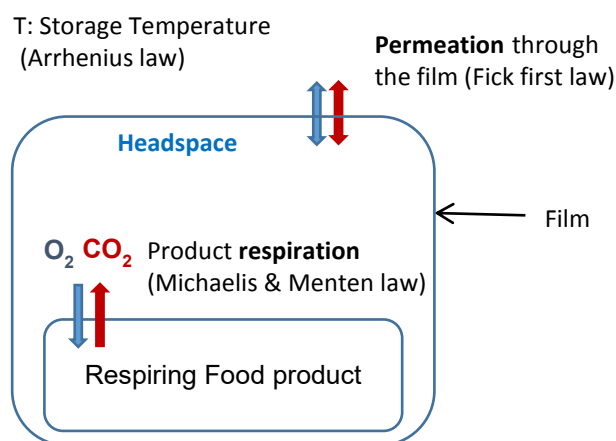


Figure 4: Mechanisms responsible of established gases composition in the headspace of the packed product

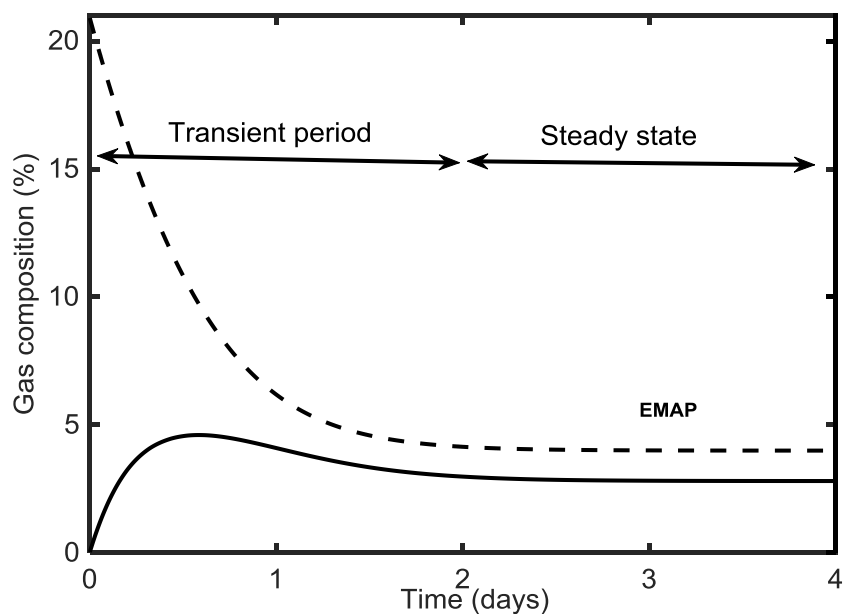
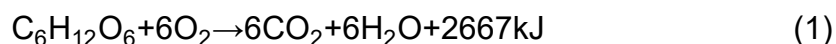


Figure 5: Transient and Steady phase leading to gases equilibrium achieved by oxygen (- -) and carbon dioxide (-) in the headspace of packed product.

Two types of MAP exist: active and passive. Passive MAP refers to modifying the atmosphere in the headspace of the product due to only the respiration of the product and the permeability of the gases through the film packaging (Mattos et al., 2012; J. Robertson, 2010; Sandhya, 2010). Active MAP refers to the modification of the internal gas composition using either a flush and/or active packaging compounds such as gas scavengers/emitters (G. L. Robertson, 2010; Sandhya, 2010). Among these additional active compounds, we can cite the small sachets added to the packaging, containing oxygen scavengers, carbon dioxide emitter, ethylene absorber, antimicrobial substances or humidity absorbers (Falagán and Terry, 2018).

MAP technology is generally used to increase the shelf life of packed fruit and vegetables by preventing ripening of the fruit and associated changes (Angellier-coussy et al., 2013a; C Guillaume et al., 2010; Li et al., 2010). It aims at reducing available oxygen and increasing carbon dioxide around the product. A decrease of oxygen inhibits respiration rate. In fact, during respiration process, one molecule of sugar is combined to six molecules of oxygen to form six molecules of carbon dioxide, water and energy as follow:



This energy is produced to contribute to the integrity of the cells but also tend to increase the temperature of the commodity leading to an increase in transpiration (Becker et al., 2014). In addition, the limited sugar reserves of the fruit are being consumed and the fruit is losing water participating to its dehydration. Thus, respiration is related to senescence and product degradation. In consequence, by slowing down product's respiration and degradation, MAP can increase the shelf life of the product.

MAP design is complex and requires knowledge on packaging material, food characteristics and optimal gases composition of a given product (Belay et al., 2016). Tailorpack (<http://plasticnet.grignon.inra.fr/lateTools/TailorPack>) is an example of a user friendly software able to design packaging for fresh produce such as fruit and vegetables. A mass balance of gases composition in the headspace is done by taking into account the permeation of the gases through the film via Fick first law and the respiration of the fruit through Michaelis and Menten law (Figure 4) as follow:

$$\frac{dn_{O_2}}{dt} = \frac{P_{O_2} A}{u} (p_{O_2}^{out} - p_{O_2}^{in}) - \frac{R_{O_2max} p_{O_2}^{in}}{(Km_{O_2} + p_{O_2}^{in})} m \quad (2)$$

$$\frac{dn_{CO_2}}{dt} = \underbrace{\frac{P_{CO_2} A}{u} (p_{CO_2}^{out} - p_{CO_2}^{in})}_{\text{Fick first law}} - \underbrace{q_{RQ} \frac{R_{O_2max} p_{O_2}^{in}}{(Km_{O_2} + p_{O_2}^{in})} m}_{\text{Michaelis and Menten}} \quad (3)$$

where the variation of quantity n_{O_2} or n_{CO_2} of O_2 , CO_2 species in the headspace (mol). On one hand, parameters related to Fick first law are A the surface area of the film (m^2), u the thickness of the film (m), $p_{O_2}^{out}$, $p_{CO_2}^{out}$ the atmospheric partial pressure of O_2 and CO_2 respectively (Pa), $p_{O_2}^{in}$ the partial pressure of O_2 in the headspace (Pa), P_{O_2} , P_{CO_2} the permeability of the film for gas O_2 or CO_2 respectively ($mol\ m^{-1}\ Pa^{-1}\ s^{-1}$)

On the other hand, the parameters related to the simplest classical Michaelis and Menten equation are R_{O_2max} corresponding to the maximum respiration rate per kg of food commodity ($mol\ kg^{-1}\ s^{-1}$), Km_{O_2} the constant of Michaelis and Menten (Pa) and m the weight of the food product (kg), q_{RQ} the respiratory quotient (dimensionless). Other

respiration equation including carbon dioxide effect on the respiration can replace the simplest equation presented here such as competitive, uncompetitive, non-competitive respiration (Fonseca et al., 2002). Tailorpack also takes into account the effect of temperature via Arrhenius law (Figure 4) as follow:

$$k(T) = k_{ref} \exp\left(\frac{-E_{a,k}}{R} \left(\frac{1}{T} - \frac{1}{T_{ref,k}}\right)\right) \quad (4)$$

where k refers to the temperature dependent parameter, i.e. permeability of material to oxygen and carbon dioxide P_{O_2} and P_{CO_2} , respectively, and R_{O_2max} the maximal respiration rate, k_{ref} is the value of parameter k at reference temperature T_{ref} , $E_{a,k}$ is the activation energy for parameter k ($J\ mol^{-1}$), R is the universal gas constant ($J\ mol^{-1}\ K^{-1}$), $T_{ref,k}$ is the reference temperature (K) for the parameter k .

This tool can predict the oxygen and carbon dioxide variation in the headspace (Figure 5). Thus, it can be used to predict the gases composition reached at steady state according to the weight, respiration rate of the packed produce, temperature of storage, thickness and permeabilities of the chosen film (Cagnon et al., 2013). Inversely, knowing the optimal gases compositions to be achieved, respiration rate and weight of the fruit, dimensions and thickness of the film, the model is able to propose adequate packaging permeabilities.

By improving the preservation of the food, MAP is expecting to have significant benefit on shelf life gain consequently contributing to overall decrease of food waste and losses (Conseil National de L'Emballage, 2011; Verghese et al., 2015).

1.2.3.2 MAP technology and its positive role on food shelf life extension and food losses reduction

Available scientific papers discussing the impact of MAP on the shelf life of packed fresh fruit or vegetables are numerous. This is evidenced by an overview of the current published articles using easy web of science tool. If we select all the database available and launch a query gathering the following keywords: 'Modified Atmosphere packaging', 'Fresh Fruit and vegetables', 'Shelf life in days' separating those three keywords with the connector 'AND', we obtain 268 articles discussing this as a topic on march 2018. This indicates that, 268 articles discussed shelf life during the days of fresh fruit and vegetables in MAP.

A closer look more into details of the 268 selected articles show that these articles could be divided in two groups:

A first group of articles representing 35% (94 articles) of the 268 articles that discuss the combined effect of MAP and other technologies such as effect of antimicrobial agents, coating substances, etc. This combination of more than one technology is called hurdle technology and will not be discussed in this review.

However, the second group of 174 articles (65%) discuss primarily the effect of MAP on the fruit and vegetables shelf life. But in this group of articles, shelf life is very rarely quantified. i.e. estimated in days of storage. In fact, a shelf life of a fresh product is a period of time from harvesting till the consumer stage during which the product quality is still accepted by the consumer (J. Robertson, 2010). Thus, in order to be quantified in days of storage, the quality parameter assessed should be confronted to a limit of acceptability. The time at which this limit is crossed corresponds to the shelf life of the product.

The importance of quantifying a shelf life in days is to compare different studies while unifying the unit of shelf life measure independently of the quality parameter used to define the shelf life. Following that, we will be able to compare shelf lives of a same fruit or vegetable stored in different MAP conditions and temperatures of storage.

93 % of the articles in this group (161/174 articles) do not quantify the shelf life of the product. What is here done is only a comparison of the quality parameters assessed at an arbitrarily chosen day of storage. For example, among the most recent articles, Gantner et al 2016, studied the effect of different active MAP compositions on the quality of white mushrooms (*Agaricus bisporus*) stored at 4°C during 14 days. They concluded that the optimal condition of mushrooms storage was in medium oxygen level packed with film of high permeability. They identified shelf life by measuring the value of two quality indicators lightness and brown index value at day 14 equal to 85 and 23 (Gantner et al., 2016). Another study done by Al Eid et al 2012, on the impact of MAP on khalal fresh dates quality. It was shown that dates fruits on days 18 and 27 had a reduced rate of ripening such as signs of weight loss and darkening in dates color (Al-Eid et al., 2012).

The very rare articles (7% = 13/174) who initiated a quantification approach are gathered in [Table 2](#). In this kind of articles, the quality of the product is assessed at multiple days of storage and afterward the quality of the product is compared to a predefined limit to identify the shelf life of the product in days. For example, the shelf life of pomegranate arils at 5°C under passive MAP conditions was of 10 days. This day was set when the threshold limit of sensorial value was crossed (Kizilirmak Esmer and Yalcin Melikoglu, 2016). Another study done by Conte et al recorded a shelf life of 14 days limited by visible moulds, for Cime de rapa (*Brassica rapa L*) stored in 10% O₂, 2% CO₂ and 88% N₂ MAP system (Conte et al., 2011).

However, these values of shelf life in days are in reality a maximal shelf life of the product since it was confronted to predefined microbiological or sensorial limits. In reality the consumer might reject the product long before this limit is crossed. Because, during the purchase act, the first thing on which the consumer relay on to make his decision i.e. whether to buy or not the fresh product packed in MAP, is the visual appearance of the product. Thus, visual acceptability of the product by the consumer might occur before the physicochemical or microbial or sensorial characteristics limits are reached. The consumer won't be able to smell or touch the product packed in MAP before purchase.

In addition, The estimated maximal shelf life in days is reached only by reproducing the exact same conditions of storage indicated in [Table 2](#) i.e. temperature, film properties, dimensions of the systems, mass of the product, etc. Thus the repeatability of the experiment is very difficult.

In parallel, a more powerful approach of quantified shelf life is being developed by using models predicting shelf life of the product in days as a function of a quality parameter. Models are able to estimate a shelf life while diminishing the experimental work to be done. For example, Oliveira et al 2012, by using a model predicting the evolution of the firmness as a function of time, he showed that the shelf life of sliced mushrooms stored in MAP at 0°C is of 7.5 days according to the firmness acceptable limit (Oliveira et al., 2012b). Adobati also quantified the shelf life of raspberries in MAP by modeling their firmness as a function of time using a Weibull equation. It was found that considering the shelf life assessment through the survival analysis and using a strict limit of product acceptability (i.e. 50 % of consumers' rejection), raspberries

proved suitable to be purchased up to 4 days when packaged only into PET trays; 6 days when stored in passive solutions, and 8 days when packaged in active solutions (Adobati et al., 2015). By using models, the time t at which the shelf life is estimated is done without necessarily having an experimental value at that time t . This shows the convenience of mathematical model in predicting shelf life.

Following the increasing product shelf life, MAP packaging can thus avoid losses and wastes and reduce the corresponding useless negative impact that producing and distributing uneaten or inedible food has on our environment and economy (Verghese et al., 2015). However, even if the ability of MAP to reduce food losses and wastes is a known fact (Muriana, 2017; Porat et al., 2018), none of the 268 studies pushed the approach further into highlighting or measuring the amount of food losses and wastes reduced or generated by the use of MAP packaging. In consequence, no quantitative data is available on this subject making it difficult to have an accurate estimation of the reduction of food losses and waste due to MAP and their environmental impact. Muriana et al 2017, confirmed that food losses and wastes are not yet considered as a variable that is to be optimized when modelling supply chain strategies (Muriana, 2017), i.e. FLW should be considered as a non-stationary phenomenon.

The scarcity of food losses and waste data can be surpassed by developing models able to link shelf life increase to food losses and waste reduction and corresponding environmental impact.

Table 2: Summary of articles measuring a shelf life in days in MAP and corresponding proprieties of the MAP system

Reference	Fruit or Vegetables	Shelf life (d)	Temperature (°C)	Film + tray properties	Film or tray dimension	Weight of the fruit (g)	Type of MAP	Quality parameter for shelf life identification
(Yun et al., 2017)	Strawberries (cv. <i>Confidante</i>)	22	5	Film Material: Poly(ϵ -caprolactone) PCL2 film Thickness : 45.7±3.4 μ m Permeability CO ₂ /O ₂ :ratio about 9.7 at 5°C	Film: 17 x 12 cm ²	60±5	Passive	Sensory Weight loss Firmness Total solid
(Mele et al., 2017)	Ligularia fischeri (cv. <i>Ledeb.</i>)	4	24	Film: Material: 30 000 cc OTR, perforated film 0.6 cm diameter of 4 holes	not indicated	not indicated	Passive	Highest chlorophyll content Total phenolic content Leaf toughness Antioxidant activity Vitamin C Less off-flavor
		13	8	Film: Material: 10 000 cc OTR, perforated film 0.6 cm diameter of 4 holes				
(Hernández et al., 2017)	Fresh cut broccoli (<i>Brassica oleracea var. italica</i> ; cv. <i>Parthenon</i>)	21	5	Tray: Rigid polypropylene Film: Material: polypropylene (PP), Thickness: 35 μ m Film sealed on top of the tray	Tray: 12 x 17 x 5 cm ³	200	Passive and Active (10% O ₂ and 5%CO ₂)	Weight loss Color Chlorophylls Phenolic compounds Total antioxidant activity Senory characteristics
(Kizilirmak Esmir and Yalcin Melikoglu, 2016)	Pomegranate (cv. <i>Wonderful</i>)	10	5	Film: Material: (PMAP1-PMAP8) Permeability OTR : 125-290 cm ³ /m ² /day	Film: 11.5 x 37.5 cm ²	50	Passive	Sensorial values

Reference	Fruit or Vegetables	Shelf life (d)	Temperature (°C)	Film + tray properties	Film or tray dimension	Weight of the fruit (g)	Type of MAP	Quality parameter for shelf life identification
(Ranjitha et al., 2015)	Fresh cut green bell pepper (<i>cv. Capsicum annuum L.</i>)	9	8	Film: Material: Cryovac PD961 film Thickness: 31.25 µm Permeability: 7400 - 8500 O ₂ and 21000 - 24000 CO ₂ ml/m ² .day.atm	Film: 17 x 17 cm ²	200	Passive	Sensorial values
(Fagundes et al., 2015)	Cherry tomate (<i>S. lycopersicum L. var. cerasiforme cv. Josefina; syn.: Lycopersicon esculentum Mill.</i>)	25	5	Film: Material: Multilayer plastic low density polyethylene and bioriented polypropylene (LDPE-BOPP) Thickness : 75 mm. Permeability : of O ₂ 7.64 x10 ⁻¹⁰ mol µm.m ² . s ⁻¹ . Pa ⁻¹ and of CO ₂ 2.09x10 ⁻⁹ mol. mm. m ⁻² .s ⁻¹ .Pa ⁻¹	Film: 17.5 x 24.0 cm ²	100	Active (5% O ₂ + 5% CO ₂)	Senescence inhibition (sugars, organic acids, lycopene, colour)
(Banda et al., 2015)	Pomegranate (<i>cv. Wonderful</i>)	9	5	Tray: Polyethylene terephthalates (PET) Film: Material 1: low barrier polymeric Thickness: 26 mm,	Tray: 11.5 x 11.5 x 3.5 cm ³	300	Passive	Sensory scores Microbial loads

		12	5	Permeance rate: $3.5 \times 10^{-13} \text{ mol.m}^{-2} \cdot \text{s}^{-1}$. $\text{Pa}^{-1} \text{ O}_2$, $7.0 - 9.4 \times 10^{-14} \text{ mol. m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$ CO_2 at 23°C and) Material 2: high barrier polymeric Thickness: 55mm Permeance rate of $9.8 - 10.8 \times 10^{-14} \text{ mol. m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$ O_2 , $7.0 - 9.4 \times 10^{-14} \text{ mol.m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$ CO_2 at 23°C) film sealed on top of the tray			Active (30 kPa O_2 + 40 kPa CO_2 + 30 kPa N_2)	
(Odrizola-Serrano et al., 2008)	Fresh cut tomato (<i>Lycopersicon esculentum</i> Mill. cv. Bola)	14	5	Tray: Polypropylene (PP) Film: Permeability: of O_2 and CO_2 were $5.2419 \times 10^{-13} \text{ mol O}_2 \text{ m}^{-2} \text{ s}^{-1} \text{ Pa}^{-1}$ and $2.3825 \times 10^{-12} \text{ mol CO}_2 \text{ m}^{-2} \text{ s}^{-1} \text{ Pa}^{-1}$ at 23°C	not indicated	100	Active (5 kPa O_2 + 5 kPa CO_2)	Microbial growth
(Oliveira et al., 2012b)	Fresh sliced mushrooms (cv. <i>Agaricus bisporus</i>)	1	15	Tray: Material: not indicated Film: Material: cellophane film™ 335 PS film Thickness: 23.3 μm Permeability: $3 \text{ ccm}^{-2} \cdot \text{d}^{-1} \cdot \text{Bar}^{-1}$ for O_2 at 23°C at 38°C) perforated with a needle of diameter 0.33 mm	Tray: 11.1x 15.5 x 3.4 cm3	110	Passive	Firmness
		2	10					
		4	5					
		7.5	0					

Reference	Fruit or Vegetables	Shelf life (d)	Temperature (°C)	Film + tray properties	Film or tray dimension	Weight of the fruit (g)	Type of MAP	Quality parameter for shelf life identification
(Conte et al., 2011)	Fresh-cut Cime di rapa (<i>cv. Brassica rapa L.</i>)	14	5	Film: Material: Oriented polypropylene Thickness: 20 mm	Film: 500 cm ²	25	Active MAP1 10 %O ₂ , 2 %CO ₂ and 88 %N ₂	Visible moulds
		9				25	Active MAP2 8 %O ₂ , 2% CO ₂ and 90 %N ₂	Mesophilic bacteria
(Karacay and Ayhan, 2010)	Orange segments (<i>cv. Citrus sinensis</i>)	10	4	Tray: Polypropylene (PP) Lidding: Material : CPP/OPP with Permeability : O ₂ and CO ₂ of 1296 cm ³ m ⁻² day ⁻¹ and 3877 cm ³ m ² day ⁻¹ , respectively at 24°C	Tray 14.4 × 19.0 × 5.0 cm ³	350	Passive and Active (80% O ₂ , 10% CO ₂ , 10% N ₂)	Sensory panel
(Villalobos et al., 2014)	Breba fruit (<i>cv. San Antania</i>)	14	0	Tray: Polyethylene (PE) Film: Material: Microperforated biaxially oriented polypropylene (BOPP) M50 (1 hole per 50 mm) Thickness: 40 µm Film on top of the tray	Tray: 26 × 16 cm ²	300	Passive	Fruit softening Control of postharvest decay
	Breba fruit (<i>cv. Banana</i>)	21						

Reference	Fruit or Vegetables	Shelf life (d)	Temperature (°C)	Film + tray properties	Film or tray dimension	Weight of the fruit (g)	Type of MAP	Quality parameter for shelf life identification
(Sahoo et al., 2015)	Pointed ground (cv. <i>Trichosanthes dioica</i> Roxb.)	16	4	Film: Polypropylene (PP) Thickness: 45 µm	Film: 0.625 m ²	500	Passive	Physiological loss in weight (PLW)
		4	23	Film: Material: Low density polyethylene (LDPE) with 5 pin holes of 0.3 mm in each side of the film Thickness: 25 µm				

1.2.3.3 Linking shelf life increase in MAP, food losses reduction and resulting environmental impact is not straightforward

MAP technology able to increase shelf life of the food product and in consequence reduce food losses and wastes, will inevitably have an impact on the environment (Figure 6). To the best of our knowledge, environmental impact of the food/packaging system as a whole is not yet measured. In addition, so far in the literature no studies were conducted on the quantification of the link between food shelf life increase due to MAP technology and the reduction of food losses and wastes (FLW) (Link 1- Figure 6), resulting in a decrease of the environmental impact (FLW) (Link 2- Figure 6).

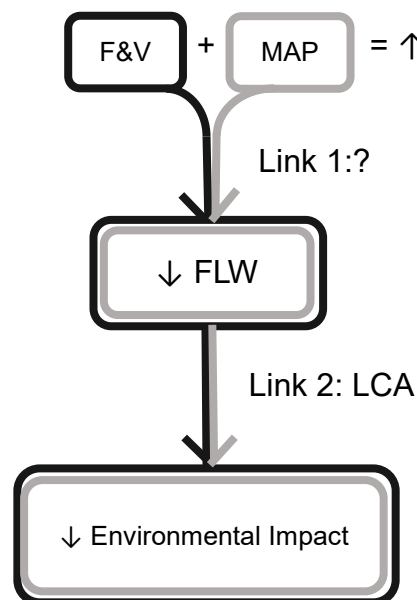


Figure 6: Schematic representation of the 2 links between packed food under MAP and Food losses and wastes reduction (FLW) (Link 1) and FLW and reduction of the environmental impact (Link 2). The grey line represent and black line represent the contribution of the MAP packaging and food product respectively in the identification of food losses and wastes and consequently their environmental impact.

The most widespread technique to assess environmental impact of a product at all the stages of its life, from production till its disposal, is life cycle analysis (LCA). LCA is a cradle to grave approach that has taken a leading role with a strong expansion at international level and that is largely used for packaging materials. The aforementioned technique takes into account at each step inputs and outputs material flows having an environmental impact. Among the published articles assessing the environmental impact of food by LCA, the majority of the studies are focusing mainly

on the food product waste. The environmental impact of food waste is discussed all along the supply chain without considering at all the usage benefit of the packaging technology. We can cite for instance a study conducted in Finland that evaluated the impact of food wastes emission in GHG emission at the retailers, restaurant, food industry and household food level (Katajajuuri et al., 2014). Similarly, another study conducted worldwide, treated food waste environmental impact at each stage of the supply chain from agricultural production till consumer level (Scialabba, 2013b).

Scarcer LCA studies are working on integrating the packaging in the system boundary, including packaging material production, waste and packaging usage benefit (in terms of reduction of food waste and losses) in the assessment of the environmental impact of food/packaging system.

One of the rare studies on this subject was done by William et al who developed a mathematical model able to link environmental impact of food losses and waste reduction due to the use of a new packaging to the overall energy use or environmental impact of food losses. The model can calculate the environmental impact of food packaging system as a function of food losses generated by the use of this packaging. The objective is to analyze the possible environmental gain from developing packaging that reduces food losses (Wikstrom and Williams, 2010).

The unit of calculation e considered in the study, represents environmental impact per unit of food eaten by the consumer. e can be explained through the following equation:

$$e=B(1 - L) \quad (5)$$

where L is the fraction of food lost at the consumer phase (dimensionless) ($L = 0$ means no losses, $L = 1$ means that all purchased food is lost). Thus, eaten food e (kg, L, nutrient, etc.) is equal to the amount of purchased food B (kg, L, nutrient, etc.) minus the lost part of purchased food BL .

William et al 2010, created a model balance where the environmental impact of the eaten food, E^i , is equal to the environmental impact of the purchased food plus the environmental impact of the waste handling of the lost food at the consumer level. The environmental impact of the purchased food includes postharvest chain, packaging

production and packaging waste stages and are expressed through the following equation:

$$E^i = B(F^i + P^i + W_P^i) + W^i BL \quad (6)$$

where E^i is the overall energy use or environmental impact (MJ, carbon dioxide equivalent), the environmental impact category, i , can be energy use, global warming potential, eutrophication potential, etc. the environmental impacts were not aggregated in this model. B the amount purchased food (kg, L, nutrient, etc.). F^i Energy use or environmental impact to produce and distribute one unit of purchased food to the consumer, with the exception of packaging, F^i includes storing of food at home (MJ, carbon dioxide equivalents, etc. per unit of purchased food). P^i represents the energy use or environmental impact to produce the packaging for one unit of purchased food to the consumer (MJ, carbon dioxide equivalents, etc. per unit of purchased food). W_P^i Waste handling of packaging, W^i is the energy use or environmental impact of waste handling of the food lost at the consumer phase (MJ, carbon dioxide equivalents, etc. per unit of lost food in the consumer phase) (Figure 7).

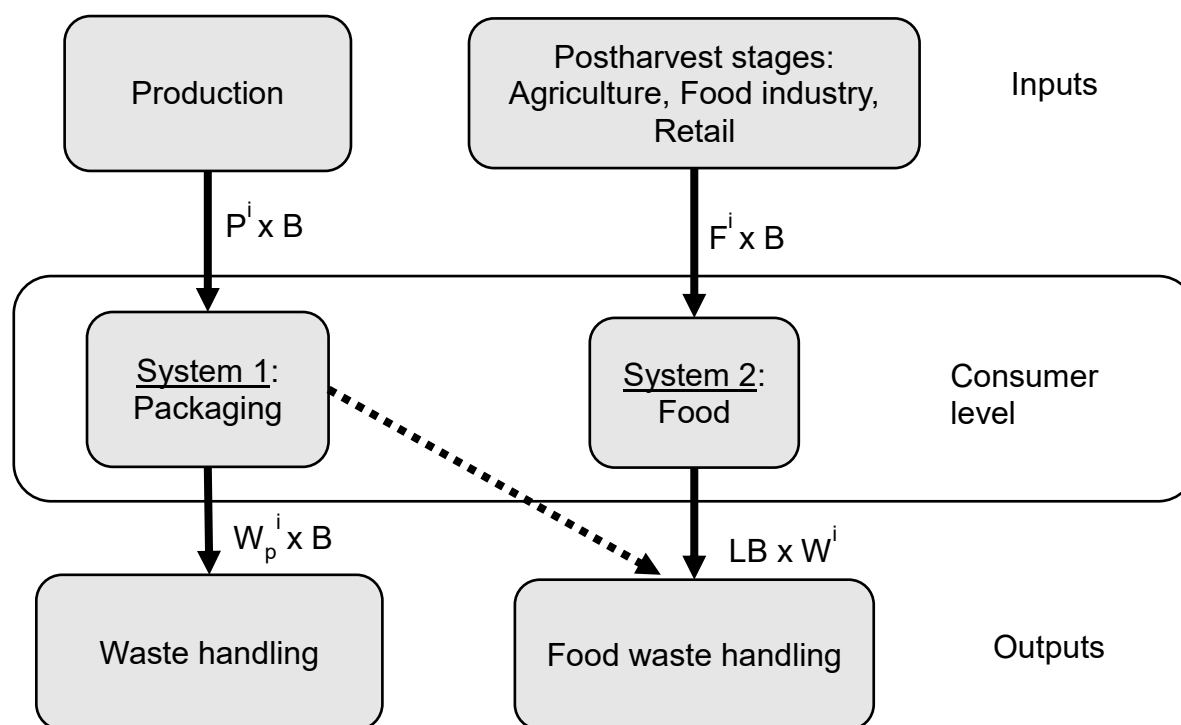


Figure 7: Stages taken into account in the environmental assessment of packed food system at the consumer level, done by Williams et al 2010. Dotted line and full lines represents respectively the missing and established link taken into account while assessing the environmental impact assessment of the packed product.

To compare the overall environmental impact of two different packaging, the ratio of E_1^i and E_2^i respectively, environmental impact of packaging one and two is done by rearranging Eq. (6) as follow :

$$\frac{P_2^i}{P_1^i} < \frac{1-L_2}{1-L_1} + \frac{W_{P_1}^i(1-L_2) - W_{P_2}^i(1-L_1) + W^i(L_1-L_2) + F^i(L_1-L_2)}{P_1^i(1-L_1)} \quad (7)$$

In addition, P^i , F^i and W_p^i values of the studied food product were found in LCA databases and studies and data from waste handling studies implemented the model parameter W^i . However, L_1 and L_2 representing fraction of lost purchased food were more difficult to identify. In fact, this fraction of losses is highly depending on the packing used. Thus to each type of packing used, a corresponding fraction of losses L is attributed. To overcome this problem, William, emitted hypothesis on losses fraction resulting from packaging used because no link is yet established between the packaging and its impact on food (Figure 7- dotted line). Thus, packaging is seen only as an environmental burden, consuming some resources and generating some wastes and is excluded from the system.

For example, in a recent article, Wikström et al 2016, compared two packaging alternatives for packing 500 g of minced meat: Tube and tray packaging and to estimate the amount of food losses and wastes related to the packaging. The value of FLW for each packaging was determined experimentally by weighting the packaging before and after washing following the discard act. Thus losses only related the packaging design are taken into account, however, the impact of the packaging on the shelf life of the product was not studied. Perhaps the tube packaging will preserve longer the quality of the product and thus increase the shelf life of the product (Wikström et al., 2016).

Other examples were developed on bread and cheese (Williams and Wikström, 2011). Thus, by assuming that losses L_1 and L_2 between packaging 1 and 2 passes from 20 to 15%. It was found that packaging can have a significant impact on reducing food waste in the food supply chain. In some cases, a new packaging with higher environmental impact is capable to reduce the overall food losses and waste (Williams and Wikström, 2011). Thus, reducing food losses will need more rather than less packaging. The tolerated impact of the packaging increase depends on the size of the initial food loss, the size of the food losses reduction, the ratio between the impact of the food and the impact of the packaging, the size of the reduction of food losses, the handling of food waste and packaging waste. Therefore developing an optimal packaging require considering the product and its package as a whole system (Verghese et al., 2015).

To date, in the F&V sector, no study was conducted on the environmental impact of fresh fruit and vegetables losses and wastes coupled with packaging production and waste in the postharvest chain.

To sum up, in spite of its high interest in reducing FLW and thus reducing the environmental impact of the food/packaging system as a whole, this positive usage benefit of packaging is never quantified in classical LCA approach (Figure 7 - dotted line or Figure 6 - Link 1), although, this quantification would be peculiarly relevant to allow stakeholders of the food chain to make decision as regard their packaging solutions.

1.2.4 Toward a more sustainable food packaging system: quantification of packaging benefit in real usage condition

So far researchers were interested independently in the estimation of product shelf life, food losses and wastes; ways to reduce it and the environmental impact of postharvest chain. Those three main topics were not yet clearer linked together even if it is already known that there is a relation between them (Figure 8).

On one hand, scientist well demonstrated that food losses and wastes are unneglectable and one of the ways to reduce it, is to increase the shelf life of the product. For fresh produce MAP was one of the emerging technologies able to increase shelf life of fresh produce. Questions are still asked around the percentage or quantity of food losses reduction that an increase of shelf life could lead to. In other words, how much FLW could be reduced if MAP packaging is applied. To answer this question, a quantification of the link between shelf life increase and food losses and waste reduction is needed (Figure 8 – Link 2). For this end, we can imagine conducting a test in the supermarket where fresh F&V packed in MAP are disposed on shelves for consumers to buy them. In the meanwhile, the quality evolution of the product is measured with time as well as the generated food losses and wastes.

On the other hand, the environmental impact of food losses and wastes and packaging used in the post-harvest chain, were studies independently in the literature. To accurately choose a packaging that will reduce the FLW and thus reduce the environmental impact, in addition to its production, the benefit of the packaging on shelf life increase or FLW reduction should be included in the LCA of the postharvest chain. This will enable us to know which environmental impact is permitted for a packaging material that will simultaneously decrease the overall environmental impact of the food product and packaging system in the postharvest chain.

In addition, linking directly the benefit of product packed in MAP and the resulting increase of shelf life is still unclear. i.e. how to quantify the shelf life increase of the product packed in MAP (Figure 8 - Link 1). To do this, an experimental methodology should be developed for quantifying the benefit of packaging on the shelf life increase by assessing shelf life as a function of packaging characteristics i.e. in case of MAP O_2 and CO_2 established by the packaging system.

Once the links between MAP packaging and shelf life increase (Link 1) and FLW reduction (Link 2) will be quantified, many other questions will emerge. For instance, the percentage of losses reduction that should be reached to be able to have a significant positive impact on the environment should be identified (Link 3). Furthermore, the cost of this switch to MAP technology in the post-harvest chain should be studied. When it comes to distributors, their awareness toward the MAP packaging on product shelf life is still uncertain questioning their willingness to invest more money in the packaging to reduce food losses and wastes. Thus, more research and knowledge is needed to answer these pending questions.

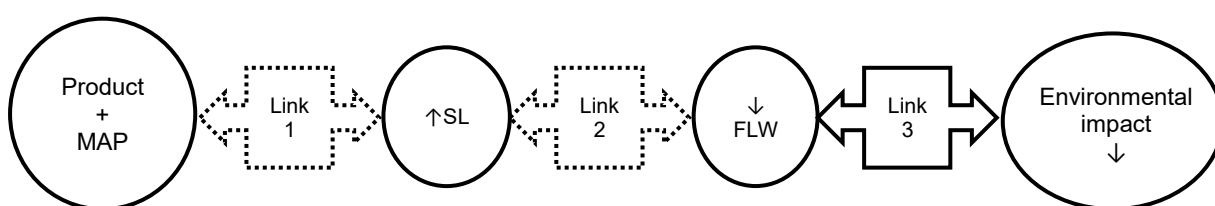


Figure 8: Missing links between represented in dotted lines and existing links represented in full lines between shelf life (↑SL) increase, food losses and wastes reduction (↓FLW) and environmental impact decrease

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1.3 Quantifying/Modelling shelf life of fruit and vegetables in MAP: A multicriteria decision based on product's quality and postharvest actors' behavior (Review 2)

Matar Céline, Gaucel Sébastien, Gontard Nathalie, Guilbert Stéphane & Guillard Valérie*

Joint Research Unit, Agro polymers Engineering & Emerging Technology, UM - INRA- Supagro & CIRAD, 2 place Pierre Viala, Bat 31, 34060 Montpellier cedex 01 France

*valerie.guillard@umontpellier.fr

Abstract

20 million people currently are at risk of famine while half of the fruit and vegetables is wastes. Fruits and vegetables' high perishability is one of the causes behind this high amount of losses. Modified atmosphere packaging (MAP) is a technology based on modifying the internal gases composition of the packed product and is used to increase product shelf life. Many predicting approaches were conducted to assess the shelf life of the product in MAP but very few of them quantified it in realistic conditions. This paper aim to discuss the current available modelling approaches developed to quantify shelf life of a product in MAP highlighting their advantages and drawbacks and future needs. It was shown that no studies assessed the shelf life of the product using one global representative quality parameters. Shelf life predictive models are either considering consumer acceptability or gases composition in the headspace but not both at the same time. No realistic storage conditions with consumer behaviour were tested in the laboratory to build more realistic predictive models. Researchers need to conduct survey to identify actor's behaviour in the postharvest chain in order to take it into account in the modelling approach. This will lead to the development of decision support tools with gases prediction, shelf life and consumer aspects.

Keywords

Consumer behavior, prediction, shelf life in days, realistic storage, headspace gases composition, Decision support tool

Nomenclature

Symbols	Definition	Unit	Equation
A_w	Water activity	Dimensionless	
pH	Potential hydrogen	Dimensionless	
D_{inci}	Decay incidence	%	8
n_{tot}	Total number of strawberries in the tray		8
n_{inf}	number of infected strawberries		8
α	Scale parameter (estimated)	day	9, 14
β	Shape parameter (estimated)		9, 14
$E_{a\alpha}$	Activation energy for parameter α	$KJ.mol^{-1}$	9
$E_{a\beta}$	Activation energy for parameter β	$KJ.mol^{-1}$	9
t	Time	days or s	9, 14
F	Firmness	N	9, 12, 14
T	Temperature	$^{\circ}C$	9, 13, 14
T_{ref}	Reference temperature	$^{\circ}C$ ou K	9, 12, 13, 14
R	Gas constant	$Kj.mol^{-1}.K^{-1}$	9, 12, 13
β_0 to β_{13} or β_{14}	Fitting parameters	Dimensionless	10, 16
ΔE	Color measurement	Dimensionless	10, 16
S.Eval	Sensorial evaluation	Dimensionless	10
SCC	Soluble solids content	$^{\circ}Brix$	10
UNSD	Ultrasound treatment		10, 16
SL_{MAX}	Shelf life according to bacterial development	day	11
E_{Bac}	Enumeration of bacteria growth	CFU/g	11
α_0 and α_1	Fitting parameters	Dimensionless	11
E_A	Activation energy	$Kcal.mol^{-1}$	12
K_{ref}	Reaction rate constant at T_{ref}	day^{-1}	12
Y	Value of the sensory attribute at time t		12
Y_0	Value of the sensory attribute at time $t=0$		12
ϕ	Normal cumulative distribution		13
S	Rejection function		13
μ_T	Fitting parameter		13
σ	Fitting parameter		13
μ_{Tref}	Fitting parameter		13
N	Percentage of strawberries affected	%	15
K_s	Spoilage rate	day^{-1}	15
N_{max}	Maximum spoilage	%	15
Rel_{MR}	Relative metabolic rate	Dimensionless	15

R_{CO_2}	O ₂ consumption rate	$cm^3.kg^{-1}.day^{-1}.atm^{-1}$	16
R_{O_2}	CO ₂ production rate	$cm^3.kg^{-1}.day^{-1}.atm^{-1}$	16
SL	Shelf life	days	10, 16
D	Percentage of surface deterioration	%	17
D_{max}	Maximum percentage of deterioration	%	17
δ_{CO_2}	¹ Inhibiting effect of carbon dioxide on the deterioration rate	dimensionless	17
k_D	Deterioration rate constant	s^{-1}	17
D^{-1}	inverse function of the deterioration, i.e. the function which compute the time (s) corresponding to an input value of deterioration	%	18
t_{SL}	Shelf life	days	18
D_{acc}	maximal acceptable deterioration	%	18

1.3.1 Introduction

Fruits and vegetables (F&V) accounts for around half of the total food losses and wastes (Gustavsson et al., 2011). In fact, F&V are living organisms which explains their perishability and very short shelf life. Reducing their losses and wastes will have a major health, environmental and economic impact (Porat et al., 2018). First, it will increase the product availability knowing that F&V contains essential elements for the human diet such as vitamins, fibres, minerals etc. In parallel, precious natural resources will be saved such as fresh water, energy, fertilizers etc. In consequence, food availability will be increased contributing in feeding the 20 million people currently at risk of famine (von Grebmer et al., 2017) and reducing the overall environmental impact of the postharvest chain.

One major way to reduce food losses and wastes of fresh F&V is to increase their shelf life. Thus, scientists are focusing on developing technologies able to control food quality with time while reducing the addition of additives having poor reputation among consumers. Among them, modified atmosphere packaging (MAP) technology is specially designed to extend the shelf life of the product (C Guillaume et al., 2010) and thus contribute to reduce the food losses. MAP could be defined as the modification of the atmosphere inside the package in order to reduce physicochemical, microbiological and physiological food degradation rates. MAP could be passive or active. In passive MAP, two processes are involved in the establishment of the optimal

gas composition (i) gases transfer through the packaging and (ii) products' respiration (Falagán and Terry, 2018). After passing through a transient period, a steady state is established due to the equilibrium of gases in the headspace. Usually the equilibrium consists of low O₂ concentration and intermediate to high CO₂ contents. These latter are used for simultaneously reducing the risk of oxidation and adding a fungi static effect. The proportions of each gas (O₂/CO₂/N₂) depend on the nature of the product and the ratio of volume of the package to the volume of food. N₂ is commonly used as a filler (C Guillaume et al., 2010). Establishing MAP is usually a case by case study depending on the product packed (Kader et al., 1989). Active MAP is obtained by adding external compounds or by flushing gases at the packing stage. The objective here is to establish faster the optimal gases equilibrium in the headspace. The external compounds could be oxygen scavengers or carbon dioxide emitters (Falagán and Terry, 2018; Gontard and Guillaume, 2010).

Supermarket and consumer postharvest steps are responsible of around 50% of the total losses in the postharvest stage due to inadequate storage duration, storage temperature, handling conditions, etc. that contribute to shorten product shelf life ((Quested et al., 2013). This is often due to a lack of knowledge about the product physiology and postharvest needs. Porat et al 2018, in their latest review on postharvest losses of fruit and vegetables during retail and in consumers' homes in UK and USA, highlighted the importance of multidisciplinary research incorporating consumer and distributors behavior in studies related to postharvest storage (Porat et al., 2018).

The positive impact of MAP for F&V on their shelf life extension is very well known by the scientific community. Around 400 articles could be found by a query done on march 2018 on the Web of Science after typing the three keywords MAP, F&V and shelf life as topics in all databases separated by AND connector. All these articles demonstrated directly or indirectly that MAP could increase fresh products' shelf life. However, very rare quantitative approaches exist i.e. shelf life is very rarely determined and expressed in days. The most elaborated approaches for shelf life estimation in MAP are the use of mathematical models. However, no complete quantifying modeling approach exists considering at the same time realistic storage conditions and stakeholders behaviors including consumers.

Firstly, the impact of surrounding atmosphere (O_2 and CO_2) on shelf life of fruit and vegetables remains unsatisfactorily explained, understood and mastered. A large number of studies exist on the impact of quality parameters in predefined gases composition established due to MAP system. This pack and pray approach is fully empirical without any elucidation of the link between quality and level of O_2 and CO_2 in the headspace.

Secondly, no studies took into account simultaneously the effect of modified atmosphere and storage conditions and the impact of the behavior of the postharvest stakeholder on the evolution of product quality during the postharvest step.

A complete, quantitative shelf life approach combining technological effects such as MAP and cold chain and stakeholders' common practices would permit to have a holistic and more efficient approach of the postharvest chain. It would contribute to minimize the number of experiments and the economic and safety hazard consequences of empirical "pack and pray" or "trial and error" approaches so widely used at present.

The aim of this review is to display current knowledge about the quantitative evaluation of shelf life in MAP, on the parameters used to define it and on the implication of the post-harvest actors in the definition of shelf life. This review focus on articles discussing only the impact of MAP on the quality and, voluntarily discards articles discussing the impact of hurdle technologies, i.e. use of combination of technologies such as coating, irradiation, etc... with MAP, to increase even more the food shelf life.

In a first part, shelf life definitions and available experimental methods to assess shelf life of a product will be reviewed and discussed, followed by a description of current quantifying shelf life modeling approaches for F&V in MAP. Exhaustive discussion will be provided highlighting ways to complete and improve the current approaches. In a second part, impact of post-harvest stakeholders' behaviors and habits on the "true" shelf life of a given F&V will be debated. The last part will discuss the possibilities of building an efficient decision support tool able to predict shelf life in MAP followed by an identification of the future research needs.

1.3.2 Overview of shelf life definition

“Shelf life is defined as the time during which the food product will, (1) remain safe, (2) be certain to retain desired sensory, chemical, physical and micro-biological characteristics and (3) comply with any label declaration of nutritional data when stored under the recommended conditions” (*Shelf life of foods: guidelines for its determination and prediction*, 1993). The aforementioned definition is the most detailed one suggested by ‘The Institute of Food Science and Technology’ (IFST) in the UK. A Standardized shelf life definition applied by all scientists and industrials is difficult to establish.

In fact, the product shelf life and quality are closely related because sensory, chemical, physical and microbiological characteristics also take part in defining the quality of a product (Figure 9). In addition, the quality of the product also depend on the satisfaction of consumer’s demands (Valero et al., 2012). Defining food quality is complex. The frequently cited definition of food quality is “The combination of attributes or characteristics of a product that have significance in determining the degree of acceptability of the product to a user.” Attributes and characteristics of the product include the perception of the food’s safety, convenience, cost, value; thus, not just its sensory attributes (J. Robertson, 2010). In all the definitions when the user decides of the acceptability of a product, the quality is compared to a threshold value, the acceptance limit. The product is only accepted if the quality exceeds the acceptance limit (Figure 9). Thus, acceptability of a product depends on product quality and on the level of the acceptance limit (Steele, 2004).

Acceptability is directly related to keeping quality of a product. For fruit and vegetables (F&V) products, properties such as color, firmness and taste change over time. Keeping quality is “the time before the product attributes drops below the acceptance limit”. Hence, keeping quality combines 2 aspects of product acceptance, the acceptance limit and product quality into a generally applicable index of quality. Keeping quality and shelf life are terms often interchangeable and are indeed closely connected. Shelf life is the keeping quality under standardized conditions (Steele, 2004) (Figure 9).

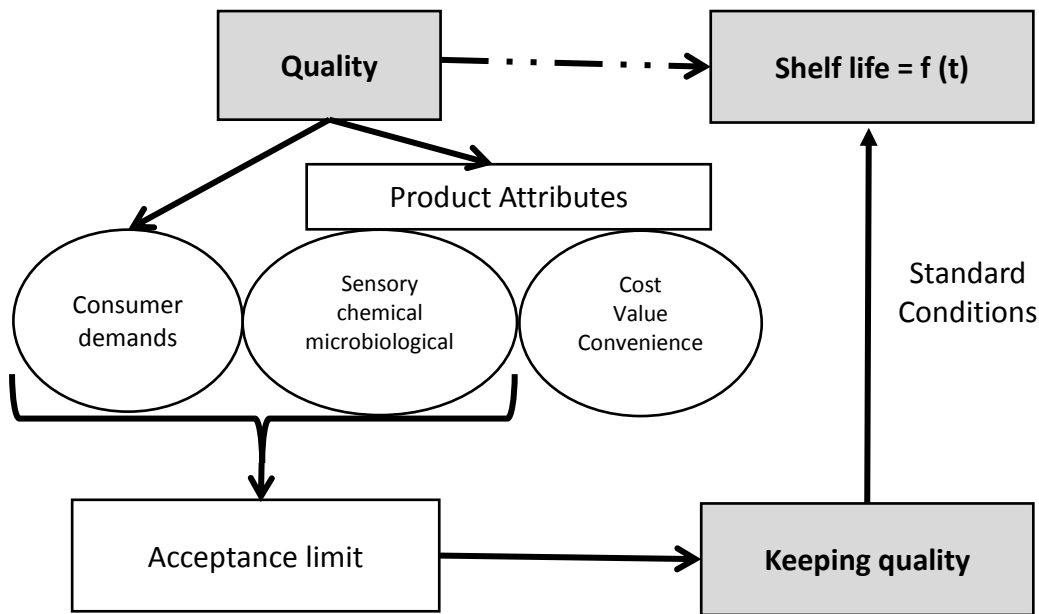


Figure 9: Relationship between shelf life, quality and keeping quality

Factors affecting food shelf life. Internal and external factors can influence the shelf life of a product (Steele, 2004). Intrinsic factors gather the characteristics of the food matrix and extrinsic factors are external conditions encountered by the product as it moves through the food chain from processing and storage to distribution i.e. surrounding environment and headspace of the packed food (Figure 10).

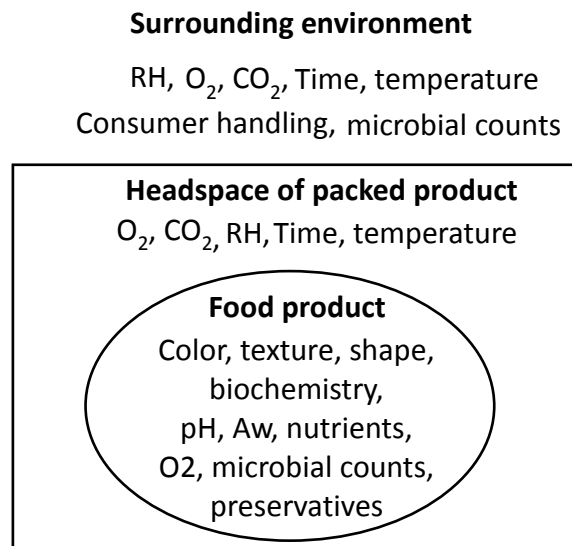


Figure 10: Intrinsic and extrinsic factors influencing product's shelf life

The interaction of intrinsic and extrinsic factors either inhibits or stimulates a number of processes which limit shelf life. All these factors can operate in an interactive and

unpredictable way. If the combination of factors is able to prevent microbial growth, it will allow manufacturers to use milder preservation techniques. In consequence, most of product's sensory and nutritional properties are retained (Kilcast and Subramaniam, 2000). The most important extrinsic factors affecting F&V quality are:

- **Temperature.** A low temperature is commonly used because it slows down respiration and thus decay. But it can induce shrinkage of the F&V because of the dry air in the refrigeration system (Hertog et al., 2014). Thus, optimum temperature is set according to each F&V to maintain its quality and maximize their shelf life (do Nascimento Nunes et al., 2014).

- **Humidity.** High humidity is considered optimal because it prevents F&V dehydration. But it has the disadvantage of increasing fungal development on F&V (Hertog et al., 2014) and leads to condensation inside the current available packaging materials (do Nascimento Nunes et al., 2014).

- **Headspace gases composition** established around the product. Decreased O₂ and increased CO₂ concentrations are used as a replacement of ambient atmosphere. This modified atmosphere contributes to reduce the respiration of the F&V and thus increase shelf life. In fact, in the representation of the respiration via Michaelis and Menten law, an apparent constant K_m stand for the value to which the percentage of oxygen should be reduced to, in order to divide by two, the respiration rate of the product. For example, K_m of strawberries is equal to 8100 Pa. Thus in that case, an oxygen concentration equal to 8% would divide by half the respiration rate of the strawberries. CO₂ is also known to reduce microbial growth (Hertog et al., 2014) and keep a better texture, color and a more attractive product for the consumer (do Nascimento Nunes et al., 2014). For example, 20% of CO₂ is recommended for optimal fig storage. But, carbon dioxide could also have some deleterious effect and high levels of CO₂ could not be systematically used for all crops such as tomato, lettuce and endive that tolerate a maximum of 2% of CO₂ (Zagory and Kader, 1988).

A '**use by**' or '**best before**' date is specified on the label according to products' shelf life. For highly perishable food, a 'use by' date is indicated when microbiological factors are the limiting ones such as for fish, meat products, ready prepared salads, etc. A 'best before' date is needed for medium or long shelf life products where the chemicals

and sensory characteristics have to be controlled such as dried or tinned food product (Kilcast and Subramaniam, 2000; Ministry for Primary Industries, 2014). Other less common open shelf life dates include a **sell by** date, a **best if** used by date or a **better if** used by date (Steele, 2004). No date is displaced on F&V label. In fact, the identification of fresh F&V degradation is very easy and simple unlike previous cases. Because, F&V will rotten and changes of taste, color or odor are signs for the consumer to reject the product way before consumption.

1.3.3 Monitoring quality parameters needed for shelf life estimation in MAP

During shelf life estimation in MAP, quality parameters frequently assessed in parallel, are divided in three main groups: physicochemical analysis, decay identification and sensorial analysis.

Physicochemical analysis. Physicochemical analysis gathers mainly measurements including colour, texture, weight loss, pH, acids and TSS (total soluble solids). For assessing colour, a Chromameter is frequently used. CIELAB colour system composed of $L^*a^*b^*$ colour parameters are used to calculate a colour index (CI) (Pathare et al., 2013). a^* for red/green colour attribute, b^* for yellow/blue colour attribute and L^* for lightness coordinate. L^*a^* and b^* are dimensionless (Aday and Caner, 2013; Adobati et al., 2015; Guillaume et al., 2013; Oliveira et al., 2015). A less common tool to measure colour change is a digital processing image as done by Guillaume et al 2013. In their work, photos of the studied parsley were taken along 8 days, then the photos are processed using photoshop software to select parts of the images corresponding to a browning or lightening of the leaf. Next, identified areas of different colours were attributed to corresponding CIE lab parameters (Guillaume et al., 2013). For texture analysis, firmness is measured using a texture analyser and expressed generally in N or N/s. Weight loss is measured by weighing the content of the packages, before and after the storage period and expressed as the percentage of weight loss with respect to the initial weight (Gantner et al., 2016; Oliveira et al., 2012a; Villalobos et al., 2016). Apart pH and total soluble solids content (SSC) are often monitored using a refractometer and expressed in °Brix. Organic acids are sometimes identified using high performance liquid chromatography (HPLC) method. The organic acids identified depend on the fruit or vegetable studied. For instance, malic and tartaric acids are specifically investigated

in tomatoes, lactic acid in iceberg lettuce (Fagundes et al., 2015; Paillart et al., 2017). Instrumental analysis provide repeatable, quick results compared to analysis done using a panel of consumer where a large effort should be done to gather consumers. However, instrumental analysis does not reflect consumer acceptability of the product and result should be interpreted with precaution.

Decay characterization. General fruit decay is usually characterized using two approaches: classical microbiological analysis or visual evaluation of the number or % of spoiled products. Microbiological analyses are done after grinding and incubating the sample in a dedicated media with appropriate time and temperature to each microorganism studied. Finally, enumerating of microorganisms on the petri dish is done. Microbiological analysis are expressed in colony forming units per g of sample (CFU/g) (Guillaume et al., 2013; Lareo et al., 2009; Paillart et al., 2017; Villalobos et al., 2016). Visual identification of decay is done by enumeration of spoiled product or weighting of damaged fruits. Aday et al 2013, visually assessed strawberries decay by counting the number of fruits with visual moulds lesions. The % of spoiled strawberries was then expressed as follows:

$$D = \frac{n_{\text{inf}}}{n_{\text{tot}}} \times 100 \quad (8)$$

where n_{inf} is the number of infected strawberries, n_{tot} is the total number of strawberries in the tray and D is the decay in % (Aday and Caner, 2013). Adobati et al 2015, followed the same enumeration approach in their work on the assessment of raspberries shelf life in MAP at 5°C, and considered not only mouldy berries but also fruits damaged by other causes such as mechanical chocks, etc. Results were expressed in % damaged berries (Adobati et al., 2015). Contrary to these previous works, Villalobos et al 2016, in their study of MAP on whole figs quality assessment in MAP, chose to weight the fruits with visible damage. The considered disorders were skin damage, fungal rots, smut, souring and fermentation. The decay was expressed as a percentage of original weight of the packed fruit (Villalobos et al., 2016). Decay analysis are simple to conduct but relying only on this visual analysis doesn't give any information about the change in the taste or odour of the product.

Sensorial analysis. Sensorial analysis is mainly conducted by trained panel of consumers. These latter are provided a score for each product or quality attributes evaluated, according to a numbered scale graduated generally, from 1 to 10, in order to assess the global quality of the product. Most common sensorial parameters are external appearance i.e. welting appearance, skin and flash colour, firmness, presence of brown and necrotic strains or flavour attributes such as sweetness, sourness, bitterness (Aday and Caner, 2013; Lareo et al., 2009; Paillart et al., 2017; Villalobos et al., 2016). This approach has revealed many advantages and drawback. The assessment of fresh product quality requires the availability of a panel of consumer during a long period of time which is sometimes difficult to accomplish. In addition, the panel should be well representative of the target population. However, the consumer's point of view is taken into account which is important for a realistic evaluation of product quality.

Globally, the main disadvantages of all the methods listed above for assessing quality of products packed in MAP, are the numerous and time consuming sampling that should be done in parallel to have a complete assessment of the quality (evolution with time and repetitions needed). In addition, it is sometimes difficult to aggregate all the information gained from these tests in a single, unique quality parameter that could help the user/consumer to take a decision. What would be needed is a global quality parameter that is able to encompass more than one of the aforementioned quality parameters in order to evaluate product's quality in MAP conditions and its evolution with time. It would permit to decrease the cost of multiple quality parameters analysis. In the same purpose of decreasing experimental cost, mathematical models have also been proposed to predict food shelf life.

1.3.4 Current modeling approaches of shelf life

Modelling shelf life of F&V is a widespread practice to reduce the large amount of experimental tests. Many modeling approaches were proposed, claiming to be shelf life predicting. However, among these approaches, a majority focused on the prediction of one quality parameters as a function of time and very few models quantified product shelf life in days. A query on the web of science, in March 2018 using the following keywords 'MAP', 'Fresh fruit and vegetables', 'shelf life', 'modeling'

separated by the connector 'AND', has revealed that among the 87 articles found, only 7 predicted food shelf life in days (Table 3).

The approach used to develop a predictive model of food shelf life in MAP is always the same: starting by an experimental assessment of shelf life using quality parameters, followed by fitting experimental data with the appropriate equation such as linear, non-linear or Weibull equation mimicking the behavior of the chosen quality parameter as a function of time. This first class of models constitute in the following, the so-called **basic modelling approaches**. Later on, some improvements were proposed to these models including the acceptability of the consumer or linking shelf life evolution to the impact of headspace gases composition. These type of **upgraded models** will be discussed in a second part. In a third one, further **advances needed** will be proposed for a complete shelf life modelling approach.

Simplified modelling approaches. This category of models predicts product shelf life in MAP based only on experimental quality parameters. For instance, Oliveira et al 2012, developed a kinetic model to predict shelf life of sliced mushrooms and studied the influence of temperature on the firmness of mushrooms. First, the optimal storage condition in MAP was set by identifying the number of perforations needed in a cellophane 335 PS film at three temperature of storage 5, 10 and 15°C. Next step was to assess the quality of the product by measuring weight loss, pH, firmness and color. To each quality parameters, a Weibull equation was fitted to describe the kinetic degradation of quality parameters as a function of time. Firmness was identified as the critical parameter since it was the most affected by temperature. For a given firmness and temperature, a shelf of the product can be deduced in days (Eq. (9), Table 3). Thus, in this article, the shelf life was expressed through one quality parameters 'the firmness' affected by the temperature of storage with predetermined number of films perforations to establish desired MAP conditions (Oliveira et al., 2012a). Another example is the work done by Putink et al 2017b, where the shelf life of fresh cut apples varieties *Golden delicious* and *Cripps pink* treated with anti-browning agents such as ultrasound treatment, ascorbate and citric acid was assessed. To identify the shelf life of the product, all the measured physicochemical parameters were integrated in one shelf life linear regression model. In fact, pH, sensory evaluation, color measurements, soluble solids of apples were linked to estimate a shelf life as presented in Table 3 Eq.

(10). *Golden Delicious* and *Cripps Pink* are the apple varieties studied. Treatments applied on the fruit are: Ca-ascorbate, USND + Ca - citric acid and ultrasound treatments. This is another possible strategy where each quality parameter is given the opportunity to participate in the assessment of shelf life unlike Oliveira et al 2012 who used only firmness to represent mushrooms quality. In addition, Puntik et al 2017, developed another linear model for microbial development (Eq. (11), Table 3). From Eqs. (10) and (11) in Table 3, a shelf life in days could be deduced. Thus, compared to Oliveira et al 2012, Puntik et al 2017 proposed a more complete assessment of the quality by taking into account many physicochemical parameters and the microbial quality.

However, to be able to reproduce the two previously cited works, one should be able to work under similar experimental conditions than the ones experienced by the authors i.e. oxygen and carbon dioxide headspace compositions. But these values and especially their evolution with time were not mastered in the previous studies. Therefore, a lot of preliminary experimental work is needed to be able to achieve similar storage conditions. In addition, in none of the aforementioned examples, the shelf life was measured according to consumer acceptability. We don't know at what time the consumer won't accept to buy the product anymore. To sum up, these modeling approaches are simply explicative and not really predictive: they could be reused to extrapolate some results in the same conditions but could not be used to predict a shelf life in different conditions.

Upgraded shelf life models in MAP: Combining consumer acceptability and quality models. Another category of works went farther in the shelf life modelling approach, combining modelling of quality parameters with estimation of consumer acceptability for a fairer determination of product's shelf life as done in the work of Lareo et al 2009 on butterhead lettuce. Nonlinear regression equation was used to represent the sensory quality parameters such as wilting appearance, presence of brown and necrotic strains, browning on the midribs and off odors. In this purpose, sensory shelf life estimation was done by a trained panel. Quality parameters that have been modeled were represented through Eq. (12) in Table 3. In parallel, for each sample, before destructive assessment of the quality parameter, consumers had to evaluate product appearance and respond "yes" or "no" to the question "Imagine you

are in a supermarket, you want to buy a minimally processed lettuce, and you find a package of lettuce with leaves like this, would you normally buy it? The rejection function is given by Weibull equation (Eq. (13), Table 3). Using this equation, consumers' rejection percentage could be predicted as a function of storage time (Lareo et al., 2009). By the time 25% of the consumers rejected the product, the limit of acceptability in days was identified. Shelf life of the product in these experimental conditions, considering consumer acceptability is equal to the limit of acceptability in days (Eq. (13), Table 3). In this approach, consumer acceptability was taken into account in the determination of product shelf life. In Another example, **Adobati et al 2015** calculated consumer rejection of raspberries concomitantly with the assessment of product firmness. For this end, 40 untrained panel of consumers were asked to conduct visual assessment of the acceptability by answering yes or no to the question 'Imagine you are in a supermarket to buy raspberries; would you buy this tray?'. The limit of acceptability in days was set by the time 50% of the consumers rejected the product. In parallel, the product firmness at different storage time was represented using Weibull equation (Eq. (14), Table 3) (Adobati et al., 2015). The intersection between the limit of acceptability in days and firmness predictive model enable us to have the value of the firmness at the limit of acceptability.

Despite this improvement, these experiments are still not easily repeatable because the gases composition surrounding the product need to be established and modelled to be easily reproduced. If this composition changes, its effect on firmness could not be anticipated limiting the interest of these models.

Upgraded shelf life models in MAP: Combining virtual MAP models and shelf life models. One of the rare examples is a model developed in a controlled atmosphere situation by **Hertog at al 1999**. A logistic equation was built to assess spoilage development on strawberries. Spoilage representing the number of spoiled strawberries expressed in percentage (Eq. (15), Table 3). In this equation, the effect of CO₂ was added. Thus, the product's spoilage as a function of time will be affected by gases composition surrounding the product. In this case, whatever the gases composition surrounding the product, one can predict a spoilage development on strawberries. It is thus not necessary to achieve the same gases composition surrounding the product as the author (Hertog et al., 1999). Another most recent trial

of integrating O₂ and CO₂ impact during shelf life assessment in MAP was done by Puntik et al 2017a. This author studied the influence of apple color change in MAP as a function of antibrowning treatments, gases composition in the headspace of the packed product and shelf life in days (Eq. (16), Table 3) . Gases composition in the headspace are the result of a mass balance between product respiration rate and permeability of the packaging film (Putnik et al., 2017a).

However, in these works, when shelf life is combined to gas effect, the consumer acceptability is usually missing. Therefore, this predictive approach does not permit to fully evaluate and predict product shelf life.

Advances needed. Ideally, for a complete shelf life approach, one global quality parameter should be measured while taking into account simultaneously consumer acceptability and the impact of headspace gases composition on product shelf life (Figure 11). This approach was recently initiated by Matar et al 2018, who predicted through a logistic function the deterioration of the strawberries as a function of time (Eq. (17), Table 1.3.1). The only quality parameter used here was the visual evaluation of the strawberries surface deterioration in percentage. In this deterioration equation, the impact of carbon dioxide is taken into account. In addition, consumer acceptability was identified after asking 30 untrained consumers whether they will buy or not the product. This limit of acceptability was also taken into account in the prediction of product shelf life through Eq. (18) in Table 3.

Modelling Shelf life in MAP

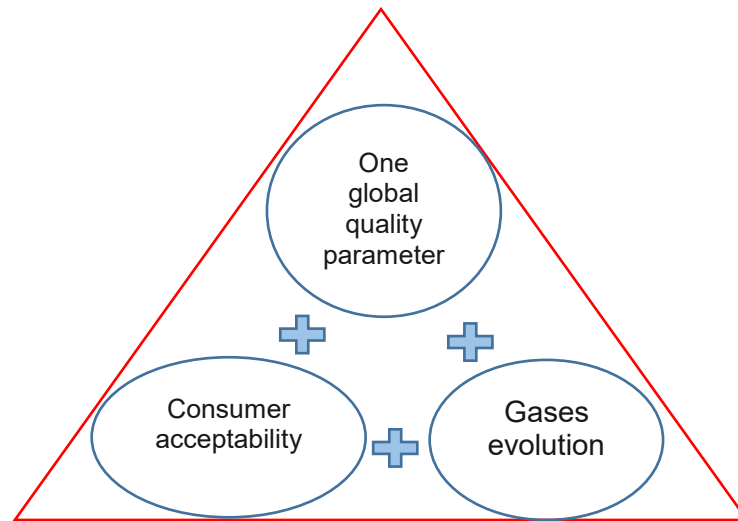


Figure 11: Proposed complete shelf life approach assessing simultaneously the evolution of a quality parameter, gases in the headspace and consumer acceptability with time.

Table 3: Type of models used for modelling shelf life of F&V in MAP or MA as a function of time

Type of shelf life model	Eq	Mathematical equation used for shelf life determination	Values of parameters	Environmental parameters used in the model	Fruit studied	Consumer panel	References
Weibull model	(9)	$\frac{F - [T + 325.32]}{141.14 - [T + 325.32]} = \exp \left(- \left[\frac{t}{\alpha \exp \left(-\frac{E_{a\alpha}}{R} \left[\frac{1}{T} - \frac{1}{T_{ref}} \right] \right)} \right]^{\beta} \exp \left(-\frac{E_{a\beta}}{R} \left[\frac{1}{T} - \frac{1}{T_{ref}} \right] \right) \right)$ <p>α: Scale parameter (d^{-1}); β: Shape parameter (dimensionless); t: time (d); F: Firmness (N); T: Temperature ($^{\circ}C$); T_{ref}: Reference temperature ($^{\circ}C$); $E_{a\alpha}$: Activation parameters for α ($KJ.mol^{-1}$); $E_{a\beta}$: Activation parameters for β ($KJ.mol^{-1}$); R: Gas constant ($KJ.mol^{-1}.K^{-1}$).</p>	<p>$T = 0,5,10,15^{\circ}C$ $E_{a\alpha} = 76.4 KJ.mol^{-1}$; $\alpha = 2.33$; $\beta = 1.05$; $E_{a\beta} = 39.2 KJ.mol^{-1}$</p>	Temperature T via Arrhenius law	Sliced mushrooms	No	(Oliveira et al., 2012a)
Linear regression model	(10)	$SL = \beta_0 + \beta_1 \times \log(pH) + \beta_2 \times \log(SSC) + \beta_3 \times \log(S.Eval) + \beta_4 \times \log(\Delta E) + \beta_5 \times (Golden\ Delicious) + \beta_6 \times (no\ treatment) + \beta_7 \times (ascorbic + citric\ acid) + \beta_8 \times (Ca - ascorbate) + \beta_9 \times (UNSD + Ca - ascorbate) + \beta_{11} \times (Golden\ Delicious) \times (ascorbic + citric\ acid) + \beta_{12} \times (Golden\ Delicious)(Ca - ascorbate) + \beta_{13} \times (Golden\ Delicious) \times (UNSD + Ca - ascorbate)$ <p>β_0 to β_{13}: Fitting parameters (dimensionless); SSC: Soluble solids</p>	<p>$T = 4^{\circ}C$ $\beta_0 = 10.07$; $\beta_1 = -10.28$; $\beta_2 = -2.77$; $\beta_3 = -0.40$; $\beta_4 = 0.04$; $\beta_5 = 0.42$; $\beta_6 = 0.22$; $\beta_7 = 0.02$; $\beta_8 = 0.04$; $\beta_9 = 0.14$; $\beta_{10} = -0.04$; $\beta_{11} = -0.02$; $\beta_{12} = -0.04$; $\beta_{13} = -0.24$;</p>	Treatments	Apple Golden delicious	No	(Putnik et al., 2017b)

		contents (°Brix); S.Eval : Sensorial evaluation; ΔE : Color measurement (dimensionless); UNSD: Ultrasound treatment.																									
	(11)	$SL_{MAX} = \alpha_0 + \alpha_1 \times \log(EBac) + \text{error}$ SL_{MAX} : Shelf life according to bacterial development (days); α_0 and α_1 : Estimated parameters; EBac : Enumeration of bacteria growth (CFU/g).	$T = 4^\circ\text{C}$ $\alpha_0 = -0.66; \alpha_1 = 3.52$																								
Weibull distribution	(12)	$Y = Y_0 \exp \left(k_{ref} \exp \left(- \frac{E_A}{R} \left(\frac{1}{T} - \frac{1}{T_{ref}} \right) \right) t \right)$ <p>Y: Sensory quality parameter; E_A: Activation energy representing the effect of temperature, R: Gas constant; T_{ref}: Reference temperature (K); t time (s), T: Temperature of storage (K); Y₀: Value of the sensory attribute at time t = 0; K_{ref}: Reaction constant at T_{ref} (days⁻¹).</p>	$T = 5, 10, 15^\circ\text{C}$ <table border="1"> <thead> <tr> <th>Parameters \ Sensory quality</th> <th>Y₀</th> <th>K_{ref} (days⁻¹)</th> <th>E_A (kcal.mol⁻¹)</th> </tr> </thead> <tbody> <tr> <td>Wilting appearance</td> <td>0.15 ±0.02</td> <td>0.41 ±0.05</td> <td>13.5 ±0.7</td> </tr> <tr> <td>Presence of brown and necrotic stains</td> <td>0.12 ±0.01</td> <td>0.51 ±0.04</td> <td>14.7 ±0.6</td> </tr> <tr> <td>Browning of the midribs</td> <td>0.10 ±0.01</td> <td>0.41 ±0.03</td> <td>12.6 ±0.5</td> </tr> <tr> <td>Off odors</td> <td>0.02 ±0.01</td> <td>0.64 ±0.04</td> <td>14.1 ±0.6</td> </tr> </tbody> </table>	Parameters \ Sensory quality	Y ₀	K _{ref} (days ⁻¹)	E _A (kcal.mol ⁻¹)	Wilting appearance	0.15 ±0.02	0.41 ±0.05	13.5 ±0.7	Presence of brown and necrotic stains	0.12 ±0.01	0.51 ±0.04	14.7 ±0.6	Browning of the midribs	0.10 ±0.01	0.41 ±0.03	12.6 ±0.5	Off odors	0.02 ±0.01	0.64 ±0.04	14.1 ±0.6	Temperature in μT via Arrhenius law	Butterhead lettuce	Yes	(Lareo et al., 2009)
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	(13)	$S(t) = \phi \left(\frac{\ln(t) - \mu_T}{\sigma} \right)$ $= \phi \left(\frac{\mu_{T_{ref}} - \frac{E_A}{R} \left(\frac{1}{T} - \frac{1}{T_{ref}} \right)}{\sigma} \right)$ <p>S: Survival function; ϕ : Normal cumulative distribution; μ_T and σ: Model's parameters; μ_T depend on the temperature; R: Gas constant; T_{ref}: Reference temperature (K); E_A: Activation energy representing the effect of temperature (Kcal.mol⁻¹).</p>	<p>T = 5, 10, 15°C $\sigma = 0.27 \pm 0.03$; $E_A = 1129 \pm 118.7$ kcal.mole⁻¹; $T_{ref} = 298$ K</p>				
Weibull distribution	(14)	$F(t) = e^{-\left(\frac{t}{\alpha}\right)^\beta}$ <p>F: Firmness (Nmm); t: Time (days); α: Scale constant parameters of the distribution (dimensionless); β: Shape constant parameters of the distribution (dimensionless).</p>	<p>T = 5°C $\alpha = 4.12$; $\beta = 2.25$</p>	-	Whole Raspberries	Yes	(Adobati et al., 2015)
Logistic equation	(15)	$\frac{dN}{dt} = Rel_{MR} K_s N \left(\frac{N_{max} - N}{N_{max}} \right)$ <p>N: Percentage of strawberries affected (%); N_{max}: Maximum spoilage equal to 100%; K_s: Spoilage rate of tissue deterioration (day⁻¹). Rel_{MR}: Relative metabolic rate i.e. ratio between CO₂ production rate in constant predefined O₂ and CO₂ concentrations (μmol.kg⁻¹.s⁻¹) and CO₂ production rate in atmospheric conditions with 21 %O₂ and 0 %CO₂ (μmol.kg⁻¹.s⁻¹).</p>	<p>T = 8, 10, 12°C $N_{max} = 100\%$; $K_{s,ref} = 0.60 \pm 0.045$ day⁻¹; $T_{ref} = 10^\circ\text{C}$; $N_0 = 0.72\%$ ou 2%</p>	Temperature in K_s and $k_{Q,dyn}$ via Arrhenius law CO ₂ via V_{CO_2}	Whole Strawberries	No	(Hertog et al., 1999)

<p>Linear regression model</p>	<p>(16)</p>	$\Delta E = \beta_0 + \beta_1 \times L^* + \beta_2 \times a^* + \beta_3 \times b^* + \beta_4 \times SL + \beta_5 \times R_{O_2} + \beta_6 \times R_{CO_2} + \beta_7 \times R_{CO_2} + \beta_8(\text{golden delicious}) + \beta_9(\text{cripps pink}) + \beta_{10} \times (\text{no treatment}) + \beta_{11} \times (\text{ascorbic} + \text{citric acid}) + \beta_{12} \times (\text{Ca} - \text{ascorbate}) + \beta_{13} \times (\text{USND} + \text{Ca} - \text{ascorbate}) + \beta_{14} \times (\text{USND} + \text{ascorbic} + \text{citric acid}) + \text{error}$ <p>Golden delicious and crippls pink are the two apple cultivar studied ΔE: Color measurement (dimensionless), L^*, a^*, b^* : CIE LAB parameters; β_0 to β_{14} : Fitting parameters (dimensionless), R_{CO_2} : Respiration rate represented in CO₂ production (cm³.kg⁻¹.day⁻¹.atm⁻¹), R_{O_2} : Respiration rate represented in O₂ consumption (cm³.kg⁻¹.day⁻¹.atm⁻¹); SL: Shelf life (days)</p>	<p>T = 4 ± 2°C The exponential of the equation will give the following parameters $\beta_0 = 54.50$, $\beta_1 = -0.83$, $\beta_2 = -0.01$, $\beta_3 = 0.86$, $\beta_4 = -0.22$, $\beta_5 = 0$, $\beta_6 = 0$, $\beta_7 = 1.29$, $\beta_8 = -2.76$, $\beta_9 = 0$, $\beta_{10} = 42.14$, $\beta_{11} = 1.15$; $\beta_{12} = -1.30$; $\beta_{13} = -0.52$, $\beta_{14} = 0$, error = 0</p>	<p>Treatments CO₂ via R_{CO₂} O₂ via R_{O₂}</p>	<p>Apple of the 2 varieties Golden delicious and Cripps Pink</p>	<p>No</p>	<p>(Putnik et al., 2017a)</p>
<p>Differential equation</p>	<p>(17)</p>	$\frac{dD}{dt} = k_D D \frac{D_{max} - D}{D_{max}} \delta_{CO_2}$ <p>D : Percentage of surface deterioration (%) at time t (s); D_{max} : Maximum percentage of deterioration (%); k_D : Deterioration rate constant (s⁻¹), δ_{CO_2} : Inhibiting effect of carbon dioxide on the deterioration rate (dimensionless).</p>	<p>T= 5, 10, 20°C $D_{max} = 100\%$; $k_{D,5^\circ C} = 6.98 \times 10^{-06}$ (6,19 × 10⁻⁰⁶; 7,77 × 10⁻⁰⁶) s⁻¹; $k_{D,10^\circ C} = 9.93 \times 10^{-06}$ (8.97 × 10⁻⁰⁶; 1,08 × 10⁻⁰⁵) s⁻¹; $k_{D,20^\circ C} = 3.16 \times 10^{-05}$ (3.09 × 10⁻⁰⁵; 3.24 × 10⁻⁰⁵) s⁻¹.</p>	<p>Temperature O₂ via $\frac{dn_{O_2}}{dt}$ CO₂ via $\frac{dn_{CO_2}}{dt}$</p>	<p>Whole strawberries of the variety Charlotte</p>	<p>Yes</p>	<p>(Matar et al., 2018)</p>
	<p>(18)</p>	$t_{SL} = D^{-1}(D_{acc})$ <p>D^{-1}: inverse function of the deterioration, i.e. the function which compute the time (s) corresponding to an input value of deterioration (%); t_{SL}: shelf life (days); D_{acc}: maximal acceptable deterioration (%).</p>	<p>T= 5, 10, 20°C $D_{acc} = 13\%$</p>				

1.3.5 Testing realistic postharvest scenarios

Products' shelf life is ineluctably influenced by storage conditions and actor's behavior along the postharvest chain. Actors are mainly stakeholders in each of the postharvest stage for instance, wholesalers, supermarket managers, consumers at the household stage. Porat et al 2018, insisted on the importance of incorporating the supermarket and consumer stages in the postharvest chain studies (Porat et al., 2018). In addition, Muriana et al 2017, concluded that to optimize supply chain strategies, the impact of the shelf life on the demand behavior has to be taken into account (Muriana, 2017). Thus, in order to accurately assess shelf life of fresh F&V in MAP, information regarding possible storage conditions (time and temperature), behavioral tendencies of the stakeholders are needed.

So far, postharvest storage conditions of the product such as at the distribution, supermarket or consumer level were not yet taken into account. Most of the researchers worked on one constant temperature of storage without mimicking realistic post-harvest time and temperature. For example, Adobati et al 2015, assessed shelf life of raspberries at 5°C, thus mimicking only the ideal conditions of storage that could be in the storage room or in a refrigerated lorry (Adobati et al., 2015). But, fruit are not stored at these ideal temperatures in a realistic supply chain. Other researchers such as Lareo et al 2009, studied the quality of butterhead lettuce stored at three different temperatures 5, 10 and 15°C covering a wider range of temperature (Lareo et al., 2009). However, these temperatures of storage were applied to three different fruit batches, unlike realistic storage conditions where a single batch is subjected to a fluctuating temperatures. The ideal situation is to apply consecutive different temperatures of storage on one batch of fruit.

In addition, in France, quantitative studies on the behavior of the stakeholders linked to fresh fruit or vegetables shelf life are not yet available. This information would permit a more realistic estimation of product shelf life at the consumer level. For instance, in the USA, a study conducted by Pma, a trade organization, aims at understanding the buying habits and preferences of consumers in purchasing packed fresh F&V. Internet and in store surveys were conducted. Results showed that 80 % of consumers purchase at least once a week fresh fruits and vegetables and only 10-25% of the purchase is packed. According to the American consumer, the most important attribute

for packaging is that it preserves freshness and taste. However, Half of the shoppers prefer buying bulk produce because they believe they are cheaper and they are able to better inspect the produce before buying it. Thus similar probabilities related to buying habits are needed in France in order to integrate them in the shelf life estimation of the product. The objective will be to identify the behavior of the French consumer during purchase i.e. will the French consumer be ready to buy packed fresh fruit and vegetables. A typology of storage conditions i.e. duration of storage in the fridge and/or in ambient conditions will help the scientists assess product shelf life in a more realistic scenarios taking into account their probability of occurrence among the consumers.

In summary, for a more accurate shelf life assessment at the experimental level, quality parameters should be assessed in realistic temperatures profile and storage durations affected by probabilities of occurrence of actors' behaviors in the postharvest chain. Thus, the transition between the experiments done at the laboratory level and the application at the industrial level will be easier.

1.3.6 Toward an efficient decision support tool (DST) predicting shelf life of food in MAP

Integrative decision support tool (DST) of packed fresh food is an interdisciplinary research area involving food engineering, mathematical modeling, postharvest supply chain practices, socio economics and computer science. The objective is to combine information on storage behaviors, mathematical models to predict impact of various internal and/or external factors on food quality/shelf life of the packed food in the postharvest chain in order to eco design an adequate packaging for the studied produce. It involves development of user friendly interface to integrate various parts of food models and processes, storage conditions and behavior of the stakeholder in the postharvest chain and the environmental impact of the whole system.

Modelling tools may replace physical experiments, excepting experiments needed for model establishment and validation, by its equivalent predictive model. Therefore, it allows testing a larger number of possible storage scenarios and pointing out potential prediction limitations. Thus, Mathematical modelling offers a systematic approach of the process and can assist as a tool for data analysis and screening tests. In consequence, experiments can be done behind the computer replacing the trial and error approach minimizing the number of experiments and the economic cost of

empirical approaches called “the pack and pray approach” with “a requirement driven approach” taking into account product needs since the very beginning of its conception (Angellier-coussy et al., 2013a).

Today, little is available in terms of an integrated tool for food packaging design. Around 2400 publications are found on easy web of science discussing decision support tools based on predictive models in all science fields. Among them, only 76 publications discuss decision support tools applied on food products (This query was done in June 2018, separating the keywords ‘Decision support tool’, ‘prediction’, ‘models’ and ‘food’ with the connector ‘AND’). The most developed available user friendly software in the field of food packaging is EcoBioCap, a decision support tool (DST) proposing materials adapted to MAP of fresh F&V. This DST is able to design MAP system. MAP is set by achieving optimal atmosphere for the produce by matching the gas (O_2 and CO_2) permeation rate of the film with the respiration rate of the produce. Thus, knowing the optimal gases compositions to be achieved, the EcoBioCap is able to propose adequate film and at the same time responds to stakeholder’s demands throughout the supply chain. In fact, while launching a query, the user can ask for a packaging that in addition to its basic functionality “preserve food quality” through its optimal gas permeabilities, displays specific characteristics such as transparency, biodegradability. To answer that query, using methodologies of knowledge engineering, the software returns a ranking of films as close as possible to this query. This tool helps stakeholders of the food chain in the choice of a packaging material that would suit requirement of a given fresh fruit or vegetable, related to its biodegradability and permeability (Guillard et al., 2015).

However, in practice, the packaging material is not only driven by food quality and thus optimal film permeability. Numerous other requirements may interfere in the final decision and should be taken into account such as the potential shelf life gain, the food losses reduction due to the use of this packaging and the environmental impact, waste management of the food packaging system all over the food life cycle.

In fact, none of the current available software in the field of food packaging is able to fulfill all these requirements. What is needed is a DST able to predict the effect of packaging on shelf life of the packed food. In addition, the tool should help to estimate shelf life gain of specific produce in MAP and thus predict the reduction of food losses

along the supply chain by the use of MAP. For a sustainable food consumption, the DST interface should integrate also the resulting environmental impact of the whole system food/packaging.

1.3.7 Identifying future research needs

Despite the great interest in modelling shelf life of fresh fruit and vegetables in MAP, analysis of literature has revealed that mathematical equations able to predict simultaneously the impact of O₂ and CO₂ gases and actor's behaviours on the shelf life of food product in MAP are lacking.

The majority of available shelf life models are not linked to O₂ and CO₂ conditions, thus environmental conditions should be pre-established and fixed all along the experiments. In consequence making the experiment hardly repeatable and generalized to other packed product. Moreover, consumer and distributor behaviour are never taken into account concomitantly with the estimation of shelf life. The main reason is the unavailability of information on the behaviour of actors in the postharvest chain such as consumer at the household level.

The remaining questions to be solved are how to quantify/predict a product shelf life packed in MAP while taking into account surrounding conditions i.e. gases composition and temperatures of storage and actors' behaviour.

Research conducted in the near future should increase the accessibility of data concerning consumer and distributor behaviour by conducting surveys assembling information on time and temperatures of storages at each stages of the postharvest chain. However, How the actors such as distributors will behave in response to this shelf life gain, will this addition of MAP packaging in the postharvest chain be accepted by the consumer, will the consumer change his consumption habits due to this shelf life increase of the product. Many questions related to the consumer acceptability and distributor behaviour emerge defining interesting subjects to be studied in the near future.

Finally, an efficient mathematical user-friendly tool combining mass transfer and quantified predictive shelf life taking simultaneously into account stockholders behaviour and losses reduction and the overall environmental impact of the system is

substantial. This tool will help the decision makers in the future eco-design of packed F&V in the postharvest to minimize the overall environmental impact.

Acknowledgement

This work was conducted in the context of the Pack4Fresh project funded by the INRA-CIRAD Metaprogram GloFoodS and of the FP7-ERA-NET 618107 Eco Berries.

1.4 Concluding remarks

The state of the art concerning the role of packaging in the sustainability of the food chain highlighted the role of packaging in increasing product shelf life focusing on modified atmosphere packaging technology. At the same time, the **lack of shelf life quantification** approach in MAP was noted: less than 13 articles quantifying shelf life were reported in scientific literature before this PhD Project. In addition, **environmental impact of the food and the packaging as a whole system including the influence of the packaging on the food losses and wastes reduction** is rarely represented in a clear and simple manner. Further research is needed to quantify the links between produce packed in modified atmosphere packaging, **shelf life increase and resulting food losses and wastes reduction**.

Concerning the review on the quantification and modelling of fresh fruit and vegetables in MAP, the main findings are the **lack of complete shelf life modelling approaches** i.e. approaches focusing on **one global quality parameter** assessed as a function of time while considering the effect of gases established due to MAP technology and consumer acceptability. In addition, **realistic storage conditions** of fresh produce complemented by consumer behaviour to mimic postharvest chain are not investigated yet.

Moreover, gathering information related to quantities of food losses and wastes at each postharvest chain was one of the biggest challenges. In fact, we were confronted to **a lack of published percentages of losses and wastes for fruit and vegetables** especially for the model food 'strawberries'. The rare ranges of data found at the supermarket level (10-15%) and consumer level (2-30%) are only rough estimations. In addition, stakeholders' behaviors and post-harvest practices appear very important to consider in shelf life prediction of fresh produce.

Figure 12 summarizes the data on losses and wastes available in the literature for the postharvest chain of strawberries. Wastes are not taken into account in this study because they depend on consumer behavior and are independent of product quality such as food not consumed in time, high quantity of purchased food, bad storage conditions etc.

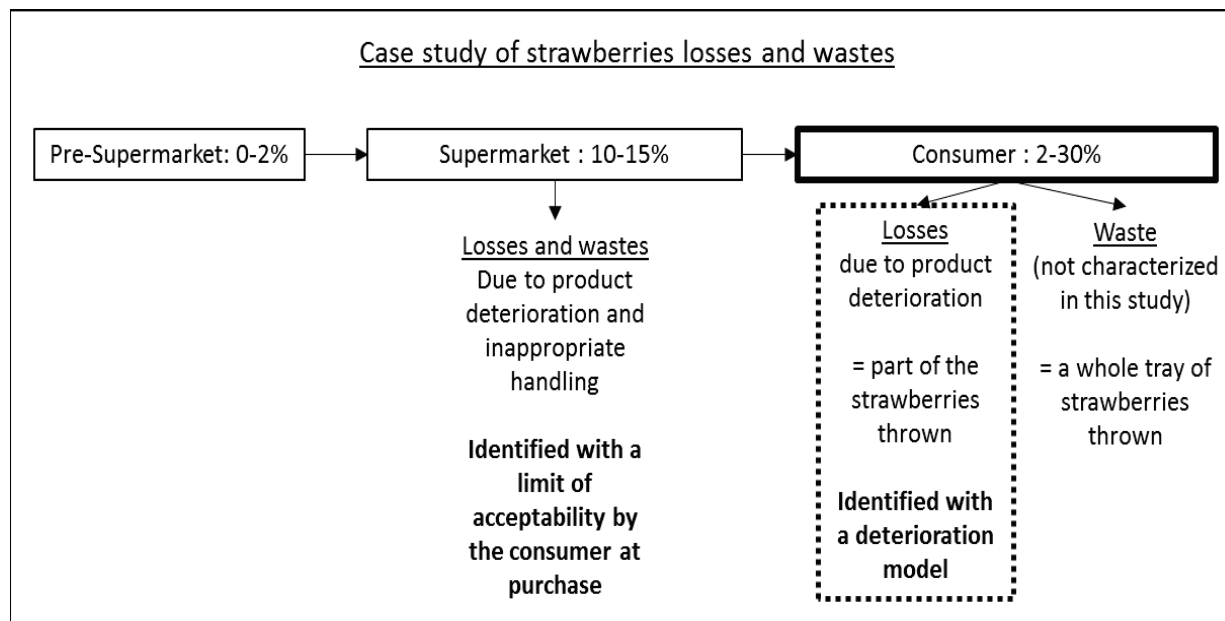


Figure 12 : Losses and wastes in the postharvest chain of strawberries. The dotted frame represents the section of the postharvest chain losses that will be quantified in this study.

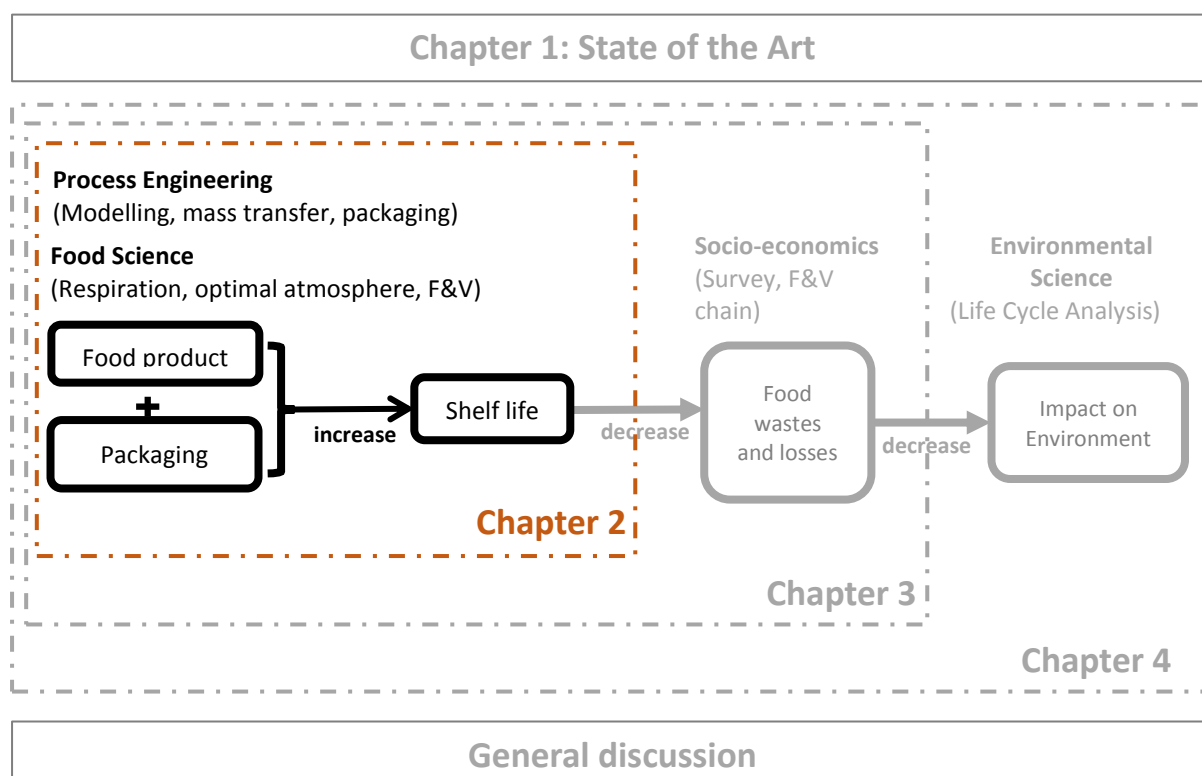
MAIN FINDINGS

- Lack of complete shelf life modelling assessment in MAP including consumer acceptability, effect of surrounding atmosphere on product quality
- No real quantification/identification of the benefit of MAP
- Absence of a link between product shelf life and corresponding percentages of losses
- Lack of clear and detailed data on the percentage of fruit and vegetables (especially for the food model in this study: strawberries)
- The objective of this PhD will be to quantify losses at the consumer level related to product quality
- Environmental impact of the postharvest chain including food losses and packaging (production, disposal and effect of food losses) is not yet done.

Chapter 2: Building a shelf life quantification model

Chapter 2: Building a shelf life quantification model

2.1 Introduction



The state of art conducted in chapter one revealed the lack of quantification approach for fresh fruit and vegetables' shelf life in MAP. This is essentially due to the lack of clear and simple methods and predictive mathematical model assessing accurately the quality of the product. The current models of shelf life in MAP mainly predict oxygen and carbon dioxide evolution in the headspace of the product.

The available methods to assess product quality in MAP were already presented in the previous chapter. This overview of the existing methods helped us to design a better method of quality assessment of fresh produce in MAP. In our study, strawberry was the model food. Thus, the first paper (Part 1.2) represents a detailed description of the method developed for the assessment quality of the strawberries and its validation in MAP packaging.

In a second paper (Part 1.3), the current mathematical model predicting gas composition (O_2 and CO_2) in MAP was improved and coupled with a deterioration

Chapter 2: Building a shelf life quantification model

model developed in the framework of this thesis. The construction and validation of this model is explained in details in this article. Afterwards, a limit of acceptability by the consumer was identified and confronted to the deterioration curve to quantify the shelf life of the product. Finally, the simulation of post-harvest storage conditions in order to mimic realistic strawberries storage conditions was done. Improvement of storage temperature, at the consumer level, to increase product shelf life were also tested.

2.2 A global visual method for measuring the deterioration of strawberries in MAP (Article 1)

Submitted in MethodX journal and currently under revision

Matar Céline, Gaucel Sébastien, Gontard Nathalie, Guilbert Stéphane & Guillard Valérie*

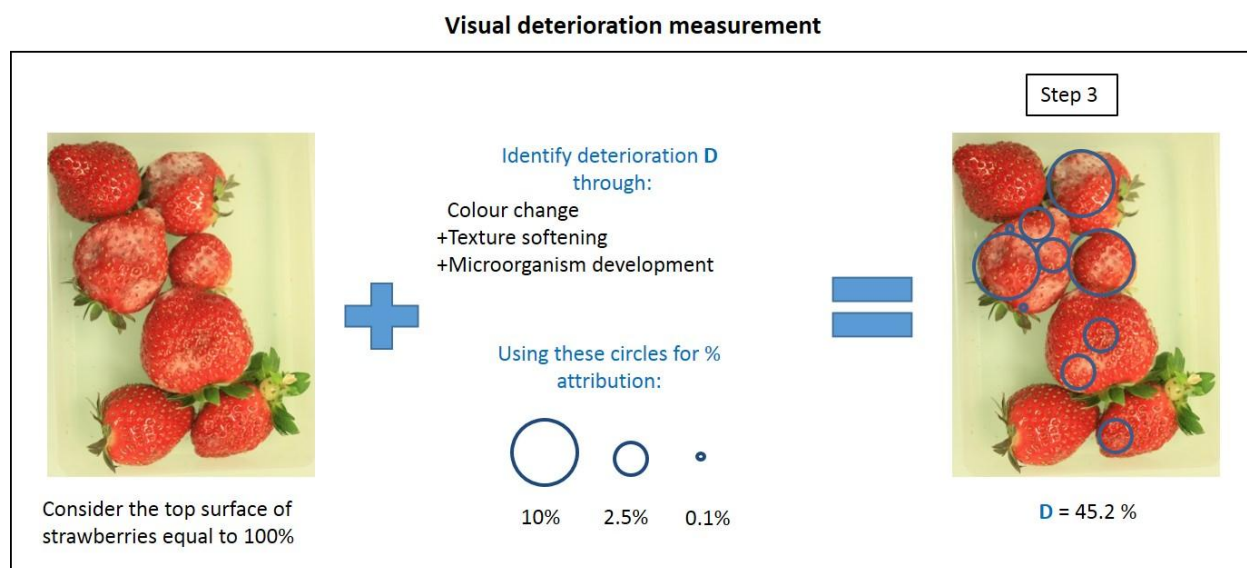
Joint Research Unit, Agropolymers Engineering & Emerging Technology, UM - INRA- Supagro & CIRAD, 2 place Pierre Viala, Bat 31, 34060 Montpellier cedex 01 France

*valerie.guillard@umontpellier.fr

Abstract:

Evaluating the quality changes of packed strawberries during storage requires multiple, time consuming and costly measurements such as sensorial, chemical and decay identification. In order to efficiently assess the quality of strawberries in Modified Atmosphere Packaging (MAP) while reducing the number of analysis done, we propose to gather the main visual quality changes under one unique, overall measurement. For this end, a protocol associated to a deterioration grid was built to evaluate surface deterioration as a function of time considering colour change, texture softening and microorganism development. The developed method has permitted to build the deterioration kinetic of strawberries packed in different conditions (MAP or no MAP). It allows to mimic the quality analysis made by the consumer, at a glance, during purchase. To the best of our knowledge, the presented method is a breakthrough unlike most common usual methods mainly relying on the number of spoiled strawberries.

Graphical abstract



- Global measurement of the deterioration encompassing microorganism development, color change and texture softening
- An annotation grid built to be used as reference for the attribution of the percentage of strawberries' deterioration
- Measurements of a percentage of surface deterioration was found more accurate than counting the number of rotten strawberries

Keywords:

Assessing deterioration, deterioration grid, Texture softening, color change, microorganism development

Specifications Table

Subject area	<i>Agricultural and Biological Sciences</i>
More specific subject area	<i>Assessing product deterioration in MAP</i>
Method name	<i>Global visual deterioration assessment of strawberries</i>

Methodology background. Assessing the quality of strawberries as a function of time is an important step for the characterization of products' shelf life. So far, many quality parameters are measured in parallel to assess the overall quality of

strawberries such as total soluble solids (TSS), firmness, color, decay on the fruit, etc. However, these multiple measurements are time consuming, require sophisticated equipment and a high amount of strawberries. In this paper, we present global visual evaluation of the strawberries' quality expressed as the percentage of deteriorated surface area, namely percentage of deterioration. This visual percentage of deterioration encompass color change and/or texture softening and/or microorganism development, similarly to the analysis made by the consumer at purchase. In tight packed system, as in Modified Atmosphere Packaging, only visual assessment could be done. This methodology aims at mimicking this act of purchase.

Method details

2.2.1 Materials

- Strawberries of the variety "*Charlotte*", grown off-ground, (Mauguio, South of France)
- Film packaging made of low density polyethylene (LDPE) (BBA emballages, Lunel – France)
- Polypropylene (PP) trays (Attitud'Pack, Chatuzange Le Goubet-France) with dimensions of 0.14 × 0.095 × 0.025 m
- Memmert incubators for controlling the temperature (Memmert, Schwabach – Germany)
- Digital camera for pictures acquisition (Canon camera EOS 450D – Japan)

2.2.2 Method

2.2.2.1 Deterioration grid




A grid for measuring the percentage of fruit surface deterioration was built based on Ctifl studies (Vaysse et al., 2015, 2011). The deterioration is expressed through a percentage of visual surface deterioration of the fruit.

During time, this percentage of surface deterioration will evolve with the visual aspect of the fruit due to the softening of the texture, colour change and development of microorganism on the surface. Only visual aspects were included while building the grid as it is the only way for a consumer to check the quality of the fruits packed in MAP for purchase decision.

The percentage of the deterioration is identified on the pictures using 3 circles of decreasing sizes as indicated in Table 4. The radius R of the big circle was set so that the area of 10 big circles represents the whole surface of the strawberries. Each big circle then corresponds to 10 % of deteriorated surface. In order to have a more accurate estimation of the deterioration, medium and small circles were also considered with radius $R/2$ and $R/10$ and associated percentages of deterioration equal to 2.5 % and 0.1 % respectively.

To estimate a percentage of deterioration, the large damaged surfaces are first identified using big circles followed by lower damaged surfaces using medium and small ones. Note that all circles should be pairwise disjoint i.e. without intersection.

Table 4: Circles sizes used to estimate the percentage of deterioration

Size of the circle		% of surface deterioration
Big		$D_{BC} = 10 \%$
Medium		$D_{MC} = 2.5 \%$
Small		$D_{SC} = 0.1 \%$

The total percentage of deterioration D_{tot} (%) is expressed through the following equation:

$$D_{tot} = n_{BC} D_{BC} + n_{MC} D_{MC} + n_{SC} D_{SC} \quad (19)$$

with n_{BC} the number of big circles, n_{MC} the number of medium circles, n_{SC} the number of small circles, D_{BC} , D_{MC} and D_{SC} the percentage of deterioration associated respectively to the big, the medium and the small circles. Examples of annotation are given in Figure 13 for different levels of deterioration.










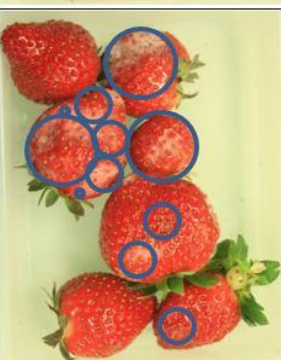
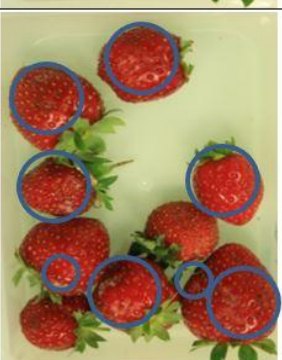

Blank photo			
Photo with annotation			
D_{tot}	0.7 %	7.6 %	20 %
Blank photo			
Photo with annotation and an estimation of the deterioration			
D_{tot}	45.2 %	65 %	82.5 %

Figure 13: Examples of deterioration annotation using small circles correspond to 0.1 % of deterioration, medium circles to 2.5 % of deterioration and big circles to 10 % of deterioration

2.2.2.2 *Experimental design*

- 1- Strawberries were harvested in the morning of experiments, cooled to 5 °C at the producer facilities, then picked up to the laboratory around 5 h after harvest where they were stored at desired temperatures for 3h.
- 2- Harvested strawberries were sorted according to maturity: over ripened i.e. fruits with soft texture, damaged or rotten were eliminated and under ripened fruits i.e. fruits with green, not fully mature, spots were discarded. Sorting was also done according to shape: oversized fruits or very small ones compared to the batch fruit sizes were eliminated.
- 3- In total 42 trays of 100 g of strawberries were prepared, 6 trays of strawberries were packed in macro perforated LDPE and were used as the control situation representing no MAP condition and 36 were put in MAP conditions at the same time $t=0$ using a non-perforated LDPE film packaging of 0.03 x 0.15 x 0.11 m dimensions and 50.5×10^{-6} m thickness (Table 5).
- 4- A first measurement of the deterioration using the grid was done for the 36 trays at $t=0$ right before packing the product in MAP conditions.
- 5- After $t=0$, every measurement of the deterioration in MAP is a destructive one. Indeed, the estimation of the percentage of surface deterioration was done after removing the film packaging, to be able to see clearly the surface of the fruit and thus after breaking the MAP condition. In consequence, each one of the 36 trays in MAP condition were for single-use. However, for no MAP condition, the same 6 trays were assessed for the whole duration of the experiment since the gases surrounding the product is always equal to the atmosphere composition and will not affect the deterioration of the product (Table 5).
- 6- Measurements of the deterioration is done twice a day, in the morning and in the afternoon during 6 days, for MAP and no MAP conditions. For each measurement, three replicates, corresponding to three trays, were evaluated (Table 5).

Note that, a picture of the opened trays is taken right after breaking the MAP condition and will later be examined and compared to the percentage of deterioration identified in the deterioration grid.

- 7- In parallel, a survey was conducted to identify the time at which the consumer will stop purchasing the product. For this end, a panel of 30 untrained consumers annotated the trays used for deterioration assessment, twice a day in the morning and in the afternoon for 6 days. The question asked to each consumer of this panel was 'Just by looking at the strawberries in the tray, are you willing to buy the product or not?' the 2 possible answers are 'Yes' or 'No'. When more than 50% of the consumer answered 'No', the product is considered not marketable anymore.

Table 5: Experimental plan indicating the label of the tray analysed at the corresponding days, for measurement done in MAP and no MAP conditions in the morning and in the afternoon.

Storage condition Number of the measurement	Control (no MAP)	MAP					
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
1 ST (Morning)	Tray 1	Tray 7	Tray 13	Tray 19	Tray 25	Tray 31	Tray 37
	Tray 2	Tray 8	Tray 14	Tray 20	Tray 26	Tray 32	Tray 38
	Tray 3	Tray 9	Tray 15	Tray 21	Tray 27	Tray 33	Tray 39
2 nd (Afternoon)	Tray 4	Tray 10	Tray 16	Tray 22	Tray 28	Tray 34	Tray 40
	Tray 5	Tray 11	Tray 17	Tray 23	Tray 29	Tray 35	Tray 41
	Tray 6	Tray 12	Tray 18	Tray 24	Tray 30	Tray 36	Tray 42

2.2.2.3 Method validation

In order to validate the visual evaluation of the strawberries' deterioration in MAP, we compared it to the common visual decay method used in the literature. The aforementioned method is based on a visual measurement of the % of decay or spoilage i.e. by counting the number of strawberries showing visible mold lesions on the surface expressed as a percentage of the total number of strawberries in the tray (Aday and Caner, 2013; Hertog et al., 1999; Riad and Brecht, 2015). Decay is thus expressed in percentage as follow:

$$S = (n_{\text{infec}} \times 100) / n_{\text{tot}} \quad (20)$$

where S is the decay in %, n_{infec} is the number of molded strawberries in the package, n_{tot} is the total number of strawberries in the package.

The evaluation of decay (based on counting spoiled strawberries (Aday and Caner, 2013; Hertog et al., 1999; Riad and Brecht, 2015)) and deterioration (based on surface (method developed in this article)) were conducted simultaneously, on the same samples using the experimental plan explained in section 2.2, for strawberries packed in MAP and no MAP conditions at 20°C.

Experimental values of decay (Figure 14(a)) and deterioration (Figure 14(b)) in MAP (○) or no MAP (●) conditions as a function of time showed a sigmoidal behaviour from 0% to 100% of decay or deterioration.

However, in Figure 14(a) the experimental points in MAP (●) and no MAP (○) for decay lead to quasi superposition of the two sigmoidal curves, depicting the same behaviour in MAP and no MAP condition. Therefore, differentiation between MAP and no MAP is difficult to assess. Thus, annotation based on a percentage of decay was not sufficient on its own in the identification of the quality difference between MAP and no MAP results. In fact, decay was identified through the number of molded strawberries in both MAP and no MAP conditions but no discrimination was made on the level of fruit's decay.

Whereas, in Figure 14(b), the percentage of deterioration in MAP and no MAP are separated in two independent sigmoidal curves. MAP condition result in a slight inhibition of the deterioration compared to no MAP condition. At 5.25 days, 100 % of the strawberries packed in no MAP are affected as compared to 82 % of strawberries in MAP condition. Unlike decay method, the deterioration grid was able to differentiate between MAP and no MAP condition because the deterioration method takes into account the surface of the fruit affected by a texture softening and/or microorganism development and/or color change at the same time.

Results of the survey showed that trays in no MAP conditions were not marketable from day 2 (morning) where more than 50% of the consumers answered 'No' to the asked question. However, trays in MAP condition were judged acceptable by the consumers until day 3 (morning). Therefore, consumer survey confirms that the kinetic

of degradation of strawberries is slower in MAP condition than in no MAP. This difference of behaviour of strawberries quality in two storage conditions, here MAP and no MAP, is well described by the deterioration factor while decay factor leads to a contradictory conclusion.

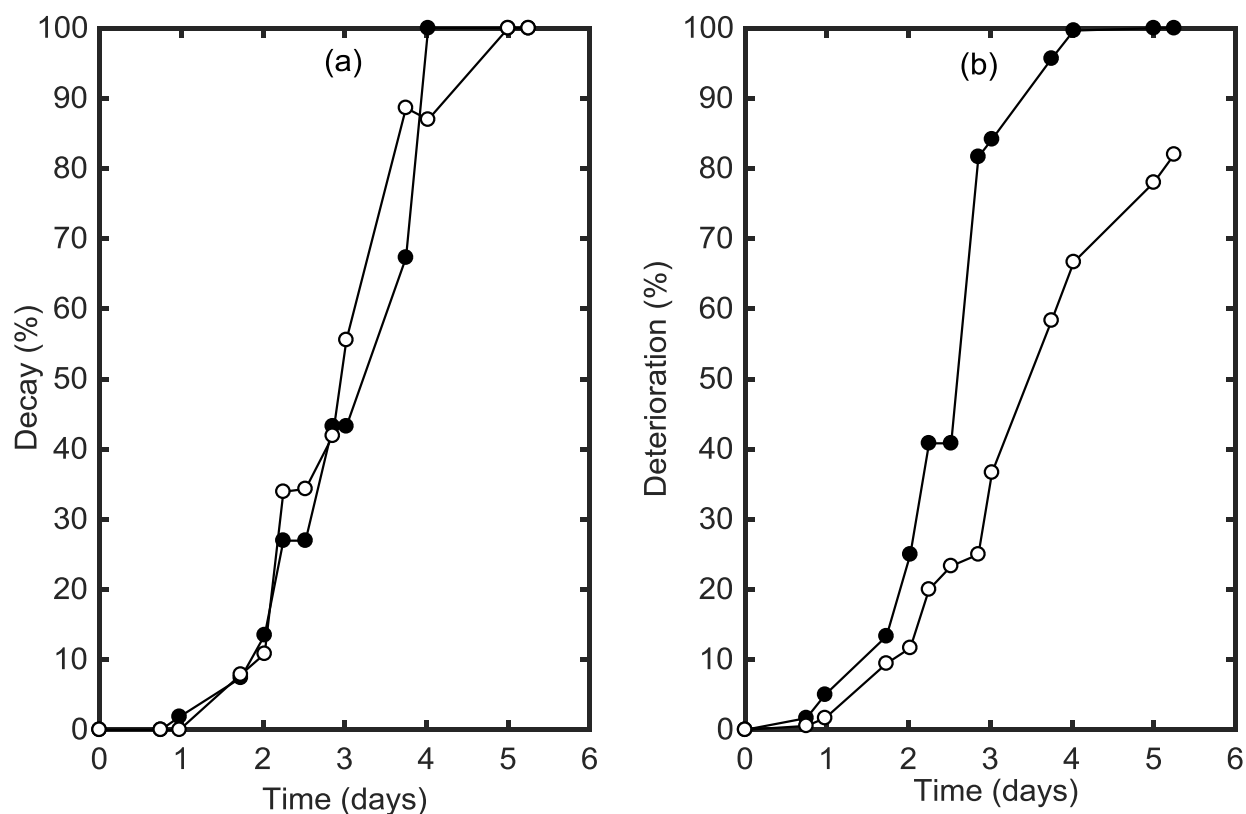


Figure 14: Visual assessment of a percentage of decay (a) and a percentage of deterioration (b) as a function of time in days, for strawberries packed in MAP (○) and no MAP condition (●) at 20 °C

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Predicting shelf life gain of fresh strawberries 'Charlotte cv' in modified atmosphere packaging



Céline Matar, Sébastien Gaucel, Nathalie Gontard, Stéphane Guilbert, Valérie Guillard*

Joint Res. Unit Agropolymers Engineering & Emerging Technology, UM - INRA- Supagro & CIRAD, 2 Place Pierre Viala, Bat 31, 34060 Montpellier Cedex 01, France

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ABSTRACT

Fresh fruit and vegetable's short shelf life is one of the main obstacle to their consumption leading to considerable food losses and wastes during the post-harvest steps. Modified atmosphere packaging (MAP) is able to significantly increase their shelf life. The objective of this work is to quantify the gain of shelf life obtained under MAP. This was applied for strawberries as model food. Deterioration was assessed to define products' shelf life. A model of food deterioration, including effects of carbon dioxide and temperature, was developed and validated in both isothermal and non-isothermal conditions. A Maximal Acceptable Deterioration (D_{acc}) of 13% was assessed from dedicated analysis of consumer willingness to purchase and deterioration curves measured. An upgraded modelling tool was then developed by coupling models of the literature, for respiration and permeation, and the proposed deterioration model. The upgraded modelling tool was validated at 5, 10 and 20 °C on strawberries and in dynamic temperatures to mimic the post-harvest storage conditions. RMSE values were lower than 2.5% for O_2 and CO_2 and deterioration curves, in both isothermal and non-isothermal conditions. A shelf life gain of 0.33 d was obtained with MAP for the proposed temperature profile. Numerical exploration for different time/temperatures storage conditions, enable us to predict a gain of shelf life greater than 1 d, allowing to expect significant benefits in terms of shelf life gain for this product in MAP.

1. Introduction

In order to increase the very short shelf life of fruit and vegetables (F & V), Modified Atmosphere Packaging (MAP) technology is a promising technique for the post-harvest chain. In fact, MAP allows to achieve an optimal gas composition in the close environment of the product (Guillaume et al., 2010; Zagory and Kader, 1988). This gas composition surrounding the product is the result of product respiration and gas permeation through the film (Belay et al., 2016). F&V are living organisms; they continue to respire after harvest, by consuming oxygen from air and producing carbon dioxide. After a transition phase, a gas equilibrium is established around the product which composition must be as close as possible to the optimal one to reduce respiration, prevent ripening, senescence, fermentation and thus increase shelf life (Gontard and Guillaume, 2009; Oliveira et al., 2015).

Shelf life of a fresh product refers to the period of time, from harvesting till consumer step, during which the product is still edible (Robertson, 2010). Shelf life of fresh F&V is complex, influenced by product characteristics (respiration, transpiration, ethylene production, etc.), surrounding environmental conditions (temperature, gas composition and relative humidity of the atmosphere) and spoilage

development (Kilcast and Subramaniam, 2000). Because of their high fragility and their very short shelf life, F&V are contributing to 45% of the global food losses and wastes recorded in the post-harvest chain (Gitz et al., 2014), principally at distribution and consumer stages.

So far, benefit of MAP has been widely demonstrated for shelf life extension but has never been quantified in a clear and simple manner (Khan et al., 2016; Villalobos et al., 2016). Consequently, although significant benefit in terms of food losses reduction is expected from shelf life extension, this direct positive effect is difficult to anticipate for the post-harvest step even though indispensable in the calculation of cost and/or environmental impact. This is due to the lack of generalized approach to quantify/predict shelf life of packed fresh products in general and that of fresh fruit and vegetables in particular. Confirming this, an exhaustive analysis of the scientific available literature revealed that if a plethora of articles mentioned shelf-life and fresh fruit and vegetables in their topic, this number reduced to 85 for papers focusing on shelf life and MAP of fresh fruit and vegetables including some modelling aspect either on the gas transfer or shelf life, but never both aspects at the same time (Table 1).

In depth analysis of the 70 articles dealing with shelf life, fresh fruit and Vegetables, modelling, MAP, quality, showed that among them, 20

* Corresponding author.

E-mail address: valerie.guillard@umontpellier.fr (V. Guillard).<https://doi.org/10.1016/j.postharvbio.2018.03.002>Received 14 December 2017; Received in revised form 1 March 2018; Accepted 4 March 2018
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2.3 Predicting shelf life gain of fresh strawberries 'Charlotte cv' in Modified Atmosphere Packaging (Article 2)

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Matar Céline, Gaucel Sébastien, Gontard Nathalie, Guilbert Stéphane & Guillard Valérie*

Joint Res. Unit Agropolymers Engineering & Emerging Technology, UM - INRA-Supagro & CIRAD, 2 place Pierre Viala, Bat 31, 34060 Montpellier cedex 01 France

*valerie.guillard@umontpellier.fr

Abstract. Fresh fruit and vegetable's short shelf life is one of the main obstacle to their consumption leading to considerable food losses and wastes during the post-harvest steps. Modified atmosphere packaging (MAP) is able to significantly increase their shelf life. The objective of this work is to quantify the gain of shelf life obtained under MAP. This was applied for strawberries as model food. Deterioration was assessed to define products' shelf life. A model of food deterioration, including effects of carbon dioxide and temperature, was developed and validated in both isothermal and non-isothermal conditions. A Maximal Acceptable Deterioration (D_{acc}) of 13 % was assessed from dedicated analysis of consumer willingness to purchase and deterioration curves measured. An upgraded modelling tool was then developed by coupling models of the literature, for respiration and permeation, and the proposed deterioration model. The upgraded modelling tool was validated at 5, 10 and 20 °C on strawberries and in dynamic temperatures to mimic the post-harvest storage conditions. RMSE values were lower than 2.5 % for O₂ and CO₂ and deterioration curves, in both isothermal and non-isothermal conditions. A shelf life gain of 0.33 d was obtained with MAP for the proposed temperature profile. Numerical exploration for different time/temperatures storage conditions, enable us to predict a gain of shelf life greater than 1 d, allowing to expect significant benefits in terms of shelf life gain for this product in MAP.

Keywords: Modelling deterioration; MAP; Shelf life prediction; Fresh fruit and vegetables; Respiration; Mass transfer

Nomenclature

Symbols	Definition	Units
x_{CO_2max}	Maximal concentration of CO ₂ withstanding by <i>Botrytis cinerea</i>	%
δ_{CO_2}	Inhibiting effect of carbon dioxide on the deterioration	dimensionless
K_{mO_2}	Apparent constant of Michaelis and Menten equation	Pa
$p_{CO_2}^{out}$	Partial pressure of CO ₂ outside the packaging	Pa
$p_{O_2}^{out}$	Partial pressure of O ₂ outside the packaging	Pa
p_j^{in}	Partial pressure of j inside the packaging	Pa
x_{CO_2}	Percentage of carbon dioxide in the headspace	%
ϕ_j	Mass flow rate of j	mol s ⁻¹
A	Surface area of the film	m ²
D	Percentage of deterioration on strawberries 'surface	%
D_{acc}	Maximal acceptable deterioration	%
D_{ini}	Initial deterioration of the fruit	%
D_{max}	Maximal deterioration of the fruit	%
e	Film thickness	m
E_{a,PCO_2}	Activation energy for carbon dioxide permeability	J mol ⁻¹
E_{a,PO_2}	Activation energy for oxygen permeability	J mol ⁻¹
$E_{a,RO_{2max}}$	Activation energy for respiration	J mol ⁻¹
i	Number of data points	
j	Gas species: O ₂ , CO ₂	
$k_{D,10\text{ }^\circ\text{C}}$	Deterioration rate constant at 10 °C	s ⁻¹
$k_{D,20\text{ }^\circ\text{C}}$	Deterioration rate constant at 20 °C	s ⁻¹
$k_{D,5\text{ }^\circ\text{C}}$	Deterioration rate constant at 5 °C	s ⁻¹
m	Weight of the food product	kg
Optimal CO ₂	Optimal CO ₂ percentage for strawberries storage	%
Optimal O ₂	Optimal O ₂ percentage for strawberries storage	%
P_{CO_2}	Permeability of CO ₂ through the film	mol Pa ⁻¹ m ⁻¹ s ⁻¹
P_{O_2}	Permeability of O ₂ through the film	mol Pa ⁻¹ m ⁻¹ s ⁻¹
q_{RQ}	Respiratory quotient	unit less
R	Universal gas constant	J mol ⁻¹ K ⁻¹
R_j	Net production or consumption rate of species j due to respiration rate of the fruit	mol kg ⁻¹ s ⁻¹
$R_{O_{2max},Tref}$	Maximum respiration rate at reference temperature	mol kg ⁻¹ s ⁻¹
S_j	Net production or consumption rate of species j due to metabolic deviation	mol s ⁻¹
T	Temperature	K
t	Time	s
t_{acc}	The limit of acceptability	d
T_{ref,PO_2} or T_{ref,PCO_2}	Reference temperature for permeability to CO ₂ or O ₂	K

T_{ref,RO_2max}	Reference temperature for maximal respiration rate	K
t_{SL}	Shelf life of the product	Days
V_H	Volume of the headspace	m ³
V_{MAP}	Volume of the sealed pouch containing the tray and the strawberries	L
V_{straw}	Volume of 0.100 kg of strawberry	L
V_T	Volume of the tray	L
\hat{y}_i	Experimental data	
y_i	Predicted data	
$\beta_{CO_2,10\text{ }^\circ C}$	Rate of CO ₂ production due to the deterioration at 10 °C	mol s ⁻¹ % ⁻¹
$\beta_{CO_2,20\text{ }^\circ C}$	Rate of CO ₂ production due to the deterioration at 20 °C	mol s ⁻¹ % ⁻¹
$\beta_{CO_2,5\text{ }^\circ C}$	Rate of CO ₂ production due to the deterioration at 5 °C	mol s ⁻¹ % ⁻¹
$\beta_{O_2,10\text{ }^\circ C}$	Rate of O ₂ consumption due to the deterioration at 10 °C	mol s ⁻¹ % ⁻¹
$\beta_{O_2,20\text{ }^\circ C}$	Rate of O ₂ consumption due to the deterioration at 20 °C	mol s ⁻¹ % ⁻¹
$\beta_{CO_2,5\text{ }^\circ C}$	Rate of O ₂ consumption due to the deterioration at 5 °C	mol s ⁻¹ % ⁻¹

2.3.1 Introduction

In order to increase the very short shelf life of fruit and vegetables (F&V), Modified Atmosphere Packaging (MAP) technology is a promising technique for the post-harvest chain. In fact, MAP allows to achieve an optimal gas composition in the close environment of the product (C Guillaume et al., 2010; Zagory and Kader, 1988). This gas composition surrounding the product is the result of product respiration and gas permeation through the film (Belay et al., 2016). F&V are living organisms; they continue to respire after harvest, by consuming oxygen from air and producing carbon dioxide. After a transition phase, a gas equilibrium is established around the product which composition must be as close as possible to the optimal one to reduce respiration, prevent ripening, senescence, fermentation and thus increase shelf life (Gontard and Guillaume, 2010; Oliveira et al., 2015).

Shelf life of a fresh product refers to the period of time, from harvesting till consumer step, during which the product is still edible (J. Robertson, 2010). Shelf life of fresh F&V is complex, influenced by product characteristics (respiration, transpiration, ethylene production, etc.), surrounding environmental conditions (temperature, gas

composition and relative humidity of the atmosphere) and spoilage development (Kilcast and Subramaniam, 2000). Because of their high fragility and their very short shelf life, F&V are contributing to 45 % of the global food losses and wastes recorded in the post-harvest chain (Gitz et al., 2014), principally at distribution and consumer stages.

So far, benefit of MAP has been widely demonstrated for shelf life extension but has never been quantified in a clear and simple manner (Khan et al., 2016; Villalobos et al., 2016). Consequently, although significant benefit in terms of food losses reduction is expected from shelf life extension, this direct positive effect is difficult to anticipate for the post-harvest step even though indispensable in the calculation of cost and/or environmental impact. This is due to the lack of generalized approach to quantify/predict shelf life of packed fresh products in general and that of fresh fruit and vegetables in particular. Confirming this, an exhaustive analysis of the scientific available literature revealed that if a plethora of articles mentioned shelf-life and fresh fruit and vegetables in their topic, this number reduced to 85 for papers focusing on shelf life and MAP of fresh fruit and vegetables including some modelling aspect either on the gas transfer or shelf life, but never both aspects at the same time (Table 6).

Table 6: Number of articles found on November 2017 using all Web of Science databases with AND as a connector between the keywords, keywords in the topic

Keywords	Number of Articles
Shelf life	37584
Shelf life, fresh fruit and vegetables	1801
Shelf life, fresh fruit and Vegetables, modelling	234
Shelf life, fresh fruit and vegetables, modelling, MAP (Modified Atmosphere Packaging)	85
Shelf life, fresh fruit and vegetables, modelling, MAP (Modified Atmosphere Packaging), quality	70
Shelf life, fresh fruit and vegetables, modelling, MAP (Modified Atmosphere Packaging), quality, consumer limit of acceptability	0

In depth analysis of the 70 articles dealing with shelf life, fresh fruit and Vegetables, modelling, MAP, quality, showed that among them, 20 articles focused on the design of MAP system and/or the modelling gases composition in the headspace of MAP packages without considering product internal quality factors. 18 others studied the

effect of external factors such as temperature, gas composition on the respiration rate of the packed product. The last 32 articles discussed shelf life of packed fruits and vegetables by measuring only one quality indicator for instance firmness and/or colour and/or microbial load as a function of time. But among the aforementioned articles, shelf life of the packed product was never evaluated in its entirety including consumer acceptance nor modelled and predicted in function of external factors such as temperature and gases composition. Thus, shelf life of whole fresh fruit and vegetables in MAP is currently still empirically assessed without any pre-established approach based on the use of mathematical modelling tool to help the user in assessing shelf life of fresh product in MAP. Some Tools exist in the literature such as Tailorpack (<http://plasticnet.grignon.inra.fr/lateTools/TailorPack>) to simulate MAP of fresh produce based on modelling respiration by using Michaelis and Menten law and permeation via Fick first law. But these tools currently do not predict food shelf life. In addition, existing shelf life models in the literature were not developed for MAP conditions and thus do not take into account the effect of gases composition resulting for MAP condition on the shelf life of the packed product. Moreover, they only focused on one criteria (e.g. moulds development) and not on the overall deterioration which is yet the key criteria of consumer act of purchase.

Lastly, if we go further and look for paper dealing with shelf life evaluation and modelling together with quality evolution and consumer limit of acceptability in MAP system for F&V, no studies were found (Table 6). In other words, so far, in all published articles, the methodologies to predict shelf life in MAP stopped at the construction of a model based on a single quality parameter without going further and linking this quality prediction to consumer acceptability. Thus, it makes it difficult to use an equation based only on one quality indicator (colour, firmness, etc.) to quantify the overall shelf life of a product without identifying the quality threshold below/above which the product won't be accepted by the consumer.

In this context, the objective of this work is to quantify and predict the shelf life benefit due to MAP for fresh produce. To do this, a mathematical model aiming to predict product deterioration as a function of time, temperature and internal gas composition (O_2/CO_2) was developed and validated on a respiring fresh product. Product shelf life can then be calculated in comparison to consumer limit of acceptability. In this study,

we chose to work on strawberries as a model food because of its high perishability, high respiration rate $50\text{-}100\text{ ml CO}_2\text{ h}^{-1}\text{ kg}^{-1}$ produced at $20\text{ }^\circ\text{C}$ (Ozkaya et al., 2009) and its challenging post-harvest storage, allowing it to be a good representative of worst case scenario. In this study, we propose a complete mathematical modelling tool able to predict shelf life in days for fresh produce packed in MAP, which is an indispensable tool for the stakeholders to optimize the post-harvest chain and further minimize food losses.

2.3.2 Modelling

The model developed combines gas transfer through the packaging, respiration, metabolic deviation and deterioration of the food product in the food/packaging system.

2.3.2.1 Model assumptions

The geometry of the food/packaging system (tray + flexible wrapped pouch + food sample + headspace) considered in this study, as well as the mass transfer, biological phenomenon (respiration and deterioration) taken into account in the modelling approach are schematically represented in Figure 15.

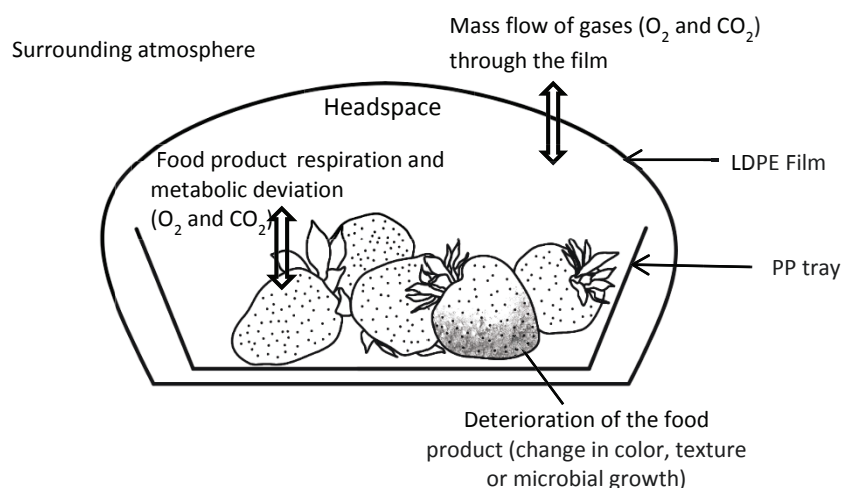


Figure 15: Description of the food packaging system considered in this modeling approach coupling mass transfer and deterioration of the product during time. Main biological and physical mechanisms modelled are indicated in this figure.

Concerning mass transfer, the tray is assumed impermeable to mass transfer and gases permeation occurs only through the flexible pouch, except at the bottom of the pouch where the flexible pouch and the tray are in contact.

During conservation, the food/packaging system is surrounded by an atmosphere with constant composition equal respectively to 20.9 %O₂, 0.03 %CO₂ and 79.07 %N₂ (Widory and Javoy, 2003). The atmospheric pressure is considered constant. In addition, due to the inert character of nitrogen, the flow of nitrogen in the headspace is not considered in this study. The volume of the headspace is assumed to be constant during time and its gas composition is considered uniform whatever the position. Concerning heat transfer, heat diffusion is assumed to be fast in comparison to mass transfer. In addition, the system temperature is assumed uniform in space and in thermal equilibrium with the surrounding atmosphere. Finally, the temperature of the food product, headspace, packaging material and surrounding atmosphere are equal at time t and when a change of temperature occurs in the surrounding atmosphere, the temperature of the whole system varies instantaneously.

2.3.2.2 Modelling product's deterioration

The rate of deterioration is calculated using a logistic equation as primary model, and including temperature and CO₂ effects to obtain the secondary model given by Eq. (21) :

$$\frac{dD}{dt} = k_D D \frac{D_{\max} - D}{D_{\max}} \delta_{CO_2} \quad (21)$$

where D is the percentage of surface deterioration (%) at time t (s), D_{\max} is the maximum percentage of deterioration (%), k_D represents the deterioration rate constant (s⁻¹) and δ_{CO_2} a dimensionless weighting parameter representing the inhibiting effect of carbon dioxide on the deterioration rate. The benefit of CO₂ on delaying fruit's deterioration is mainly due to its inhibiting effect on fungus growth. Therefore, the δ_{CO_2} parameter is calculated, as in predictive microbiology, to describe the effect of environmental factors such as inhibitor concentrations on microorganisms growth rate (Alfaro et al., 2013; Chaix et al., 2015) :

$$\delta_{CO_2}(t) = 1 - \frac{x_{CO_2}(t)}{x_{CO_2_{\max}}} \quad (22)$$

where x_{CO_2} is the quantity (%) of carbon dioxide in the headspace at time t and $x_{CO_2_{\max}}$ is the maximal quantity (%) of CO₂ withstanding by the microorganisms. It considers

that below the threshold value, $x_{CO_2_{max}}$, the inhibiting effect of CO₂ linearly decreases with the decrease of CO₂ concentration following a weighting parameter starting from 1 and levelling off at 0.

2.3.2.3 Modelling variation of gaseous species in the headspace

First, a basic model was considered, where the variation of quantity n_j (mol) of gaseous species j (O₂, CO₂) in the headspace depend on the (i) mass flow φ_j (mol s⁻¹) of species j occurring through the packaging film between the surrounding atmosphere and the headspace, (ii) the net production or consumption rate R_j (mol s⁻¹) of species j due to product's respiration

$$\frac{dn_j}{dt} = \varphi_j + R_j \quad (23)$$

The mass flow φ_j (mol s⁻¹) of gas species j (O₂, CO₂) through the film is expressed using Fick's first law and assuming a steady state regime for mass transfer through the film:

$$\varphi_j = \frac{P_j A}{e} (p_j^{out} - p_j^{in}) \quad (24)$$

where A is the surface area of the film (m²), e the thickness of the film (m), p_j^{out} is the atmospheric partial pressure of gas j (Pa), p_j^{in} is the partial pressure of gas j in the headspace (Pa), P_j is the permeability of the film for gas j (mol m⁻¹ Pa⁻¹ s⁻¹).

Respiration of the fruit is expressed following Michaelis and Menten equation. It can be expressed by using one of the 4 types of Michaelis and Menten equations, each one representing one of the inhibition mechanism of CO₂ (Fonseca et al., 2002; C Guillaume et al., 2010). In this work, the O₂ respiration rate, R_{O_2} (mol s⁻¹) is given by the simplest classical Michaelis and Menten equation without CO₂ inhibition as done by (Cagnon et al., 2010) as follows:

$$R_{O_2} = - \frac{R_{O_2_{max}} p_{O_2}^{in}}{(K_{m_{O_2}} + p_{O_2}^{in})} m \quad (25)$$

where R_{O_2max} corresponds to the maximum respiration rate per kg of food commodity ($\text{mol kg}^{-1} \text{s}^{-1}$), Km_{O_2} is the constant of Michaelis and Menten (Pa), $p_{O_2}^{in}$ is the internal partial pressure of oxygen (Pa) and m is the weight of the food product (kg). R_{CO_2} is given by:

$$R_{CO_2} = -R_{O_2} q_{RQ} \quad (26)$$

where, q_{RQ} is the respiratory quotient (dimensionless).

Equations (27) and (28) summarize the O_2 and CO_2 mass flow in the headspace, respectively, for the so called basic model.

$$\frac{dn_{O_2}}{dt} = \frac{P_{O_2} A}{e} (p_{O_2}^{out} - p_{O_2}^{in}) - \frac{R_{O_2max} p_{O_2}^{in}}{(Km_{O_2} + p_{O_2}^{in})} m \quad (27)$$

$$\frac{dn_{CO_2}}{dt} = \frac{P_{CO_2} A}{e} (p_{CO_2}^{out} - p_{CO_2}^{in}) - q_{RQ} \frac{R_{O_2max} p_{O_2}^{in}}{(Km_{O_2} + p_{O_2}^{in})} m \quad (28)$$

An upgraded model is proposed by adding to Eq. (23) the effect of the metabolic deviation of the product. This latter represents O_2 consumed and/or CO_2 produced due to fruit senescence, fermentation and development of microorganisms on the fruit. The net production or consumption rate S_j (mol s^{-1}) of species j due to metabolic deviation is represented in Eq. (29).

$$\frac{dn_j}{dt} = \varphi_j + R_j + S_j \quad (29)$$

The effect of deterioration on metabolic deviation and consequently on gas consumption/production is considered proportional to the deterioration D , as the simplest possible relationship. The consumption or production rates S_j (mol s^{-1}) of gas species j due to metabolic deviation are thus given by:

$$S_{O_2} = -\beta_{O_2} D \quad (30)$$

$$S_{CO_2} = \beta_{CO_2} D \quad (31)$$

Where, β_{O_2} and β_{CO_2} represent the rate of oxygen consumption due to the deterioration and the rate of carbon dioxide production due to the deterioration ($\text{mol s}^{-1} \%^{-1}$), respectively.

Equations (32) and (33) compile all described phenomena in Eq. (29) for O_2 and CO_2 respectively.

$$\frac{dn_{O_2}}{dt} = \frac{P_{O_2} A}{e} (p_{O_2}^{\text{out}} - p_{O_2}^{\text{in}}) - \frac{R_{O_2\text{max}} p_{O_2}^{\text{in}}}{(K m_{O_2} + p_{O_2}^{\text{in}})} m - \beta_{O_2} D \quad (32)$$

$$\frac{dn_{CO_2}}{dt} = \frac{P_{CO_2} A}{e} (p_{CO_2}^{\text{out}} - p_{CO_2}^{\text{in}}) - q_{RQ} \frac{R_{O_2\text{max}} p_{O_2}^{\text{in}}}{(K m_{O_2} + p_{O_2}^{\text{in}})} m + \beta_{CO_2} D \quad (33)$$

2.3.2.4 Modelling temperature dependence

Arrhenius law Eq. (34) is used in each of the previous equations to consider temperature effect on mass transfer parameters (permeation) and biological ones (respiration, deterioration, metabolic deviation).

$$k(T) = k_{\text{ref}} \exp\left(\frac{-E_{a,k}}{R} \left(\frac{1}{T} - \frac{1}{T_{\text{ref},k}}\right)\right) \quad (34)$$

where k refers to the temperature dependent parameter, i.e. permeability of material to oxygen and carbon dioxide P_{O_2} and P_{CO_2} , respectively, and $R_{O_2\text{max}}$ the maximal respiration rate, k_{ref} is the value of parameter k at reference temperature T_{ref} , $E_{a,k}$ is the activation energy for parameter k (J mol^{-1}), R is the universal gas constant ($\text{J mol}^{-1} \text{K}^{-1}$), $T_{\text{ref},k}$ is the reference temperature (K) for the parameter k .

2.3.3 Materials and Methods

2.3.3.1 Materials

Strawberries of the variety “Charlotte”, grown off-ground, were provided by a local producer (Mauguio, South of France). Strawberries were harvested in the morning of experiments, cooled to about 5 °C at the producer facilities, then picked up to the

laboratory around 5 h after harvest where they were stored at respective desired temperatures 5, 10 and 20 °C for 3h. Harvested strawberries were sorted according to maturity: over ripened i.e. fruits with soft texture and under ripened fruits i.e. fruits with green, not fully mature, spots were discarded. Sorting was done also according to shape: oversized fruits or very small ones compared to the batch fruit sizes were eliminated. Finally, damaged or rotten fruits were removed. The film packaging was low density polyethylene (LDPE) (BBA emballages, Lunel – France). The trays used were made of polypropylene (PP) (Attitud'Pack, Chatuzange Le Goubet-France) with dimensions of 0.14 × 0.095 × 0.025 m.

2.3.3.2 Methods

2.3.3.2.1 Permeation measurements

The permeability of the gases through the film was measured using the permeation device from Presens (Germany), Fibox 4. This system consists of two chambers separated by a grid where the film with unknown permeability is placed. The two chambers each have an inlet and an outlet to establish different gas compositions on both sides of the film. A chemical optical sensor was placed in the upper cell to assess oxygen variation during time. The system was used here in a static flux, thus the total pressure on both sides of the film is equal to the atmospheric pressure. First, nitrogen was injected in both chambers to eliminate the oxygen completely. After that, the upper cell, where the sensor stands, was closed and the lower chamber was set in contact with ambient air (20.9 %O₂ and 0.03 %CO₂). By permeation, the O₂ content of the upper chamber increased with time. The system was left measuring oxygen in % for 1.5 d. Fick's first law (Eq. (24)) was rewritten in order to calculate the permeability of oxygen through the film, P_{O_2} :

$$P_{O_2} = \frac{\varphi_{O_2} A}{e} (p_{O_2}^{out} - p_{O_2}^{in}) \quad (35)$$

where φ_{O_2} represents the slope of the curve of %O₂ as a function of time. The permeability

measurement was done in triplicate at the three different temperatures 5, 10 and 20 °C. Knowing that a selectivity of 1/4 exists between permeabilities of LDPE for O₂ and CO₂, P_{CO_2} can be calculated from P_{O_2} value (G. L. Robertson, 2010; Siracusa, 2012).

2.3.3.2 Respiration rates measurement

The closed system method was adopted to measure the respiration rates of the strawberries (Fonseca et al., 2002). Strawberries were placed in a hermetic glass jar, without interaction with the external atmosphere. Oxygen was assessed inside the jar using O₂ spots glued on the internal part of the jar (Fibox 3, Presens - Germany) while the CO₂ was trapped using sodium hydroxide to get rid of the inhibitory effect of CO₂ on the respiration rate. The initial slope of the O₂ decreasing curve was then calculated and permitted to fix the maximal respiration rate. This R_{O_2max} included in the Michaelis and Menten simplest form (Eq. (25)), without CO₂ inhibition, with $K_{m_{O_2}}$ equal to 8100 Pa of Cagnon et al., 2013 was found suitable to predict respiration of strawberries *Charlotte* in closed jars. Measurements were done in triplicate at the three different temperatures 5, 10 and 20 °C to update and verify literature data found on respiration rate of '*Charlotte*' strawberries (Cagnon et al., 2013).

2.3.3.2.3 Setting up MAP and Conventional systems

Strawberries were placed in PP trays, each tray containing 0.100 ± 0.003 kg of strawberries, and then packed in the LDPE pouch. The film packaging has $0.03 \times 0.15 \times 0.11$ m dimensions and 50.5×10^{-6} m thickness. 2 pouches were designed: macro-perforated and non-perforated pouches. Macro-perforated pouches were considered as the conventional situation named no MAP and used as benchmark. The design of the experimental MAP system is detailed in supplementary material 1. The temperature was controlled in Memmert incubators (Memmert, Schwabach – Germany).

2.3.3.2.4 Headspace volume measurement

In order to determine the volume of the headspace i.e. empty space inside the sealed pouch, Eq. (36) was used

$$V_H = V_{MAP} - (V_T + V_{straw}) \quad (36)$$

where V_H is the volume of the headspace (L), V_{MAP} is the volume of the sealed pouch containing the tray and the strawberries (L), V_T is the volume of the tray (L), V_{straw} is the mean volume of 0.100 kg of strawberry (L).

Archimedes' principle was used to measure the 3 required volumes: the total volume of the MAP system i.e. the sealed pouch containing the tray and the strawberries, the volume of the tray alone and the volume of the strawberries. For this end, a large jar was filled to the top with water till it stabilizes. Then, the strawberries or MAP package or the tray were immersed in water with a load of known volume on the top to prevent them from floating. The weight of the displaced water was measured and converted into volume. Finally, the total volume of respectively the MAP system, the tray itself, and the strawberries were obtained by subtracting the known volume of the load. Measurements for the volumes were done in triplicates for each object. For measuring the volume of strawberries, 10 lots of 0.100 ± 0.003 kg of strawberries were measured. Then the mean of the obtained volumes was calculated.

2.3.3.2.5 Gases evolution inside the package

A micro gas chromatography (MicroGC 3000, SRA Instruments) was used for measuring internal O₂ and CO₂ molar fraction (%) in packed fruits. 10×10^{-6} L of gas collected in packaging headspace was analysed every 2h (resolution: 0.005 % and detection limit 0.001 %). To assess CO₂ and O₂ in the headspace, a needle was inserted in the headspace via a septum glued on the external part of the MAP pouch. Septum (Septum white 15×10^{-3} m diameter, Dansensor, Italy) was used to prevent crack propagation in the film package due to the puncture (Charles et al., 2008; Guillaume et al., 2013). After the analysis with the GC, the perforated septum was closed to avoid leakage. For each measurement, triplicates were done on three different trays. In total, 12 trays were measured every day which correspond to four measurements a day, separated by a waiting time of 2h. Every tray was measured once a day and reanalysed the second day (Table 7). Volume change was neglected since 10 µL were withdrawn with every GC measurement (i.e. a total 60 µL during the whole experiment). At the end of each experiment, all the pouches were immersed in water to make sure there was no leakage leading to false measurements.

Three trays with macro perforated LDPE film representing the control situation (without modified atmosphere) were assessed during time. CO₂/O₂ assessment in these trays revealed that their gas composition was always equal to ambient conditions (20.9 %O₂ and 0.03 %CO₂).

Table 7: Experimental plan used to assess gases evolution in the package. Enclosed numbers represent the labels of the trays used for each measurement along the 6 days in MAP or Control situation.

Day	1				2...5	6			
Number of the measurement Storage Condition	1 st	2 nd	3 rd	4 th	...	1 st	2 nd	3 rd	4 th
MAP	① ② ③	④ ⑤ ⑥	⑦ ⑧ ⑨	⑩ ⑪ ⑫	...	① ② ③	④ ⑤ ⑥	⑦ ⑧ ⑨	⑩ ⑪ ⑫
Control	① ② ③	① ② ③	① ② ③	① ② ③	...	① ② ③	① ② ③	① ② ③	① ② ③

2.3.3.2.6 Assessing fruit shelf life

Shelf life of strawberries was calculated by intersecting the kinetic of deterioration and a maximal acceptable deterioration (D_{acc}). The maximal acceptable deterioration was deduced from assessment of the deterioration kinetic and a limit of acceptability by consumers' panellist based on a visual acceptance of the product by the consumer and the willingness to purchase it. Both limit of acceptability by consumers and deterioration kinetic were assessed in the framework of this study as described in the following and were used to determine the maximal acceptable deterioration.

2.3.3.2.6.1 Kinetic of deterioration of fresh fruits

Deterioration of fresh fruits was defined as the percentage of deteriorated surface, quantified by visual detection. Visual detection aims to determine the surface of spoiled strawberries (in % of the total surface area) due to three phenomena: change of colour, texture softening and microorganism development.

A grid was built to evaluate the percentage of deterioration, based on Ctifl studies (Vaysse et al., 2015, 2011) (see chapter 2.2 of this PhD). 6 classes were created from 0 to 100 % of fruits' surface deteriorated. For the lowest class from 0-10 %, additional 10 subclasses were created to have a more accurate measurement of the deterioration. Deterioration assessment was done for MAP and no MAP systems, in isothermal conditions (5, 10 and 20 °C) and for a temperature kinetic. Measurements were performed in triplicate by the same person, twice a day, for 5 to 9 d depending

on storage temperatures. For a better evaluation of the deterioration, packaging was removed leading to disruption of MAP, thus measurements were destructive. For each sample, before packaging removal, a measurement of gases composition in the headspace was also done using micro gas chromatography (MicroGC 3000, SRA Instruments).

2.3.3.2.6.2 Identification of the limit of acceptability and set up of a Maximal Acceptable Deterioration

A panel of 30 untrained consumers participated in a survey to set the limit of acceptability of packed strawberries. The question asked to each consumer of this panel was: 'Just by looking at the strawberries in the tray, are you willing to buy the product or not?'. The possible answers were 'Yes' or 'No'. The panel annotated the trays twice a day, in the morning and in the afternoon during the whole period of the experiment. The limit of acceptability represents the time t_{acc} in days at which more than 50 % of the panel rejected the product i.e. answered 'No' to the asked question (Adobati, 2015; Cardelli and Labuza, 2001; Gim et al., 2005; Lareo et al., 2009).

To have an accelerated deterioration/aging of the fruit, the limit of acceptability t_{acc} , in days, was identified at 20 °C where all physiological processes i.e. maturation and degradation of the fruits are faster. Next step was to identify the corresponding % of deterioration. The deterioration curve at 20 °C was used to identify the deterioration at time t_{acc} . The obtained value was then defined as the Maximal Acceptable Deterioration (D_{acc}) by the consumer. D_{acc} is expressed in percentage of deterioration. Above this value, the tray is discarded, considered not marketable anymore.

2.3.3.2.6.3 Shelf life determination in days

Shelf life t_{SL} (days) is estimated by the time when the deterioration of the product, predicted by Eq. (21) reaches the Maximal Acceptable Deterioration (D_{acc}). This relationship is formalized in Eq. (37):

$$t_{SL} = D^{-1}(D_{acc}) \quad (37)$$

where D^{-1} is the inverse function of the deterioration, i.e. the function which compute the time (s) corresponding to an input value of deterioration (%), and t_{SL} is the shelf life expressed in days after unit conversion.

The shelf life was calculated in isotherm conditions at 5, 10 and 20 °C and in temperature profile conditions.

2.3.3.2.7 An example of postharvest storage scenario

Model validation was conducted by imposing a time-temperature kinetic to the product in order to mimic the commercial storage of strawberries. This time-temperature kinetic represented the typical postharvest storage stages of strawberries in France with typical values of duration and temperatures (Brecht et al., 2003; Moras and Tamic, 2001; Nunes et al., 2009; Riad and Brecht, 2015).

Figure 16 represents the consecutive steps chosen for mimicking post-harvest stages of strawberries. After harvesting, the strawberries were assumed to be directly packed in the trays and then to be subjected to a precooling step at 5 °C during 1h to remove quickly the heat surrounding the fruits. This precooling step is highly recommended and usually practiced to increase product life (Picha, 2006). After that, strawberries were supposed to be transported in refrigerated trucks at 10 °C for 1.5 d. As soon as they arrived to the supermarket, during the day, they were considered stored at 20 °C (on the shelves) and at night, the unsold goods were considered stored at a lower temperature around 10 °C in refrigerators. Following that, the consumer bought the strawberries and kept them at 20 °C, assuming that strawberries were kept outside the fridge at consumer's home. This is one example of possible post-harvest stage for packed strawberries sold in supermarket.

These time-temperature conditions were replicated by placing the packed strawberries in a programmed incubator where real-time temperature was recorded. Both deterioration and gases were measured during time and were used to validate the upgraded model.

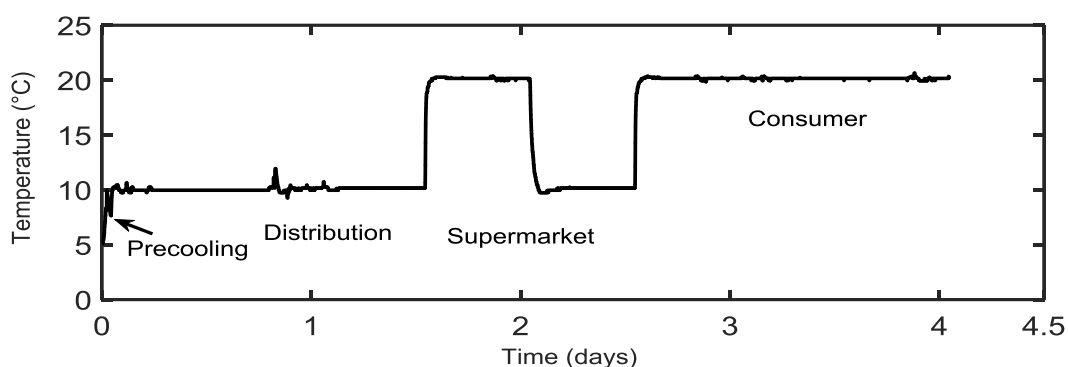


Figure 16: Temperature profile applied to mimic the postharvest chain including precooling, distribution, supermarket and consumer step

2.3.3.2.8 Numerical simulations and parameter estimation

The system of 3 ordinary differential Eq. (21), (32) and (33) was solved by using Matlab® software (The Mathworks Inc, Natick, Mass., U.S.A) and its solver “ode15s”.

The goodness of fit between model and experimental data was evaluated by calculating the root mean square error (RMSE) between predicted (y_i) and experimental data (\hat{y}_i):

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{n}} \quad (38)$$

where n is the number of data points.

To run the model developed, 10 parameters needed to be estimated.

Firstly, the 4 parameters depicting the deterioration effect i.e. D_{ini} , the initial percentage of deterioration, k_D the deterioration rate constant (s^{-1}) at 3 temperatures ($k_{D,5^\circ C}, k_{D,10^\circ C}, k_{D,20^\circ C}$), were estimated using Eq. (21). Parameter estimation was performed simultaneously for the 3 temperatures, assuming that the initial percentage of deterioration is independent of the temperature. Required input data on CO_2 concentration evolution with time in Eq. (22) were taken from experiments dedicated to evaluation of deterioration.

Secondly, the resulting identified values of D_{ini} and k_D were used in Eq. (32) and (33) and the left 6 parameters representing the effect of deterioration on the gases

evolution i.e. β_{O_2} , the rate of oxygen consumption due to the deterioration ($\text{mol s}^{-1} \%^{-1}$) at 5, 10 and 20 °C ($\beta_{O_2,5^\circ\text{C}}, \beta_{O_2,10^\circ\text{C}}, \beta_{O_2,20^\circ\text{C}}$) and β_{CO_2} , the rate of carbon dioxide production due to the deterioration ($\text{mol s}^{-1} \%^{-1}$) at 5, 10 and 20 °C ($\beta_{CO_2,5^\circ\text{C}}, \beta_{CO_2,10^\circ\text{C}}, \beta_{CO_2,20^\circ\text{C}}$) were estimated at 5, 10 and 20 °C. Experimental data of O₂ and CO₂ concentration evolution with time presented in section 2.3.3.2.5, obtained for the 3 temperatures investigated, were used for this estimation. The nonlinear fitting Matlab® procedure “nlinfit” was used for the parameter estimation.

2.3.4 Results and discussion

Two modelling tools were used during this study:

- (1) The basic modelling tool predicting the gases kinetics in the headspace, due to product respiration (Michaëlis and Menten mechanism) and permeation (Fick's first law) through the film;
- (2) The upgraded modelling tool improving the basic one, by adding prediction of the product deterioration and its concomitant metabolic deviation

Table 8: Input parameters and variables required in the upgraded modelling tool. Values indicated after ± correspond to standard deviation, values between parenthesis correspond to the confidence intervals, values followed by an asterisk (*) show that the values of the confidence intervals are very close to the value estimated.

Parameters	Definition	Values	Units	References
$p_{CO_2}^{out}$	Partial pressure of CO ₂ outside the packaging	0.0003 × 101325	Pa	(Widory and Javoy, 2003).
$p_{O_2}^{out}$	Partial pressure of O ₂ outside the packaging	0.209 × 101325	Pa	(Widory and Javoy, 2003).
A	Surface area of the film	0.04 ± 0.0003	m ²	This work
D _{ini}	Initial deterioration of the fruit	0.2*	%	This work estimated parameter
D _{max}	Maximal deterioration of the fruit	100	%	This work experimental data
E _{a, PCO₂}	Activation energy for carbon dioxide permeability	22 520 (19 417 ; 25 629)	J mol ⁻¹	This work estimated parameter
E _{a, PO₂}	Activation energy for oxygen permeability	41 070 (35 412 ; 46 741)	J mol ⁻¹	This work estimated parameter
E _{a, RO_{2max}}	Activation energy for respiration	69 780 (67 369; 72 191)	J mol ⁻¹	This work estimated parameter
$k_{D,5^\circ\text{C}}$	Deterioration rate constant at 5 °C	6.98×10^{-06} (6,19 × 10 ⁻⁰⁶ ; 7,77 × 10 ⁻⁰⁶)	s ⁻¹	This work estimated parameter

$E_{a, P_{CO_2}}$	Activation energy for carbon dioxide permeability	22 520 (19 417 ; 25 629)	$J mol^{-1}$	This work estimated parameter
$k_{D, 10\text{ }^\circ C}$	Deterioration rate constant at 10 °C	9.93×10^{-06} (8.97×10^{-06} ; 1.08×10^{-05})	s^{-1}	This work estimated parameter
$k_{D, 20\text{ }^\circ C}$	Deterioration rate constant at 20 °C	3.16×10^{-05} (3.09×10^{-05} ; 3.24×10^{-05})	s^{-1}	This work estimated parameter
$K_{m_{O_2}}$	Apparent constant of Michaelis and Menten equation	8100 ± 1.5	Pa	(Cagnon et al., 2013)
m	Weight of the food product	0.100 ± 0.003	kg	This work experimental data
Optimal CO ₂	Optimal CO ₂ percentage for strawberries storage	15	%	(Sousa-gallagher and Mahajan, 2013)
Optimal O ₂	Optimal O ₂ percentage for strawberries storage	5	%	(Sousa-gallagher and Mahajan, 2013)
P_{CO_2}	Permeability of CO ₂ through the film	$47.85 \times 10^{-16} \pm 0.43 \times 10^{-16}$	$mol Pa^{-1} m^{-1} s^{-1}$	This work experimental data
P_{O_2}	Permeability of O ₂ through the film	$9.57 \times 10^{-16} \pm 0.43 \times 10^{-16}$	$mol Pa^{-1} m^{-1} s^{-1}$	This work experimental data
R	Universal gas constant	8.31	$J mol^{-1} K^{-1}$	
q _{RQ}	Respiratory quotient	0.91	dimensionless	(Cagnon et al., 2013)
$R_{O_2max, Tref}$	Maximum respiration rate at reference temperature	$2.22 \times 10^{-07} \pm 0.27 \times 10^{-07}$	$mol kg^{-1} s^{-1}$	This work experimental data
$T_{ref, P_{O_2}}$ or $T_{ref, P_{CO_2}}$	Reference temperature for permeability to CO ₂ or O ₂	298	K	This work experimental data
$T_{ref, R_{O_2max}}$	Reference temperature for maximal respiration rate	283	K	This work experimental data
V_{MAP}	Volume of the sealed pouch containing the tray and the strawberries	0.5 ± 0.05	L	This work experimental data
V_{straw}	Volume of 0.100 kg of strawberry	0.142 ± 0.08	L	This work experimental data
V_T	Volume of the tray	0.0165 ± 0.006	L	This work experimental data
x_{CO_2max}	Maximal concentration of CO ₂ withstanding by <i>Botrytis cinerea</i>	30	%	(Garcia Gimeno et al., 2002)
$\beta_{O_2, 5\text{ }^\circ C}$	Rate of O ₂ consumption due to the deterioration at 5 °C	$7.29 \times 10^{-41*}$	$mol s^{-1} \%^{-1}$	This work estimated parameter
$\beta_{O_2, 10\text{ }^\circ C}$	Rate of O ₂ consumption due to the deterioration at 10 °C	$1.32 \times 10^{-45*}$	$mol s^{-1} \%^{-1}$	This work estimated parameter
$\beta_{O_2, 20\text{ }^\circ C}$	Rate of O ₂ consumption due to the deterioration at 20 °C	3.73×10^{-19} (-3.08×10^{-10} ; 3.08×10^{-10} ;	$mol s^{-1} \%^{-1}$	This work estimated parameter
$\beta_{CO_2, 5\text{ }^\circ C}$	Rate of CO ₂ production due to the deterioration at 5 °C	1.47×10^{-09} (7.29×10^{-09} ; 6.58×10^{-10})	$mol s^{-1} \%^{-1}$	This work estimated parameter

$\beta_{CO_2, 10\text{ }^\circ C}$	Rate of CO ₂ production due to the deterioration at 10 °C	9.13×10^{-10} (5.39×10^{-10} ; 1.12×10^{-09})	mol s ⁻¹ % ⁻¹	This work estimated parameter
$\beta_{CO_2, 20\text{ }^\circ C}$	Rate of CO ₂ production due to the deterioration at 20 °C	1.58×10^{-09} (1.17×10^{-09} ; 1.99×10^{-09})	mol s ⁻¹ % ⁻¹	This work estimated parameter
$\beta_{CO_2, 5\text{ }^\circ C}$	Rate of CO ₂ production due to the deterioration at 5 °C	1.47×10^{-09} (7.29×10^{-09} ; 6.58×10^{-10})	mol s ⁻¹ % ⁻¹	This work estimated parameter
$\beta_{CO_2, 10\text{ }^\circ C}$	Rate of CO ₂ production due to the deterioration at 10 °C	9.13×10^{-10} (5.39×10^{-10} ; 1.12×10^{-09})	mol s ⁻¹ % ⁻¹	This work estimated parameter

2.3.4.1 Shelf life modelling in MAP

2.3.4.1.1 Identifying the Maximal Acceptable Deterioration (D_{acc})

Figure 17 represents the % of accepted product at 20 °C by an untrained panel from day 1 to day 5 based on visual acceptance of the packed product. The limit of acceptability by the consumers, in days, was identified by the time at which less than 50 % of purchase occurs as generally recommended by researchers (Adobati, 2015; Cardelli and Labuza, 2001; Gim et al., 2005; Lareo et al., 2009). In this case study, day 2 was the limit of acceptability where 35 - 40 % of purchase was registered. Then, by looking at the deterioration curve, one can read a deterioration value of 13 % at day 2. Consequently, it means that, beyond 13 % of surface deterioration of the product, the consumer will reject the product. This limit was called the Maximal Acceptable Deterioration (D_{acc}). This maximal acceptable deterioration was assumed to be the same for this variety of strawberries 'Charlotte' whatever the conditions of storage, especially of temperature. We hypothesized that the consumers tolerate the same level of deterioration whatever the storage temperature.

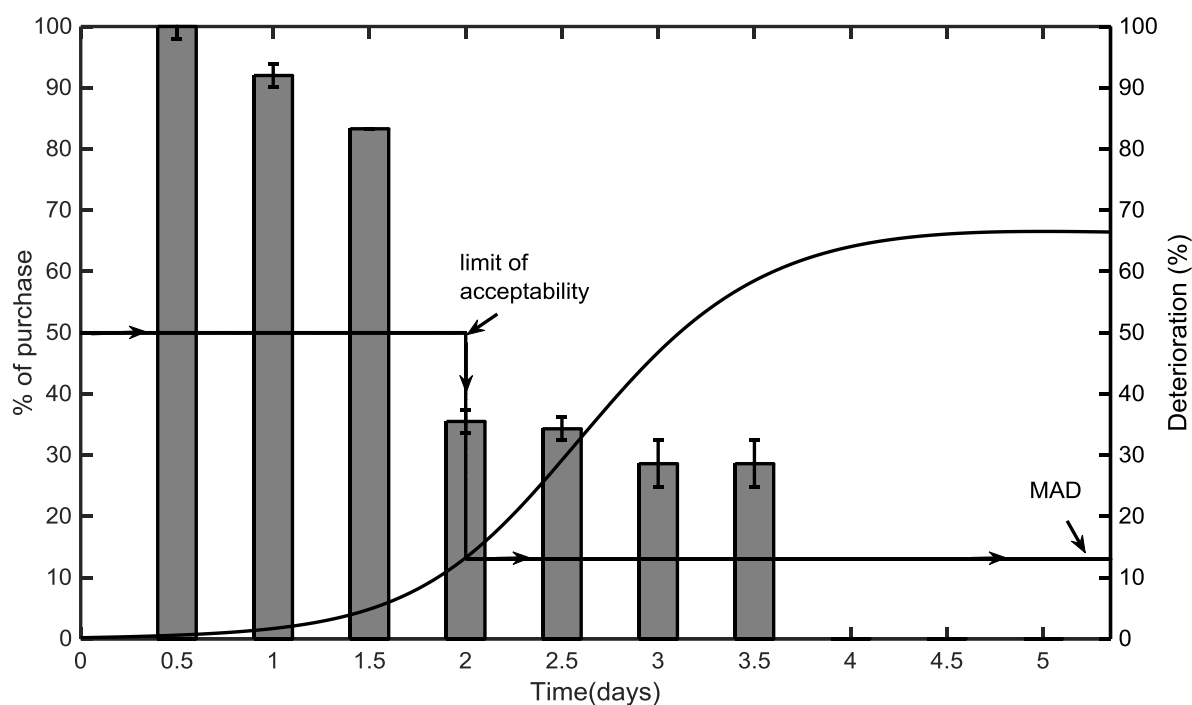


Figure 17: Determination of the Maximal Limit of Deterioration (Dacc) of packed strawberries from the consumer acceptability (based on the evaluation of willingness to purchase) and the measured deterioration curve for the product. Bar plot represents the percentage of acceptable trays at 20 °C during time. Error bars represents one standard deviation in each direction. Here the consumer acceptability is fixed at 50 %, i.e. 50 % of the panelist agreed to buy the product). This consumer limit permitted to set the limit of acceptability in days (here 2 d). Intercept of this limit with the deterioration curve gave the Maximal Acceptable Deterioration (Dacc) that is supposed to be the same whatever the storage conditions for the same strawberry variety. Error bars correspond to standard deviation.

2.3.4.1.2 Prediction of the deterioration

According to preliminary experimental results and on the basis of predictive microbiology models, evolution of deterioration was described by a logistic equation as primary model. A secondary model was then developed to include environmental factors affecting the deterioration, i.e. temperature and gas composition, as given in Eq. (21).

The effect of carbon dioxide was taken into consideration according to fungus sensitivity to this gas. In fact, fruit are mainly acidic matrices subjected to the development of fungus (Nguyen Van Long et al., 2016). The main fungus developing on strawberries at a temperature range of 0-20 °C is *Botrytis cinerea* (Hertog et al., 1999; Ozkaya et al., 2009; Shtienberg, 2007). In this study, the maximal CO₂ quantity

tolerated by *Botrytis*, $x_{CO_2_{max}}$, is considered equal to 30 % according to (Garcia Gimeno et al., 2002), values above which fungus growth is stopped.

The effect of oxygen was neglected due to its inefficiency on the development of *Botrytis* (Dock et al., 1998).

The differential equation used to describe deterioration was fitted to the experimental data at 5, 10 and 20 °C simultaneously (Figure 18). Estimated parameters in the deterioration Eq. (21), k_D and D_{ini} , are summarized in Table 8. One value of k_D was identified for each temperature 5, 10 and 20 °C therefore representing the effect of temperature on the deterioration. While the initial deterioration D_{ini} was assumed to be independent of the temperature and assumed identical for all strawberries batches.

The model proposed in Eq. (21) fits well the evolution of experimental deterioration as shown in Figure 18. The RMSE value that evaluates the goodness of model fitting is equal to 1.89 %. Same equation was applied for control samples without modified atmosphere. Same good fitting with RMSE equal to 2.4 % was obtained confirming that the model is able to predict the deterioration in both MAP and conventional conditions.

Temperature strongly impacted the deterioration rate in MAP as well as in conventional situation (Figure 18). In MAP condition, at 5 °C, the % of deterioration achieves 2.5 % at day 4. Whereas, at 10 °C, 4 % is achieved at 4 d of storage. For 20 °C, within 4 d of storage the deterioration reached 62 % at day 4. In the conventional condition, the deterioration was higher at the 3 studied temperatures. For 20 °C, at day 4 the deterioration reached 99.17 % in no MAP and 62 % in MAP. This confirms the positive impact of modified atmosphere packaging on slowing down the deterioration of the strawberries as already highlighted by Ozkaya et al., 2009; Riad and Brecht, 2015.

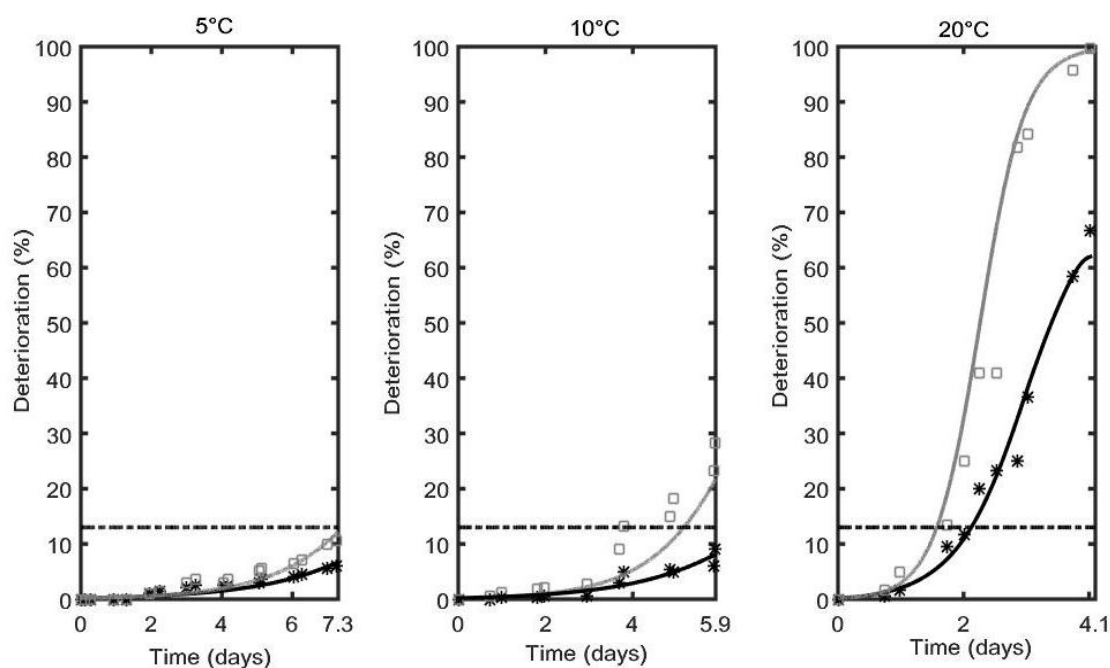


Figure 18 : Comparison between experimental (symbols) and predicted (solid lines) deterioration curves of strawberries packed in Modified atmosphere packaging MAP (*, —) and in ambient gas composition (□, —) at 5, 10 and 20 °C. The fitted curves were obtained by using equation 1 with parameters detailed in table 8. RMSE for MAP condition is equal to 1.89 % and for conventional conditions is equal to 2.4 %. Dotted lines (-.-) represents the maximal acceptable deterioration. Minimum two replications per time

In this study, the assessment of the product shelf life is original, based on modelling one global quality indicator coupled with the determination of willingness to purchase. This global quality indicator relies on the quantification in % of the visual surface deterioration encompassing texture softening, colour change and microorganism development unlike qualitative individual quality parameters assessment that prevails in most works of the literature such as (Briano et al., 2017; Ozkaya et al., 2009; Peano et al., 2014). Visual surface deterioration is the only criteria on which the consumers rely to buy packed strawberries at the distribution step. In addition, in this study the visual assessment was done twice a day in contrast with other studies on strawberries shelf life where measurements were conducted once every two days (Aday et al., 2011; Riad and Brecht, 2015). Thus, a shelf life in days can be quantified resulting from the built deterioration model confronted to the maximal acceptable deterioration D_{acc} (Figure 18).

To measure a shelf life in days, the time corresponding to the intersection between the maximal acceptable deterioration (D_{acc}) and deterioration curve was identified

according to equation (37). In Figure 18, for 5 and 10 °C experiments, deterioration stays below the maximal acceptable deterioration D_{acc} , meaning that the product is still acceptable for the customer and its shelf life is higher than the duration of the experiment i.e. more than 7 and 6 d for 5 and 10 °C respectively. Due to destructive analysis and limited quantities of strawberries provided by the farmer, it was not possible to prolong the duration of the experiments. However, for the experiment conducted at 20 °C, strawberries in MAP conditions have a shelf life of 2.13 d. After this period of time the consumer rejects the product.

2.3.4.2 Gases evolution in the headspace in isotherm conditions

In parallel to deterioration assessment, the evolution of O_2 and CO_2 molar fraction (%) in headspace was experimentally monitored in isothermal conditions at 5, 10 and 20 °C.

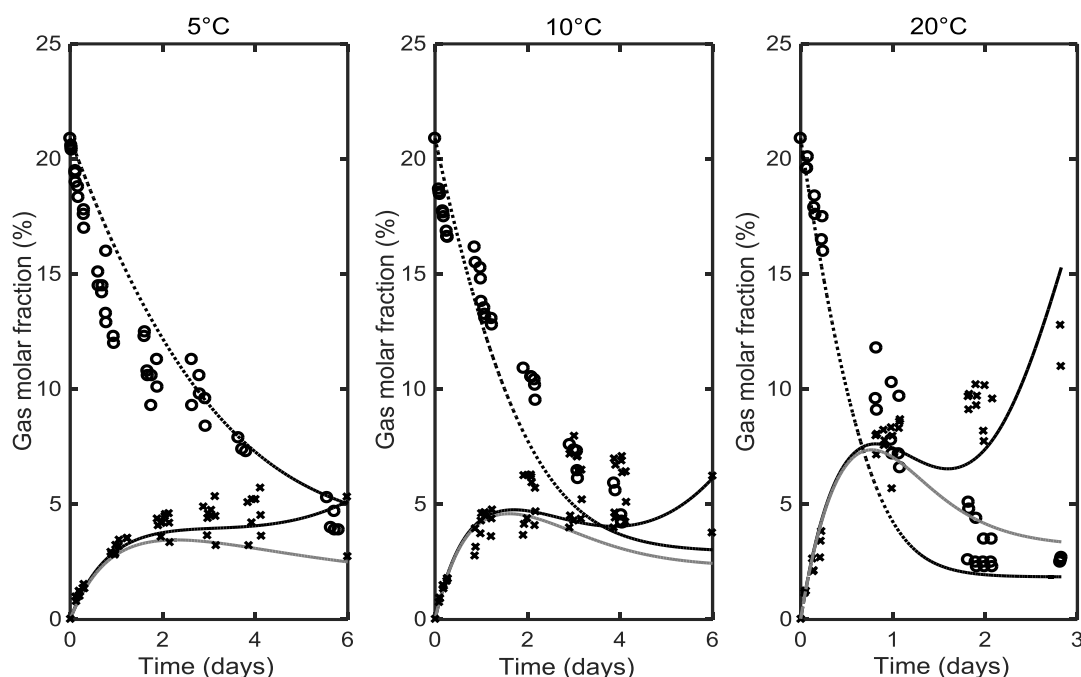


Figure 19: Comparison between experimental data (symbols), basic (grey lines) and upgraded (black lines) models for O_2 and CO_2 kinetics in headspace of a MAP system stored at 5, 10 and 20 °C. Circles ‘o’ and crosses ‘x’ correspond respectively to experimental values of O_2 and CO_2 . Dotted line ‘...’ and black line refer respectively to O_2 and the CO_2 kinetic models. The upgraded model is based on Eq. ((32) and (33)). The basic model assumes that deterioration does not impact gas evolution Eq. ((27) and (28)). RMSE for O_2 and CO_2 obtained were of 1.69 % and 2.23 % for the upgraded and basic models, respectively. Minimum three replications per time for experimental data.

Experimental assessment of CO₂ and O₂ were compared to the theoretical ones provided by the basic modelling tool combining permeation and respiration, namely Eq. (2) and (3). It is obvious from Figure 19, and especially at 20 °C, that the basic model failed to predict evolution of gases, especially that of CO₂. A significant deviation between the theoretical curve and experimental points occurred after 2 d of storage for CO₂ data at 20 °C. This deviation is smaller at 10 °C and 5 °C. An additional metabolic mechanism producing CO₂, in addition to strawberries respiration, occurs that could not be neglected.

To model this additional phenomenon and take into account its effect in the prediction of gas evolution in headspace, an upgraded model was build including permeation, respiration, deterioration and a second metabolism. It was assumed that this “second” respiration depends on the deterioration rate and would be the result of the deviation of the respiration rate of the deteriorated fruit cells concomitantly with the respiration rate of fungi that grow on the rotted surface. To this end, terms accounting for the net consumption of O₂ and CO₂ in Eq. (30) and (31): S_{O_2} and S_{CO_2} , were added to the molar flow equations. These net consumptions were assumed to be proportional to the percentage of deterioration, D , through a proportionality factor beta β Eq. (30) and (31).

The upgraded model Eq. (32) and (33) was used to fit the experimental data and to identify the β_{O_2} and β_{CO_2} factors in Eq. (30) and (31) (one set of parameters per temperature). For this fit, values of k_D at 5, 10 and 20 °C calculated in § 2.3.3 were used here to simulate Eq. (32) and (33). Results are shown in Figure 19 and identified parameters are given in Table 8.

The RMSE value of O₂ and CO₂ for the upgraded model is of 1.69 % and lower than that obtained with the basic model, 2.23 %, which confirms the suitability of the upgraded model to simulate O₂ and CO₂ curves together with deterioration and metabolic deviation. Thus, despite its simplicity, the model is able to reproduce effectively the experimental data. Clearly the space gap between the upgraded model and the basic model represents the metabolic deviation of the fruit for carbon dioxide curves which is the most visible at 20 °C where the metabolic deviation is the highest.

Analyzing β_{O_2} and β_{CO_2} estimated values at 5, 10 and 20 °C shows that metabolic deviation does not lead to an additional production of oxygen. Indeed, β_{O_2} values at the 3 temperatures were very small and the confidence intervals for β_{O_2} in Table 8 are close to zero so β_{O_2} can be neglected. This was further depicted by the O_2 curve in Figure 19 where O_2 curve from the upgraded model was overlaying the non-upgraded O_2 curve. On the contrary, β_{CO_2} values were found significant although very close to each other for the three temperatures investigated. In the following, β_{CO_2} was considered constant whatever the temperature of storage. Thus, in this experiment only additional CO_2 production seemed to occur. This additional CO_2 could be due to fermentation taken into account in the metabolic deviation definition.

Comparing curves of gases evolution at the 3 temperatures showed clearly the effect of temperature (Figure 19). On one hand, O_2 molar fraction at 5 °C decreased to 5.02 % after 6 d of storage whereas at 10 °C this value reached 3.02 %. At 20 °C, Oxygen curve showed a very rapid decrease from 20.9 at day 0 to 4.1 % at day 1 till 1.86 % at day 2.5. On the other hand, at 5 °C on day 6, CO_2 increased to achieve a value of 5.14 % while at 10 °C value of CO_2 was at 6.13 %. Carbon dioxide reached very high concentrations at 20 °C equal to 11.46 % CO_2 at day 2.5. This shows that temperature plays an important role on respiration of the fruit, microorganism development and permeation of the film. Analyzing activation energy values for permeabilities E_{a,PCO_2} , E_{a,PO_2} and maximal respiration rate $E_{a,RO_{2max}}$ of the fruit in Table 8, we can conclude that the temperature affected mostly fruit respiration, then the permeability of the film to oxygen followed by the permeability to carbon dioxide. Thus, at higher temperatures these mechanisms were accelerated as supported by Beaudry, 2000; Brecht et al., 2003.

Modifications of CO_2 concentration in headspace could notably influence fruit's deterioration, CO_2 concentration being one of the environmental factor with temperature, considered in the model of deterioration. Simulations of deterioration carried out for constant CO_2 concentrations in the headspace demonstrated that CO_2 concentration equal to 15 % will reduce by two the deterioration. Thus, the increase of CO_2 concentration in the headspace is able to significantly decrease the deterioration

percentage of the fruit. Considering only strawberries' respiration and CO₂ permeation through the LDPE pouch, the passive MAP generated was limited in its maximal level. But thanks to the metabolic deviation due to the fruit's deterioration and microorganism development and its concomitant additional CO₂ production, CO₂ concentrations close to 6 % at 5 -10 °C and close to 12 % at 20 °C could be finally reached in the package, which significantly delayed the deterioration (Figure 18, Figure 19). In fact, the increasing percentage of carbon dioxide inhibits linearly the deterioration of the strawberries as presented in Eq. (21). In the case of strawberries, 30 % of CO₂ would be needed to inhibit totally fungi development (Beaudry, 1999; Mattos et al., 2012). Thus, effect of carbon dioxide on the deterioration could be noticeable the most at 20 °C where percentage of CO₂ was the highest.

We noted that in this work the decrease of O₂ content in headspace had an effect on fruits' respiration. According to the value of Km equal to 8100 Pa for strawberry *Charlotte*, a decrease of O₂ till 8 %O₂ would divide by half its respiration rate. Thus, lowering effect on fruit's respiration of O₂ decrease was visible in this study.

2.3.4.3 Investigating realistic storage conditions

Using a realistic temperature profile recorded in Figure 20(a), we note that experimental O₂ and CO₂ concentrations obtained in the headspace (Figure 20(c)) varied in a large extend: CO₂ steeply increased while O₂ rapidly dropped reaching even values close to 0 after 4 d of storage. This was not anticipated by our preliminary design of our experimental MAP system made using the basic model, where geometry of the system was adjusted to avoid anoxia and achieve optimal recommended atmosphere. This deviation was mainly due to the metabolic deviation that superimposed to the respiration of the fruit and that strongly impacts O₂ and CO₂ mass balances in the packaging headspace. This metabolic deviation was as impacting and important as temperature and deterioration which was the case in the present case study (Figure 20).

As expected, sudden changes in the deterioration and/or gases evolution curves were observed for each temperature steps in Figure 20(b). The model fits the experimental values (RMSE values of 1.68 % for O₂, 2.53 % for CO₂) even if slight discrepancies between prediction and experiment were noted mainly attributed to the biological

variability and initial contamination by microorganisms and simplifications made in the model to represent the different mechanisms, especially metabolic deviation. In addition, the experimental carbon dioxide values after day 4 are very dispersed because of the numerous previous assays/sampling done on the same sample.

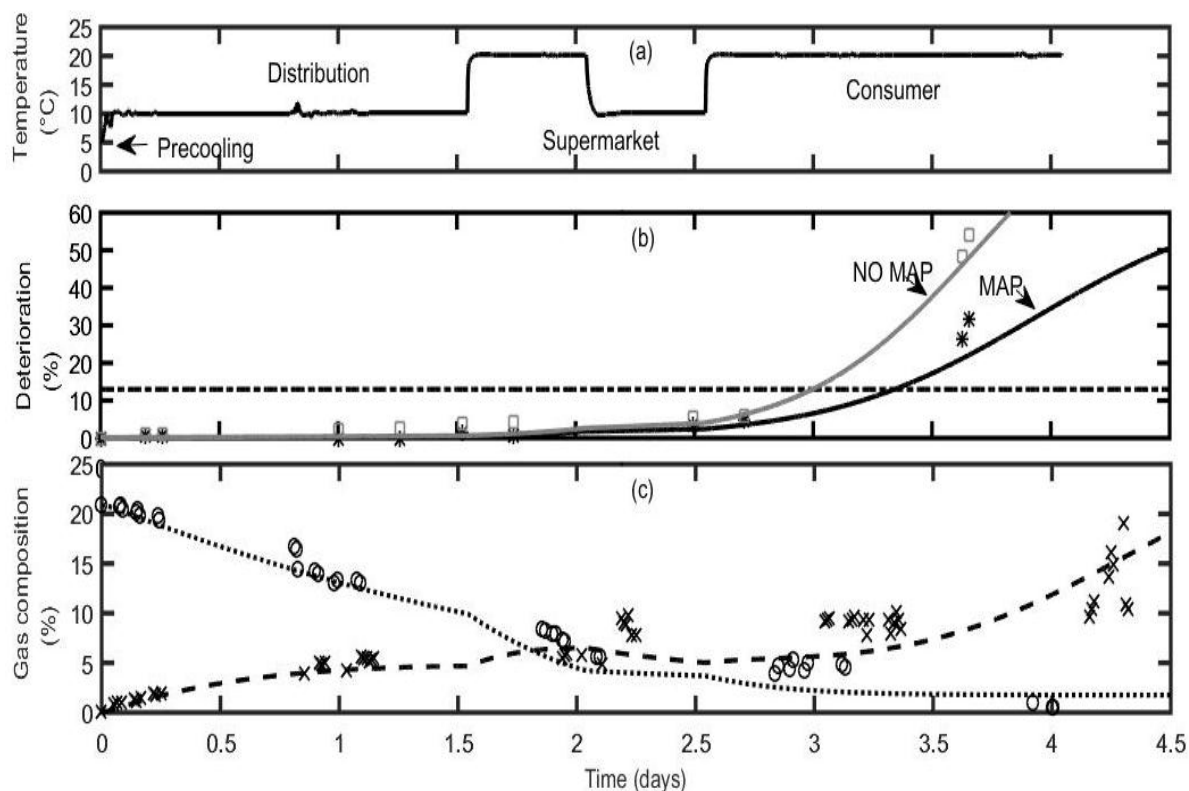


Figure 20: Model validation using (a) evolution of post-harvest temperature profile as a function of time during which (b) experimental deterioration in MAP (*) and no MAP (□) is compared to the predicted one in MAP (—) and no MAP (—) conditions. RMSE values are equal to 1.85 % for deterioration in MAP and 1.25 % for deterioration in NO MAP. A Maximal acceptable deterioration (-.-.) by the consumer is set. In parallel, in graph (c) experimental O₂ (o) and CO₂ (x) in MAP condition are measured and compared to predicted associated curves (...) for O₂ and (---) for CO₂. RMSE values are 1.68 % for O₂, 2.53 % for CO₂. Gases composition in no MAP conditions are not represented in this figure because they are equal to atmosphere composition i.e. 20.9 %O₂, 0.03 %CO₂. Minimum three replications per time for experimental data

In Figure 20(c), deterioration curves in MAP and conventional shelf life storage are shown, in accordance with experimental data, RMSE values were equal to 1.85 % for MAP deterioration, 1.25 % for no MAP deterioration.

Thus, the model succeeded in predicting the mass transfer phenomena, the deterioration and the metabolic deviation inside the studied MAP system. Low RMSE

values indicated that we can reasonably consider that the upgraded modeling tool predicting deterioration, mass transfer and metabolic deviation is validated.

Quantifying shelf life in days in this temperature profile conditions shows that, the trays in conventional conditions (NO MAP-Figure 20(c)) reached a shelf life of 2.99 d whereas in MAP conditions the storage shelf life was equal to 3.32 d resulting in a gain of 0.33 d. This is just a first comparison of two conditions that are not optimized; that's why only limited shelf life extension was obtained. Further improvement of those conditions i.e. CO₂ initial content in the pack, storage temperature at consumer's home, etc., would result in a higher shelf life gain. For instance, amelioration could be storage at 5 °C at consumer's home which will increase by 1.68 d the gain of shelf life with MAP against conventional conditions (Figure 21). Thus, optimizing the storage conditions should be considered in future studies.

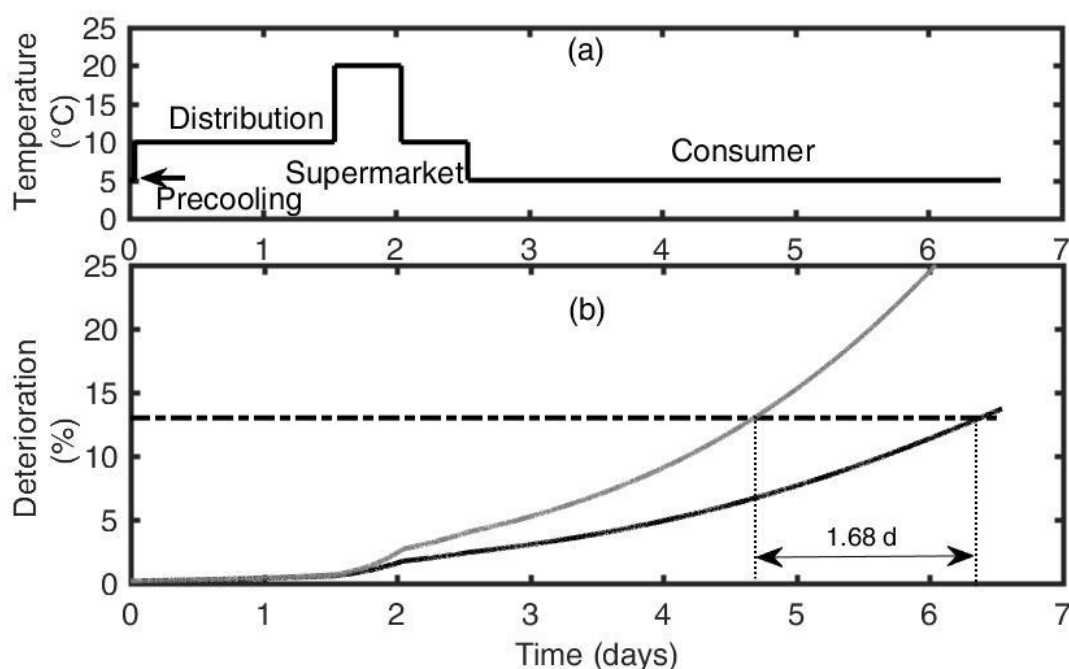


Figure 21: Estimation of shelf life gain for a predefined postharvest temperature profile (a), using predicted MAP (—) and no MAP (---) curves and their intersection with the maximal acceptable deterioration D_{max} (b).

2.3.5 Conclusion

An upgraded modelling tool able to predict mass transfer phenomena for O₂/CO₂ including gases consumed or released due to metabolic deviation and deterioration of the food in packaging system was developed. As never done before, this model can take into account the impact of gas concentration in the headspace on the percentage of deterioration of the packed product. The upgraded model succeeded in predicting O₂ and CO₂ headspace concentration, it also gave a good prediction of the experimental deterioration curve. A maximal percentage of deterioration (D_{acc}) of 13 % based on consumer's acceptability and willingness to purchase, was identified and used to quantify the shelf life gain of the product packed in MAP compared to the conventional situation. Next steps of this work will be the exploration of more scenarios that will enable us to identify which MAP/Temperatures couples will maximize the gain of product shelf life. Significant benefits of this shelf life gain are anticipated on the reduction of food losses in the postharvest chain. This feature will be explored in a next paper by adding to the present shelf life gain estimation, a prediction of the quantity of food losses avoided.

Acknowledgement

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2.4 Concluding remarks

A methodology was developed to assess the experimental deterioration of strawberries in MAP. It was based on a **visual percentage of surface deterioration** including color change, texture softening and spoilage development. The main advantage of this method presented in part 1.2 is the reliance on **one global quality parameter (% of surface deterioration)** representative of the quality evaluation done by the consumer at purchase.

The upgraded MAP modelling tool was built and validated on both isothermal and non-isothermal conditions, using in this latter case a more realistic temperature profile. This model was able to predict gases evolution in the headspace and product deterioration. On one hand, the evolution of O₂ and CO₂ considered **product respiration, gases permeation through the film, metabolic deviation** of the packed product and **fermentative activities** (due to produce or external microorganisms). On the other hand, the evolution of **product deterioration** was predicted as function of **temperature, time** and **carbon dioxide** in the headspace.

A **maximal acceptable deterioration (MAD)** by the consumer was determined and found equal to **13%**. This means that by the time the surface of the product reaches a deterioration higher than 13%, the consumer won't buy the product anymore. Thus, after crossing this limit, the whole tray of strawberries will be thrown creating additional losses and wastes. This limit of acceptability is **valid only during the purchase act** and can be used in future studies for quantifying losses and wastes at supermarket level.

The upgraded model developed for predicting **shelf life** in MAP within the investigated range of temperatures will be next linked to a percentage of **food losses and wastes focusing on household also called consumer level** (chapter 3). Household level is the main postharvest stage studied because of the possibility of identifying consumers' behaviour toward product storage unlike supermarket less motivated to cooperate/provide additional essential information.

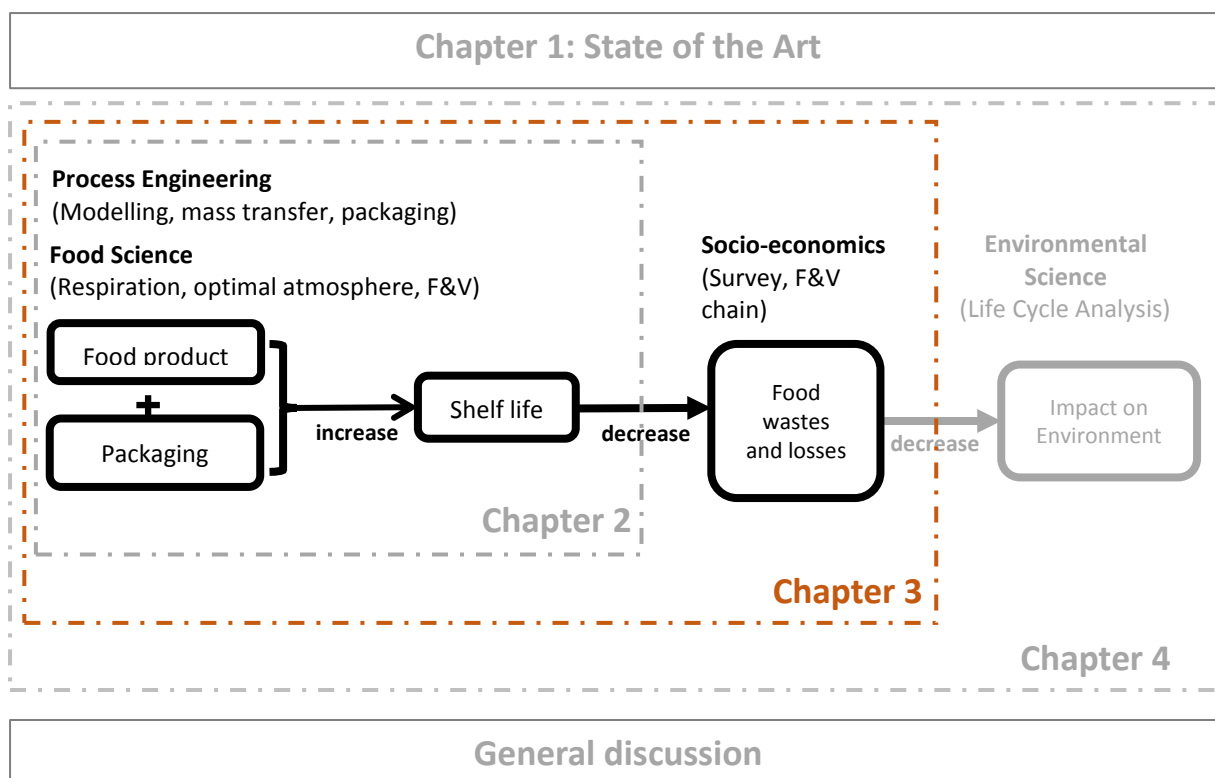
MAIN FINDINGS

- Development of a visual deterioration model based on color change, texture softening and spoilage development
- Prediction of product deterioration as a function of temperature, time and carbon dioxide concentration in the headspace
- Prediction of O₂ and CO₂ in the headspace encompassing product respiration, gases permeation through the film, metabolic deviation and fermentative activities
- Identification of a maximal acceptable deterioration (MAD) by the consumer, at purchase, equal to 13% of deteriorated surface area

Chapter 3: Predicting food losses reduction due to MAP

Chapter 3: Predicting food losses reduction due to MAP

3.1 Introduction



After upgrading the 'MAP modelling tool' able now to predict deterioration of the product concomitantly with gases assessment in chapter 2, the objective of this chapter is to go further in the approach and link product shelf life with food losses and wastes reduction.

A key step of this PhD project is to be able to attribute to a shelf life gain a corresponding reduction of percentage of losses and wastes. For this end, information on stakeholders' postharvest practices is needed. Collaborations with human and social science were thus done to understand more into details the behaviour of the postharvest chain actors. The challenge here is to be able to estimate a percentage of losses and waste to a postharvest chain scenario while considering actor's behaviour such as distributors, wholesalers, consumer etc...

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However, preliminary results and literature review revealed difficulties in obtaining data concerning supermarket and wholesaler's stages. For this end, in this chapter, **losses** will be linked only to consumer behaviour at the **household level** due to more accessible and detailed information. Losses refer to product thrown due to quality deterioration. Wastes (i.e. behavioural losses, voluntary) will not be quantified during this PhD.

Impact of temperature, duration of storage and improved consumer behaviour on the shelf life of strawberries was also investigated.

3.2 Considering consumer's behavior and practices in the prediction of postharvest losses reduction for fresh strawberries packed in Modified Atmosphere Packaging (Article 3)

Matar Céline ^a, Gaucel Sébastien ^a, Gauche Karine ^b, Costa Sandrine ^b, Gontard Nathalie ^a, Guilbert Stéphane ^a & Guillard Valérie ^{a, *}.

^a. Joint Research Unit *Agro polymers Engineering & Emerging Technology*,

^b. Joint Research Unit *Market Organizations, Institutions & Actors' strategies*,

UM - INRA- Supagro & CIRAD, 2 place Pierre Viala, Bat 31, 34060 Montpellier cedex 01 France

*valerie.guillard@umontpellier.fr

Abstract

The objective of this study is to estimate the reduction of losses when product shelf life is increased by using modified atmosphere packaging (MAP). It considers the diversity of all possible postharvest storage conditions until household stage where consumer practices were also included. Fresh strawberries supply chain in the south of France was taken as a case study. 132 post-harvest scenarios were investigated by using a mathematical modelling tool able to calculate the percentage of losses generated in the postharvest chain as function of product deterioration, while taking into account consumers' behaviour. To feed this model, distributors' and consumers' surveys were conducted in order to identify their storage habits (temperature, duration of storage and state of the packaging). For instance, it was found than more than 50% of consumers open the packaging before storing the fruits into the fridge. Therefore, the benefit of MAP is lost long before fruits' consumption. Evaluating each scenario and aggregating them in a unique score considering the occurrence of each consumers' scenario showed that, using current macro-perforated packaging for strawberries with current consumer behaviour, 9.21% of losses is generated whereas when MAP is used in the postharvest chain with unchanged consumer behaviour, the

Chapter 3: Predicting food losses reduction due to MAP

percentage of losses is reduced by 17.8. However, exploring possible future changes of consumer habits has revealed that the percentage of losses could be significantly reduced up to 74% if all the consumers store the strawberries in the fridge and keep the packaging in MAP condition.

Keywords

“Losses in MAP” modelling tool, food losses reduction, consumer behaviour, supermarket, post-harvest scenarios, fresh fruit and vegetables,

Nomenclature

Parameter	Definition	Unit
$p_{O_2}^{\text{in}}$	Internal partial pressure of oxygen	Pa
D_{max}	Maximum percentage of deterioration	%
$E_{a,k}$	Activation energy for parameter k	J mol ⁻¹
k_D	Deterioration rate constant	s ⁻¹
Km_{O_2}	Constant of Michaelis and Menten	Pa
k_{ref}	Value of parameter k at reference temperature T_{ref}	
l_{max}	Minimum percentage of losses	%
l_{min}	Maximum percentage of losses	%
l_s^p	Percentage of losses of the scenario s using the packaging p	%
L_s^p	Percentage of losses affected by stakeholder's Storage behavior	%
L_{tot}^p	Total percentage of losses affected by actor's storage behavior's for all the scenarios of a population	%
P_{O_2}	Permeability of the film to oxygen	mol m ⁻¹ Pa ⁻¹ s ⁻¹
P_{CO_2}	Permeability of the film to carbon dioxide	mol m ⁻¹ Pa ⁻¹ s ⁻¹
$p_{O_2}^{\text{in}}$	Partial pressure of oxygen in the headspace	Pa
$p_{CO_2}^{\text{in}}$	Partial pressure of carbon dioxide in the headspace	Pa
$p_{O_2}^{\text{out}}$	Atmospheric partial pressure of oxygen	Pa
$p_{CO_2}^{\text{out}}$	Atmospheric partial pressure of carbon dioxide	Pa
$R_{O_2\text{max}}$	Maximum respiration rate per kg of food commodity	mol kg ⁻¹ s ⁻¹
$T_{\text{ref},k}$	Reference temperature for the parameter k .	K
β_{CO_2}	Rate of carbon dioxide production due to the deterioration	mol s ⁻¹ % ⁻¹
A	Surface area of the film	m ²
a	Estimated parameters	dimensionless
b	Estimated parameters	dimensionless

D	Percentage of surface deterioration	%
D_{acc}	Maximal acceptable deterioration	%
e	Thickness of the film	m
k	Temperature dependent parameter	
m	Weight of the food product	kg
p	State of the packaging : MAP or no MAP	
P_d	Probability related to storage duration: one or three days at the consumer	dimensionless
P_p	Probability related to packaging state: kept or removed packaging at the consumer level	dimensionless
P_T	Probability related to storage temperatures: ambient or fridge storage at the consumer level	dimensionless
q_{RQ}	Respiratory quotient	dimensionless
R	Universal gas constant	$J mol^{-1} K^{-1}$
s	Scenario	
s_{max}	Scenario having the highest value of deterioration integral	
s_{min}	Scenario having the smallest value of deterioration integral	
t	Time	s
w	Occurrence of a stakeholder's storage behavior in the postharvest chain, w can vary between 0 and 1	dimensionless

3.2.1 Introduction

Worldwide, around one third of the agri-food produced is lost in the supply chain from agricultural production down to household consumption (Gustavsson et al., 2011). At the same time, more than 20.000 children under the age of five are dying from hunger every day. In addition, the direct economic cost of wastage of agricultural food products (excluding fish and seafood), based on producer prices, is about USD 750 billion per year, equivalent to the Gross Domestic Product of Switzerland. By 2050, the food wasted is estimated to reach over 200 millions of tons per year which will generate a considerable environmental impact such as high carbon footprint, blue water footprint and vain land use. (Scialabba, 2013a).

The latest studies showed that, in 2007, the major contributor to the total food losses volumes are fruit and vegetables representing 40 % of total losses, followed by cereals and starchy roots recording 25 and 19% of total losses respectively (Scialabba, 2013a). In Europe, Within the fruit and vegetables (F&V) supply chain, 56 % of the losses occur in the postharvest stages (Gustavsson et al., 2011). Postharvest stages are successive stages which the product pass by after harvesting till to the moment

when someone eats them (El-Ramady et al., 2014). In developed countries, the postharvest stage having the highest percentage of losses for fruit and vegetables is the consumer step with 19 % of F&V losses. This high amount of food losses is linked to the very short shelf life of the F&V (Matar et al., 2018; Muriana, 2017; Porat et al., 2018). Shelf life of a fresh product represents the duration between harvesting and household stage during which the product is edible (G. L. Robertson, 2010).

Recently, packaging was identified as an essential element to address key challenge of sustainable food consumption and is gaining interest among scientist (Angellier-coussy et al., 2013b; Licciardello, 2017). One of the technologies able to increase the shelf life of the product using an adequate packaging is modified atmosphere technology (MAP). MAP consists on changing gases composition in the headspace of the packed product (Belay et al., 2016; Chaix et al., 2015; Falagán and Terry, 2018). In the particular case of fresh fruit and vegetables, the modified atmosphere is created by the product itself after packing thanks to its respiration taking oxygen from internal packaging headspace and releasing carbon dioxide. In parallel, oxygen and carbon dioxide diffuse through the film with a rate defined by the permeability of the film used. At the steady state, the so-called equilibrium modified atmosphere (eMAP) is reached. It must be as close as possible to the optimal recommended storage atmosphere to preserve the product's quality and safety (Carole Guillaume et al., 2010). A query on easy web of science, on April 2018, with the keywords 'Modified atmosphere packaging', 'Fresh fruit and vegetables' and 'Shelf life' in field "topic", returned more than 460 available scientific articles discussing the benefit of MAP on the shelf life increase of fresh fruit or vegetables. All these studies confirm the benefit of MAP on extending the shelf life of the product even if this shelf life extension was not always quantified in a clear and fair manner. In the aim of quantifying shelf life in MAP, the most recent elaborated studies are the ones including shelf life models able to predict product shelf life as a function of time. In this purpose, Oliveira et al 2012 predicted the evolution of firmness of sliced mushrooms stored in MAP as a function of time and temperature (Oliveira et al., 2012b), Adobati et al 2018 also quantified shelf life of whole raspberries in MAP by modelling their firmness as a function of time at 5°C (Adobati et al., 2015). So far, the shelf life model developed by Matar et al 2018 has the most complete approach integrating in the shelf life prediction simultaneously the effect of MAP gases and consumer acceptability of the product. However, to the best

of our knowledge, none of the available shelf life models took into account the behavior of the postharvest chain actors (i.e. stakeholder in each stage) in the estimation of the shelf life although the importance of incorporating the supermarket and consumer stages in the postharvest chain studies has been highlighted in several studies (Muriana, 2017; Porat et al., 2018).

In all the aforementioned studies illustrating the benefit of MAP on the shelf life, none of the works attempted to go further and link this shelf life's gain with the corresponding potential positive effect on food losses reduction. In fact, thanks to the increased product shelf life, MAP packaging may avoid losses at different stages of the post-harvest chain and reduce the corresponding useless negative impact that producing and distributing uneaten or inedible food has on our environment and economy (Verghese et al., 2015). Williams et al 2010 initiated a methodology for considering food losses reduction in a LCA. But in their study, losses estimation was only based on literature survey and technical expert interview and not quantified in relation to the packaging used (Wikstrom and Williams, 2010; Williams et al., 2012).

Facing the lack of studies dealing with the quantification of the amount of food losses avoided following shelf life increase (Muriana, 2017), the objective of this study was to build a link between quantified product shelf life and resulting food losses while taking into account the behaviour of the actors of the postharvest chain. The case study chosen for illustrating our approach was the postharvest chain of strawberries in the south of France, chosen as a worst case food model because of its high perishability. To achieve the targeted objective, a mathematical model developed in Matar et al 2018, coupling deterioration of the product and gases assessment in the headspace, was used to numerically explore different post-harvest scenarios built on the basis of the results of two different surveys: distributor and consumers survey. Next, a mathematical equation was proposed to link the deterioration of the product with estimation of food losses. Both distributor and consumers survey were conducted to assess the effect of French distributors' and consumers' behaviour and practices on the estimation of postharvest losses.

3.2.2 Methods

3.2.2.1 *Building postharvest stages and conditions of storage*

This article demonstrates one typical example of strawberries' supply chain in the south of France from packaging stage till household storage. Multiples interviews and surveys were conducted. Firstly, interviews with French wholesalers (that buy, pack and sell the product) in the south of the country aimed to identify the main stages encountered in the postharvest chain. Secondly, two surveys were done at the distributor and consumer level to have more detailed information about these two stages suspected to generate high amount of losses.

3.2.2.1.1 *The choice of the postharvest stages and corresponding losses*

A typical postharvest chain for strawberries was constructed based on one hand, on visits and interviews (detailed in supplementary material) done with French wholesalers in the south of the country and on the other hand, literature review was done using studies from the Interprofessional Technical Center for fruit and vegetables (CTIFL) dealing with French strawberries supply chain (Moras, 2001; Moras et al., 2003a, 2003b; Moras and Tamic, 2001; Vaysse et al., 2015). This postharvest chain is expected to include stages starting at the packing till the consumer level. For each postharvest stage, the time-temperature history of storage was recorded as well as the percentages of strawberries losses when available.

3.2.2.1.2 *Tracking storage conditions and practices at the supermarket level*

To build scenarios with realistic storage conditions at the distributor level, operational data are essential. A questionnaire was constructed to understand the organization of procurement and distribution of strawberries in the French distribution. Thus, several objectives underpinned. First, information on the practices of mass retailing in the fruit and vegetables sector and more particularly for "strawberry" were needed. Then, we aimed at constructing a typical circuit with indication of duration and temperatures of storage, identify the locations of losses, and estimate them if any. In addition, we focused on understanding the buying decision process i.e. the selection criteria and decision makers of packaging and the impact of a shelf life increase on the distributor's practices. For example: if strawberries shelf life is extended for one more day and strawberries are stored for one more day, what will this imply as changes in supermarkets management?

The questionnaire is therefore organized around various work processes at the distributor level, considering their impact on the losses such as supplies, reception, storage, inventory management and management of fruit and vegetables department. In addition, to estimate losses, information about strawberries shelf life, storage temperatures, losses (in value and/or percentage) and limits of acceptability are requested in the questionnaire. Furthermore, the questionnaire was constructed based on a report of the Interprofessional Technical Center for fruit and vegetables (CTIFL, www.ctifl.fr) identifying the brakes and levers for reducing losses for fruit and vegetables including strawberries (Baros and Hongre, 2017). The questionnaire (in supplementary material 2.1) is composed of 60 questions built on LimeSurvey software (LimeSurvey, Hamburg – Germany) and was sent to 89 departments heads working in the fruit and vegetables supermarkets section.

3.2.2.1.3 Identifying consumers 'storage behaviour

The survey conducted at the consumer level tend to define purchase and consumption habits and was based on hypothesis found in the literature (Roty, 2011a, 2011b; Vaysse et al., 2013). This questionnaire is divided in five parts encompassing: 'Profile', 'Strawberries purchase', 'Usage after purchase', 'Awareness to wastage', 'Familiarity and expertise' (see questionnaire in supplementary material 2.2).

The first part of the questionnaire enables us to identify the profile of the respondent by asking about his age, sex and socio professional category. The second part is dedicated to the strawberries purchase habits particularly on the strategy used to select the product during purchase i.e. which of the five senses does the consumer use to evaluate the quality of the strawberries. The third part concerns the usage of the strawberries after purchase. This part aims at identifying the storage conditions at the household. In fact, strawberries can be consumed immediately or later, stored at ambient temperature or in the fridge, washed and sorted immediately after purchase or right before consumption. Questions also related to the form in which strawberries are eaten (whole, cut in cubes, etc...) as well as the time at which the product is eaten. The fourth part contains questions related to the sensibility or awareness of the consumer to food and lastly part five measure the level of knowledge of the consumer toward the product studied.

Chapter 3: Predicting food losses reduction due to MAP

The questionnaire contains in total 19 questions (see supplementary material 2.2) built on LimeSurvey software (LimeSurvey, Hamburg – Germany) and was sent to a panellist of consumers by email.

Note that questions related to the percentage of strawberries wasted at the consumer level were already asked during the interviews done with the wholesalers in the south of France since we assume that the consumer is not able to objectively quantify the percentage of losses that he generates. Unpublished studies conducted by wholesalers could have evaluated the percentage of losses generated by consumers.

3.2.2.2 Setting up a mathematical model able to predict food losses in MAP linked to product's quality and stakeholders' behaviour

A 'MAP modelling tool' taken from Matar et al 2018 was upgraded to be able to predict food losses in MAP. Details on this upgraded model are given hereafter.

3.2.2.2.1 Overview of the 'MAP modelling tool', a shelf life model in MAP used as a starting point

'MAP modelling tool' takes into account the evolution of product quality in MAP conditions. A short summary of the hypothesis and modelling equations used is presented hereunder:

The MAP system is composed of strawberries put in a PE (Polyethylene) tray and packed with an LDPE (Low Density Polyethylene) film. Thus, the tray is assumed impermeable to mass transfer and gases permeation occurs only through the flexible pouch. During conservation, the food/packaging system is surrounded by an atmosphere with constant composition equal respectively to 20.9 %O₂, 0.03 %CO₂ and 79.07 %N₂ (Widory and Javoy, 2003). The atmospheric pressure is considered constant. The volume of the headspace is assumed to be constant during time and its gas composition is considered uniform whatever the position. Heat transfer at atmospheric, packaging material, headspace and food commodity levels are assumed to occur faster than mass transfer. Consequently, the system temperature is assumed uniform in space and in thermal equilibrium with the surrounding atmosphere. Finally, only the control temperature, i.e. temperature of the atmosphere surrounding the packaging, was considered.

The rate of deterioration including temperature and CO₂ effect is represented as follow:

$$\frac{dD}{dt} = k_D D \frac{D_{\max} - D}{D_{\max}} \bar{\delta}_{CO_2} \quad (39)$$

where D is the percentage of surface deterioration (%) at time t (s), D_{\max} is the maximum percentage of deterioration (%), k_D represents the deterioration rate constant (s^{-1}) and $\bar{\delta}_{CO_2}$ a dimensionless weighting parameter representing the inhibiting effect of carbon dioxide on the deterioration rate.

For the gases evolution in the headspace, a mass balance for O_2 and CO_2 was done encompassing permeation through the film, respiration rate of the product and deterioration effect as follow:

$$\frac{dn_{O_2}}{dt} = \frac{P_{O_2} A}{e} (p_{O_2}^{out} - p_{O_2}^{in}) - \frac{R_{O_2max} p_{O_2}^{in}}{(Km_{O_2} + p_{O_2}^{in})} m \quad (40)$$

$$\frac{dn_{CO_2}}{dt} = \frac{P_{CO_2} A}{e} (p_{CO_2}^{out} - p_{CO_2}^{in}) - q_{RQ} \frac{R_{O_2max} p_{O_2}^{in}}{(Km_{O_2} + p_{O_2}^{in})} m + \beta_{CO_2} D \quad (41)$$

The first term of the expression on the right refers to the Fick's first law describing the mass flow of gas species (O_2 , CO_2) in a steady state regime through the film, the second term is the expression of the respiration rate using the simplest classical Michaelis and Menten equation without CO_2 inhibition and the third and last term is the metabolic deviation (CO_2 production) due to deterioration.

In Eq (40) and/or (41), A is the surface area of the film (m^2), e the thickness of the film (m), $p_{O_2}^{out}$ or $p_{CO_2}^{out}$ are the atmospheric partial pressure of O_2 and CO_2 respectively (Pa), $p_{O_2}^{in}$ or $p_{CO_2}^{in}$ are the partial pressure of O_2 and CO_2 respectively in the headspace (Pa), P_{O_2} or P_{CO_2} are the permeability of the film for O_2 and CO_2 ($mol\ m^{-1}\ Pa^{-1}\ s^{-1}$).

R_{O_2max} corresponds to the maximum respiration rate per kg of food commodity ($mol\ kg^{-1}\ s^{-1}$), Km_{O_2} is the constant of Michaelis and Menten (Pa), $p_{O_2}^{in}$ is the internal partial pressure of oxygen (Pa) and m is the weight of the food product (kg), q_{RQ} is the respiratory quotient (dimensionless),

β_{CO_2} represent the rate of carbon dioxide production due to the deterioration ($\text{mol s}^{-1} \%^{-1}$). Note that oxygen consumption due to deterioration was found negligible.

The effect of temperature on the deterioration, respiration and permeation is represented through Arrhenius law as follow:

$$k(T) = k_{ref} \exp\left(\frac{-E_{a,k}}{R} \left(\frac{1}{T} - \frac{1}{T_{ref,k}}\right)\right) \quad (42)$$

where k refers to the temperature dependent parameter, i.e. permeability of material to oxygen and carbon dioxide P_{O_2} and P_{CO_2} , respectively, k_D the deterioration rate constant and R_{O_2max} the maximal respiration rate, k_{ref} is the value of parameter k at reference temperature T_{ref} , $E_{a,k}$ is the activation energy for parameter k (J mol^{-1}), R is the universal gas constant ($\text{J mol}^{-1} \text{K}^{-1}$), $T_{ref,k}$ is the reference temperature (K) for the parameter k .

3.2.2.2.2 An updated deterioration model linked to actors' behaviour and food losses along the food supply chain

It was assumed that the area under the deterioration curve, D , is proportional to the percentage of losses. Thus, the percentage of losses is considered linear to the integral of the deterioration curve D as follows:

$$I_s^p = a \int_{t=i}^{t=j} D_s^p + b \quad (43)$$

where p is the type of the packaging, s the number of the scenario tested in a population P of scenarios studied, I_s^p is the percentage of losses of the scenario s using the packaging p (%), $\int_{t=i}^{t=j} D_s^p$ is the integral of the deterioration curve D for scenario s in the packaging p from $t=i$ to $t=j$ (dimensionless), i and j representing the time at which the studied postharvest stage begins and ends respectively (day). a and b are the estimated parameters of the linear regression, a and b are dimensionless.

In Figure 22 (a) an example of a temperature profile applied for a postharvest chain scenario is represented. The corresponding deterioration curves and calculations of their integrals is shown for two different packaging $p = \text{MAP}$ (black hatched area) and

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p = no MAP (grey hatched area) storage at the consumer level i.e. from $t=1.4$ days to $t=2.4$ days (Figure 22 – b).

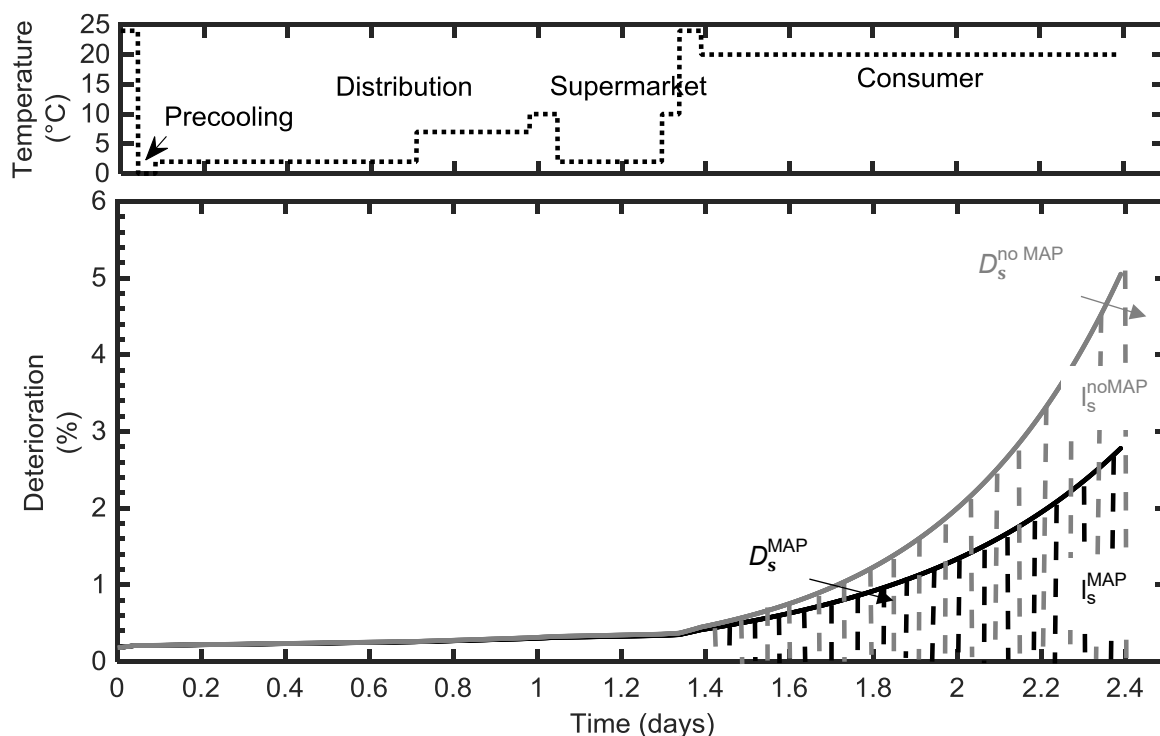


Figure 22 An example of postharvest chain scenario including precooling, distribution, supermarket and consumer stages with the applied storage temperature in dotted line (...) (a) and predicted $D_s^{\text{no MAP}}$ and D_s^{MAP} deterioration curves in no MAP (grey curve) and MAP (black curve) conditions (b). Grey and black hatched areas under the deterioration curves are linked respectively to the percentage of losses at the consumer level $I_s^{\text{no MAP}}$ and I_s^{MAP} respectively calculated using Eq (43).

Afterwards, the behaviour of the stakeholder or actor at a studied stage is linked to the percentage of losses I_s^p as follow:

$$L_s^p = I_s^p w \quad (44)$$

L_s^p is the percentage of losses affected by stakeholder's storage behaviour (%) for the scenario s with a packaging p , I_s^p the percentage of losses for the scenario s in a packaging p (%). w is the probability of occurrence of a stakeholder's storage behaviour in the postharvest chain, w can vary between 0 and 1 (dimensionless).

The cumulated percentage of losses L_{tot}^p within the sum of all scenarios s_{tot} participating in the definition of the behaviour of a population P , is expressed as follows :

$$L_{\text{tot}}^p = \sum_{s=1}^{s=s_{\text{tot}}} L_s^p \quad (45)$$

where s is the number of the scenario, s_{tot} is the total number of scenarios, p is the state of the packaging i.e. in MAP or no MAP condition.

All simulations based on Eq. (39) to (41) and calculations of the integral of D (Eq. (43)) were done using Matlab® software (The Mathworks Inc, Natick, Mass., U.S.A). The generated values of areas were after processed using Eqs. (43) to (45) on an Excel sheet (version 2016).

3.2.3 Results and discussions

3.2.3.1 Tracking typical postharvest chain actors' practices

Building the postharvest chain was divided in three steps. Step 1 consisted in the different stages between packaging and arrival to the supermarket and was called "pre-supermarket" (see § 3.2.3.1.1.). Step 2 was dedicated to the supermarket level (§ 3.2.3.1.2) and step 3 to the consumer level (§ 3.2.3.1.3).

3.2.3.1.1 Stages and food losses identified in the pre-supermarket stage

From the interviews with wholesalers and data gathered from literature (CTIFL), it was found that a typical pre-supermarket step for packed strawberries could include up to 7 different stages such as packaging, precooling, wholesaler, central purchase and 3 transport stages. All these 7 stages were considered in the following to have pre-supermarket step that is the closest to the reality. The order of appearance of the aforementioned stages is presented in Table 9. For each stage mentioned in Table 9, minimal and maximal temperatures and losses were gathered based on interviews outcome with cooperatives. The percentages of losses at each stage are also indicated when this information is available. It was indeed very difficult to estimate because of the unavailability of this data and when available, its high uncertainty. Usually, cooperatives didn't want to share the values whatever the reason. Note that transport duration between each steps in Table 9 is rather long, mimicking the case where strawberries are grown far away from the wholesaler location considered as a worst case presupermarket scenario concerning transport duration.

Table 9: Minimal and maximal time, temperature and percentage of losses considered at each postharvest stage

Postharvest stages Storage conditions and losses	Pre-Supermarket							Supermarket			Transport 4	Consumer
	Packing	Precooling	Transport 1	Wholesaler	Transport 2	Central purchase	Transport 3	Reception	Storage room	Market stall		
Time (mn, h or d)	1-5h	1-3h	14-16h	1-12h	5-12h	1-12h	0.5-3h	5mn-3h	6h-1d	1h-0.5d	0.5-2h	1-3d
Temperature (°C)	20-30	0-2	2-4	2-4	7-8	7-8	7-8	2-20	2-10	10-25	20-30	5-20
Losses in no MAP (% by weight)	1-2	-	-	1-2	-	1	-	10			-	2-30

3.2.3.1.2 Situational analysis of distributors behaviour patterns

To collect information about distributors' behaviour and practices, a survey targeted to this stakeholder was built. As expected, this survey was not very successful: only 21 answers were obtained on 89 distributors solicited, and among them, only 4 departments heads answered the whole questions of the survey. This scarce cooperation coming from the distributors was already noticed by the French Environment and Energy Management Agency (ADEME) in their latest investigation about the quantification of food losses in the food chain. In the aforementioned report, they mentioned that information on quantities lost and wasted by distribution stakeholders are poorly known and, above all, poorly communicated. They explained that: "Manufacturers and distributors who have the best knowledge in this field, are indeed rarely ready to deliver their data because they consider that they are confidential: these data are according to them, likely to provide information on the secrets of competitiveness of the company business or give rise to "malicious communications" (ADEME, 2016)".

Although few data were obtained, they will be used as guidelines (master data) to confirm information found in the literature.

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It was found that distributors who answered the questionnaire belonged to mini-markets and supermarkets, selling strawberries mainly in trays of 250 or 500g.

The results of the questionnaire showed that supermarket stage is mainly divided in three sub-stages: the reception, storage room and market stall (Table 9). As regard data related to storage conditions i.e. temperature and corresponding duration; firstly, at the reception stage, the product is either refrigerated (2°C) or kept in ambient conditions (20°C) for a short duration varying from 5 minutes to 3 hours. Next, the product is stored at low temperature in the storage room between 2-10°C for a duration between 6 hours and 1 day. Finally, in the market stall, products are either stored at 25°C or in refrigerators at 10°C from 1 to 12 hours, see Table 9. The unsold strawberries are thrown and not kept in stock. The replenishment of the market stock is done six times per week.

Information about the percentages of losses and wastes at the distributor stage was never communicated by the interviewees therefore, the percentage of losses for strawberries recorded by ADEME (equal to 10% of the quantities distributed) was considered in the following (ADEME, 2016).

Additional information has been also obtained about who is doing the order of purchase, who is deciding for the quantity and quality of strawberries ordered, etc... which are not directly used in the present work and therefore not detailed here.

A last question has been asked regarding the change of distribution practice of packed strawberries if an extended shelf life for the product could be obtained thanks to a new packaging technology. The majority of departments heads think that a packaging able to increase product shelf life is useful. They would like a gain of shelf life around 1.7 days. However, when it comes to the reorganisation of the distribution due to this increase of shelf life (for example an increase of stock or a reduction of number of transports per week due to less frequent orders of product), the opinions are diverging between heads of departments who thinks that no changes will occur in the management (1/3 of the answers), while others heads of departments who think that it will induce significant changes in distribution practices (1/3 of the answers) and last group of departments' heads who don't know (1/3 of the answers).

3.2.3.1.3 Consumers' practices and estimated losses at household

A panellist of 846 consumers replied to the consumers' survey set up. Respondents were mainly retirees and employees representing 54% of the panellist followed by managers, intermediary professions and inactive with similar percentages of representation around 10% each. Farmers, students and labourers are a minority. Respondents are mainly women (60.9%). 37.2% of the panel are in couple and the household sizes is composed principally of one, three or four persons equally represented around 18% each. A minority (7.8%) is household composed of more than four persons.

Part of the survey dedicated to purchase habits showed that a majority of the consumers use their five sense to choose strawberries but more particularly eyesight; they are 82.6% to value exclusively strawberries colour to make their choice. This is related to the fact that most of the strawberries are packed in sealed pouches and that the consumer has no other possibility to evaluate the strawberries quality then by looking at them through the pack. A minority of consumers taste the strawberries (18%) when package is open (e.g. wood basket). This practice is negatively viewed by other purchasers in supermarkets and made difficult by the presence of the packaging.

Concerning post-purchase habits, once at household, 14,5% of the consumers store the product for a maximum of 3 days, 24.5% for 2 days while 61% keeps it for a maximum of one day before consumption. This can be explained by the very short shelf life of the product. Strawberries sorting is done just before the consumption for 54.9% of the panelist. A majority (79%) of the consumers remove the packaging after purchase and don't replace it with another one. 57% of the consumers keep the strawberries at ambient temperature while 43% of them keep the strawberries in the fridge. 40.5% of consumers consume strawberries as dessert or afternoon snack.

67% of the consumer claim that they never throw all the tray of strawberries if some strawberries are damaged. They seem to prefer throwing the damaged strawberries (74.8%) or only the damaged parts of a strawberry (57.4%).

More than 60% of consumers eat strawberries fresh, without any specific cooking and whole, without cutting it in pieces. Among them, some remove the peduncle before eating and others during.

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Finally, as regard knowledge of the consumer on the product itself, 60 % of the consumers think that they have a good knowledge of the product on how to choose it and store it.

The three main information extracted from the survey, named variable in the following, and that will be further used to predicted the food losses reduction are:

- The state of the packaging: Keeping or removing the packaging after purchase
- The temperature of storage: Cold storage in the fridge at 5°C or at ambient temperature around 20°C
- The time span before consumption: One or 3 days of storage. In the core of this study, we decided to work on best and worst case scenario including shortest and longest storage duration. Thus results for day 2 were aggregated with day 3.

The percentage of answer corresponding to one of the variable listed above was calculated aggregating answers independently when necessary to obtain the probabilities of occurrence of each variable (Table 10). For instance, the probability that consumers store the strawberries before consumption at ambient temperature, namely 'high temperature' (20°C), is of 0.57 and, consequently, the rest of the consumers store strawberries at 'low temperature', i.e. in the fridge (5°C). The probability of consumers storing the basket 1 day before consumption (short duration) is equal to 0.39 whereas the probability of consumers storing the basket 3 days (long duration) is equal to 0.61. Finally, only 0.21 of consumers keep the package closed up to consumption while 0.79 of consumers remove it just after purchase before further storage of the product.

The occurrence of consumers' behaviours, w , taking into account the three variables all together was calculated using the following equation, assuming that events are independent:

$$w = P_T P_d P_p \quad (46)$$

Where P_T is the probability related to storage temperatures: ambient or fridge storage at the consumer level (dimensionless), P_d is the probability related to storage duration: one or three days at the consumer level (dimensionless) and P_p is the probability related to packaging state: kept or removed packaging at the consumer level

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(dimensionless), w is the occurrence of consumer's behaviour in the postharvest chain, varying between 0 and 1 (dimensionless).

To sum up, after aggregating the information gained from the consumers' survey, 8 behaviours were distinguished at the consumer level that covered all the diversity of consumers' practices at household collected through the present survey (Table 10).

Table 10: Description of the 8 consumers' behaviours based on the temperature, duration of storage and state of the packaging

Number of the behaviour	Probability related to storage temperature $T P_T$ (dimensionless)	Probability related to storage duration P_d (dimensionless)	Probability related to packaging state the P_p (dimensionless)	Occurrence of each behaviour w (dimensionless)
1	High temperature 0.57	Long duration 0.39	Keep packaging 0.21	0.05
2			Remove packaging 0.79	0.17
3		Short duration 0.61	Keep packaging 0.21	0.07
4			Remove packaging 0.79	0.28
5	Low temperature 0.43	Long duration 0.39	Keep packaging 0.21	0.03
6			Remove packaging 0.79	0.13
7		Short duration 0.61	Keep packaging 0.21	0.06
8			Remove packaging 0.79	0.21

Strawberries losses at the consumer level were estimated within a range of 2 to 30% identified from interviews with local wholesalers and from literature data (CTIFL) Table 9. In the following, we will consider that this 2-30% range corresponds to the damaged strawberries thrown by the consumer (pieces or whole strawberry) and that this value is directly correlated to the level of deterioration predicted by the mathematical model. We therefore excluded the cases where the whole tray is rotten and entirely thrown away. The % of losses corresponding to our scenarios analyzed corresponded to the cases where consumption of some part of the product occurred and therefore, is comprised somewhere between the min and max values of 2 and 30% respectively.

3.2.3.2 Numerical exploration of different post-harvest chain scenario for packed strawberries

3.2.3.2.1 Predicting product's deterioration using MAP modelling tool

The MAP modelling tool previously presented and validated in Matar et al 2018 was then used to predict the product deterioration in the previous listed conditions for the pre-supermarket, supermarket and consumer steps.

For this end, the pre-supermarket step was simulated using 3 different scenarios: "highest temperature and long duration", "low temperature and long duration", "mean temperature and short duration" (Figure 23). That means that, for example in the case of "highest temperature and long duration", the highest temperature of the range indicated in Table 9 for each step (cooling, packing, wholesaler, etc ...) was systematically chosen with the longest duration for building this scenario. On the contrary, the lowest temperature and longest time span were chosen for building the "low temperature and long duration" scenario, etc ... These conditions of time and temperature of storage were chosen based on preliminary simulations. The objective was to compare, for the best and worst cases scenarios, the deterioration curve evolution obtained in the two packaging conditions, MAP and no MAP. It was found that at short storage duration, the effect of MAP was not visible, thus "high" and "low temperature of storage" for "short duration" in the pre-supermarket step were aggregated in a single scenario "mean storage temperature and short duration".

For the supermarket stage, including the three sub stages of reception, storage room and market stall, the selection of scenarios was done as follows, all data of temperature and duration for each sub stage being taken from Table 9.

For the reception stage temperature varies between 2-20°C (Table 9). However, because of the short duration of this sub stage and for simplification purposes, a mean temperature (10°C) and mean time (92.5 min) were considered for this storage sub stage in all simulations. Indeed, preliminary simulations also showed that this stage has a very low impact on the quality due to its very short duration.

For storage rooms and market stall sub stages, the combination of "high" and "low temperature" with "long" and "short duration" was considered, assuming that the same conditions operate in both storage room and market stall sub stages.

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The selected couples of time and temperature for the supermarket stage including the three sub stages are summarized in Figure 23.

Following simulations of the pre-supermarket and supermarket steps considering the scenarios listed in Figure 23, some product deterioration at the end of the supermarket step exceeded the maximal threshold value of 13% (Matar et al., 2018). This means that, when the maximal acceptable deterioration was reached, the consumer was not ready to buy the product anymore. Therefore, these scenarios were not considered in the investigation of the consumer step. These scenarios were the ones with high temperature and long duration at the pre-supermarket level followed by high temperature and long duration at the supermarket level.

For the consumer step, the first step is a transport phase between supermarket and consumer household (transport 4 - shown in Table 9). For simplification reasons and due to the very small impact of this stage, a mean temperature and duration was considered for this step (1.25h at 25°C). For the household step, a combination of the highest and lowest temperature of storage combined with longest and shortest storage time taken from Table 9 was considered in the aim to cover the whole range of possibilities. At this level, 44 scenarios were obtained after combining all the cases represented in the pre-supermarket, supermarket and consumer level (Figure 23). These 44 scenarios could be applied for the control packaging (no MAP, e.g. macro-perforated packaging).

For the peculiar case of MAP packaging, additional scenarios should be added. Indeed, if packers, wholesalers, distributors, keep the packaging without opening it, it is not guaranteed anymore at the consumer level where surveys revealed that only 21% of consumers keep the package sealed or closed up to consumption. 79% of consumers remove it just after purchase even if they do not immediately consume their strawberries. This practice relies on the belief that it is better to store strawberries which are a living product without packaging. That means that when MAP technology is used, the benefit of the MAP is lost long before the consumption time. For this reason, the variable related to "the state of the packaging" collected from the surveys will be added to the probability tree drawn in Figure 23 when MAP packaging is studied. If we consider the two possible states of the packaging (keeping sealed until consumption or removing it just after purchase) for each of the 44 pre-scenarios, 88

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additional scenarios were added to the 44 control ones, when MAP packaging is used. In total, 132 scenarios were generated were 88 scenarios were in MAP condition and 44 scenarios were in no MAP conditions.

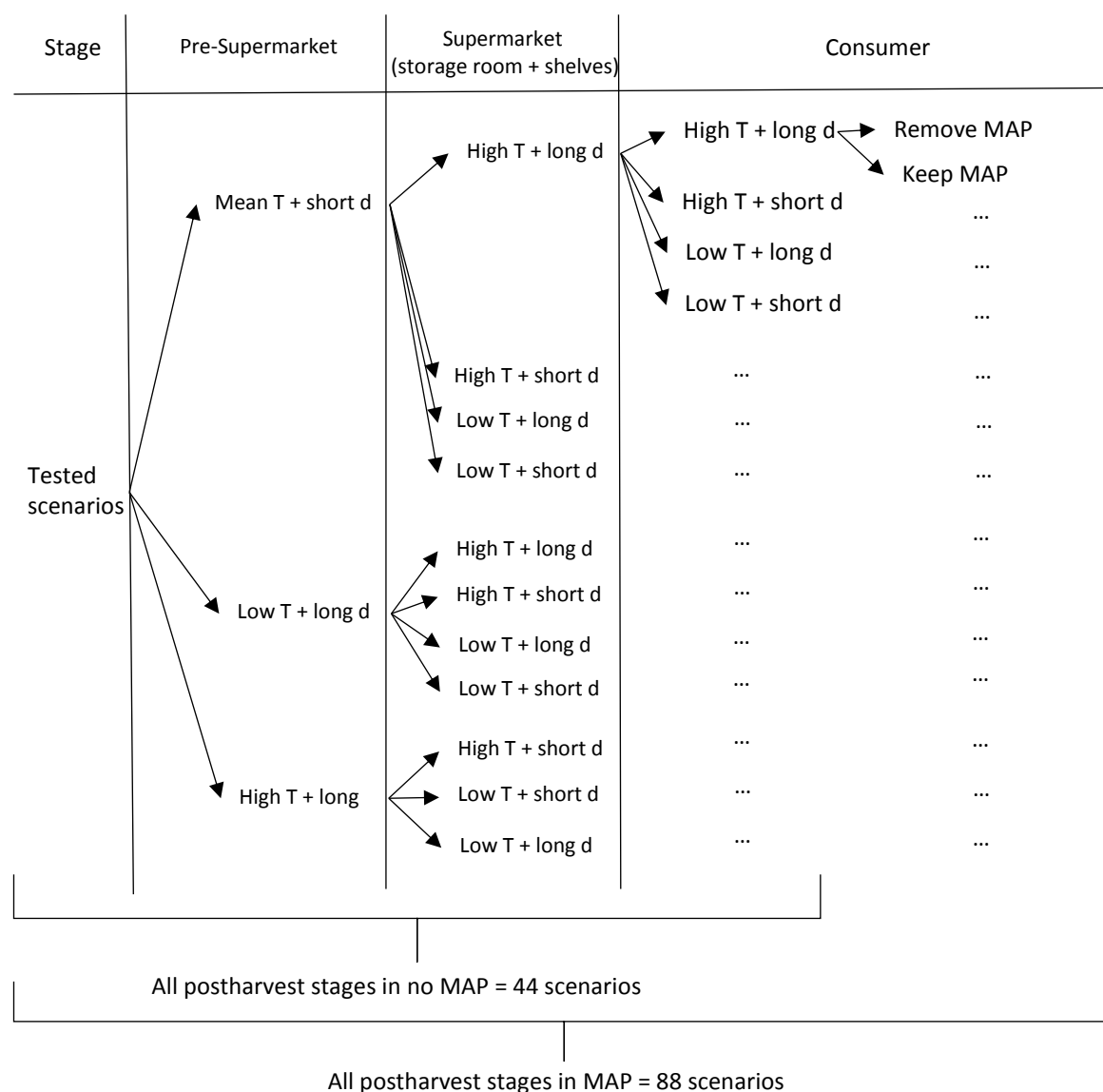


Figure 23: Construction of the 132 scenarios among them 88 in MAP and 44 in no MAP condition according to Pre-supermarket, Supermarket and Consumer storage conditions. T refers to the temperature and d to the duration of the stage

The 132 scenarios were used as inputs in the model to calculate as outputs the deterioration curve in each case and then, the corresponding losses.

24 input parameters were needed to run the model and were taken from Matar et al 2018 were: 0.100 ± 0.003 kg of strawberry *Charlotte* are packed in LDPE (low density

polyethylene) pouches with dimensions of 0.14 x 0.095 x 0.025 m calculated to achieve an internal modified atmosphere the closest to the recommended one.

To be able to run the MAP modelling tool in dynamic temperature conditions, an activation energy was calculated for K_D representing the deterioration rate constant E_{a, K_D} at reference temperature T_{ref, K_D} . E_{a, K_D} was found equal to $73514 \pm 2205 \text{ J mol}^{-1}$ with T_{ref, K_D} taken at 10°C . β_{CO_2} was found constant whatever the temperature, equal to $1.32 \times 10^{-9} \pm 2.9 \times 10^{-10} \text{ mol s}^{-1} \%^{-1}$ representing the mean of β_{CO_2} at 5°C , 10°C and 20°C .

3.2.3.2.2 Estimating a percentage of losses for a population of French consumers

For each of the 132 deteriorations curves generated, the corresponding area under the deterioration curves (i.e. the integrals of deterioration curves $\int_{t=i}^{t=j} D_s^p$) was calculated. Then these 132 scenarios were distributed in 8 groups corresponding to the 8 behaviours detected in § 3.2.3.1.3. (Table 10). At the end, 8 aggregated scenarios based on consumer's behaviour were obtained that take into consideration the diversity of behaviour for the pre-supermarket and supermarket steps. The corresponding average value for $\int_{t=i}^{t=j} D_s^p$, mean of the deterioration curve integral, was then calculated for each group in MAP and no MAP condition as shown in Table 11.

Next, the losses I_s^p are calculated using Eq.(43) from the average value of $\int_{t=i}^{t=j} D_s^p$. To calculate a and b values, in a population P of scenarios, the minimum $I_{min}^{no MAP}$ and maximum $I_{max}^{no MAP}$ percentage of losses; identified in the previous surveys or interviews; are attributed to the scenario s_{min} and s_{max} having the smallest $\int_{t=i}^{t=j} D_{s_{min}}^{no MAP}$ and biggest $\int_{t=i}^{t=j} D_{s_{max}}^{no MAP}$ value of the deterioration integral in no MAP respectively. Having two data set for $(I_{min}^{no MAP}, \int_{t=i}^{t=j} D_{s_{min}}^{no MAP})$ and $(I_{max}^{no MAP}, \int_{t=i}^{t=j} D_{s_{max}}^{no MAP})$, the values of a and b can be calculated following a linear function of the form $y = ax + b$. In this purpose, the maximal $I_{s_{max}}^{no MAP}$ and minimal losses $I_{s_{min}}^{no MAP}$ considered at consumer stage in no MAP conditions were respectively 2 and 30% (Table 9). 2% was attributed to the smallest value of the deterioration integral calculated for scenario s_{min} (2538.78) and 30% to the biggest value of the deterioration integral calculated for scenario s_{max} (81824.40) (Table 11). That means that in the best case (optimal storage

conditions and moment of consumption), the consumer throws away only 2% of his strawberries while in the worst case, 30%. Using these two points and considering that losses are linearly proportional to the deterioration curve integral, as stated in Eq. (43), the two fitted parameters a and b could be calculated and were found equal to 3.53×10^{-04} and 1.10 respectively. In consequence, losses I_s^p corresponding to all other deterioration integrals ranging from the s_{\min} to s_{\max} values could be interpolated using Eq. (43).

To calculate the overall losses value for the post-harvest chain, L_{tot}^p , considering the 8 different behaviour scenarios, L_s^p a weighted average of the 8 I_s^p values was calculated using Eq. (44) and then aggregated using Eq. (45).

Using this methodology, the average overall losses for the two cases of storage investigated in no MAP and MAP condition, considering multiple, realistic post-harvest storage scenarios and consumers' practices were found equal to 9.21% in case of no MAP (conventional packaging) and 7.57% in the case of MAP, respectively.

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Table 11 Percentage of losses calculated for each category of scenarios/behaviours with the associated area of the deterioration, occurrence of each behaviour, percentage of losses, and total percentage of losses affected by French consumer behaviour in MAP and in no MAP.

Number of the aggregated scenarios	Occurrence of each behaviour w (dimensionless)	no MAP			MAP		
		Mean of the deterioration curve integrals (dimensionless)	I_s^{noMAP} losses (%)	L_s^{noMAP} Losses related to occurrence of the behaviour (%)	Mean of deterioration curves Integrals (dimensionless)	I_s^{MAP} losses (%)	L_s^{MAP} Losses related to the occurrence of the behaviour (%)
1	0.05	81824.40	30.00	1.41	44967.60	16.98	0.80
2	0.17	81824.40	30.00	5.20	75041.23	27.60	4.79
3	0.07	6378.64	3.35	0.25	3395.70	2.30	0.17
4	0.28	6378.64	3.35	0.93	4494.68	2.69	0.74
5	0.03	12026.07	5.35	0.19	6797.08	3.50	0.12
6	0.13	12026.07	5.35	0.70	7866.65	3.88	0.50
7	0.06	2538.78	2.00	0.11	1517.30	1.64	0.09
8	0.21	2538.78	2.00	0.41	1583.14	1.66	0.34
		L_{tot}^{noMAP}		9.21	L_{tot}^{MAP}		7.57

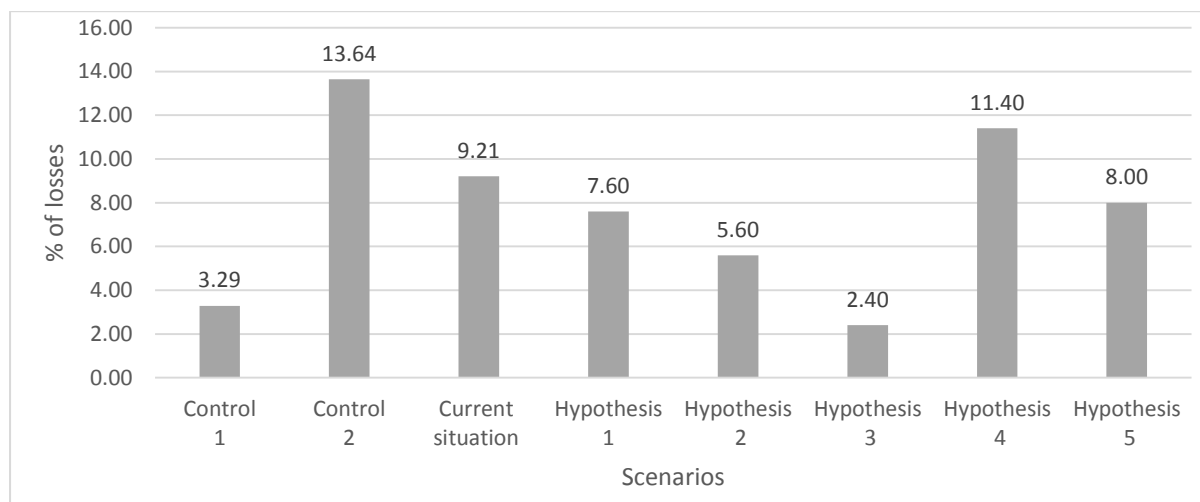
3.2.3.2.3 Impact of consumers' behaviour changes and on postharvest losses

The approach presented above could hereafter be used as to simulate a wide diversity of scenarios and specially to explore the impact of different consumers' behaviour changes on the quantity of strawberry losses at the consumer stage.

In this purpose, 7 different scenarios were tested (Figure 24) in addition to the current one (42.8 % fridge storage and 100 % macro-perforated packaging). The two first hypothesis represent control situations (100% of people store the strawberries in the fridge or 100% of people store them at ambient temperature, all strawberries being packed in macro-perforated packaging, i.e. without any specific modified atmosphere condition). Hypothesis 1 correspond to the case when MAP is applied for all strawberries sold but with the current consumers' behaviour. The 4 other hypothesis correspond to alternative behaviours for the consumer: for instance, hypothesis 3 assumes that 100% of consumers store their strawberries in the fridge and 100% of them keep the MAP effective until consumption while hypothesis 5 considered that 100% of consumers keep their strawberries at ambient temperature but in MAP, until consumption. The corresponding losses obtained for each of these 8 cases were calculated (Figure 24) as well as the percentages of losses reduction for the 5

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hypothesis normalized as regard to the control situation 1 or 2 or the current situation (Figure 25).



State of the packaging along the post-harvest chain before its arrival to the consumer	Hypothesis/Controls	Consumer behaviour (%) according to	
		Storage temperature	State of the packaging
Macro-perforated packaging (no MAP)	Control 1	100 % Fridge	100 % macro-perforated packaging
	Control 2	100 % Ambient temperature	100 % macro-perforated packaging
	Current situation	42.8 % Fridge	100 % macro-perforated packaging
Modified atmosphere packaging (MAP)	Hypothesis 1 Current situation in MAP	42.8 % Fridge	21.4 % keep packaging
	Hypothesis 2	42.8 % Fridge	100 % keep packaging
	Hypothesis 3	100 % Fridge	100 % keep packaging
	Hypothesis 4	100 % Ambient temperature	21.4 % keep packaging
	Hypothesis 5	100 % Ambient temperature	100 % keep packaging

Figure 24: Evaluation of percentage of losses for 7 different scenarios including the current case, 2 control situations and 5 hypothesis of change of consumers' behaviour. The details of all scenarios are given in the table below the graph. The state of the packaging for each situation before its arrival to the consumer stage is indicated on the left of the table.

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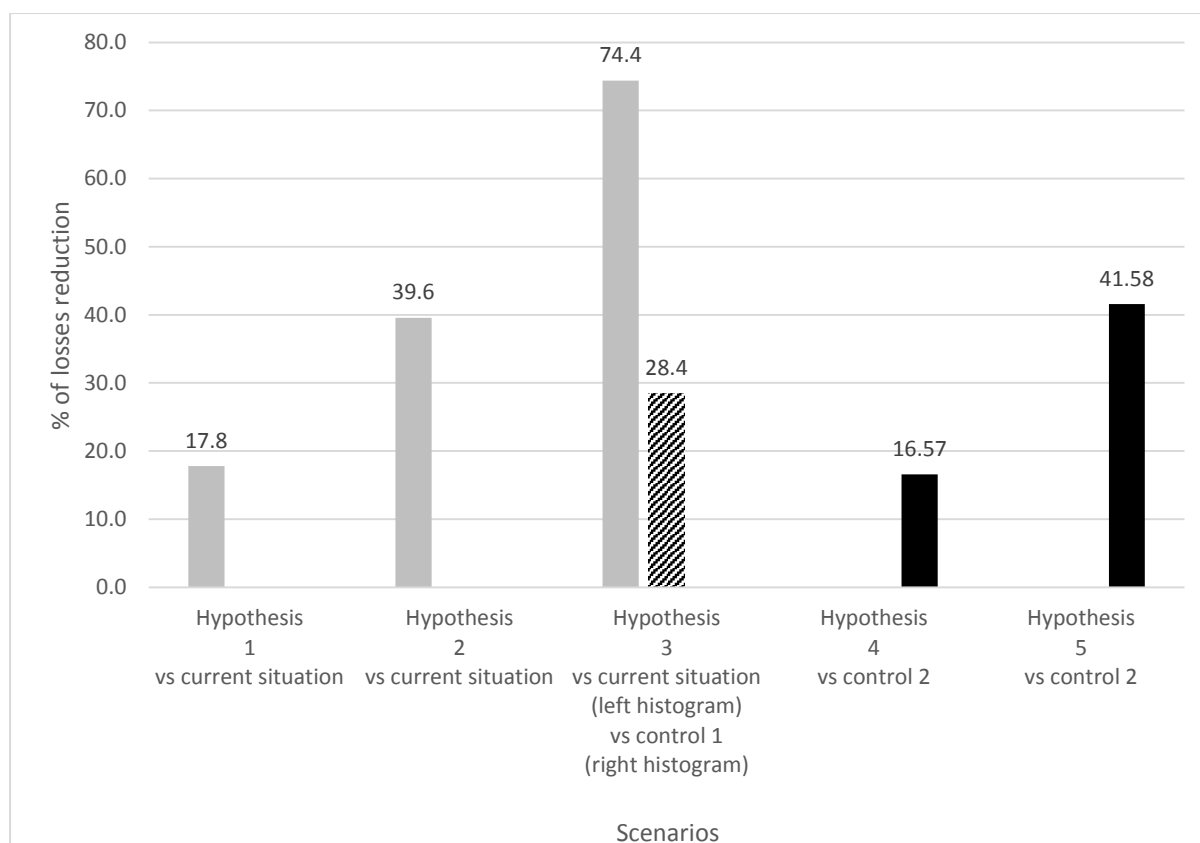


Figure 25: Percentages of losses reduction normalised with respect to losses in current situation (100% macro perforated packaging + 40% fridge), control 1 (100% macro perforated packaging + 100% fridge) and control 2 (100% macro perforated packaging + 100% ambient temperature) respectively represented by the grey, hatched and black histograms.

If MAP is established in the current post harvest chain for strawberries, considering that 42.8% of the consumers keep the product in the fridge and that 78.6 % of them remove the package just after purchase, losing thus the benefit of the MAP, the percentages of losses is reduced from 9.21% of losses (current situation) to 7.6% (hyp 1, Figure 24). This is equivalent to 17.8% of losses reduction (hyp 1, Figure 25). This result shows the benefit of using MAP in the current post harvest chain even if consumers do not change their behaviour toward packaging and continue to remove it after purchase in 78.6 % of the cases. That means also that, if we are able to “educate” the consumer in order that all of them keep the packaging sealed/closed until consumption (no early disruption of modified atmosphere), in the same temperatures of storage than those currently applied, the percentage of losses would decrease from 9.21% (current situation) to 5.60% (hyp 2, Figure 24), which corresponds to an absolute reduction of 39.6% (hyp 2, Figure 25). Thus, application of MAP technology and modification of consumer behaviour to keep the full benefit of

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modified atmosphere until product's consumption would induce significant losses reduction (about 40%). In addition, if all consumers keep the strawberries packed in MAP in the fridge instead of ambient temperature (hyp 3), the losses will decrease from 5.60% to 2.50% compared to hyp 2, which is equivalent to a reduction of 74.4% of losses (hyp 3, Figure 25). But if the cold chain is respected by all the consumers even if no MAP conditions are applied, the calculated losses are equal to 3.29% (control 1, Figure 24), which is only a bit more than the expected losses for the best case (hyp 3) with 2.50% of losses. This confirmed that in the present case study, the benefit of MAP in addition to cold chain would be negligible compared to the exclusive use of cold chain.

Analysing the effect of MAP at ambient temperature shows that, if all the consumers stored the product at ambient temperature even if only 21.4% of them keep the packaging sealed until consumption (hyp 4, Figure 24), the percentage of losses would be reduced to 11.40% compared to the same no MAP situation where losses are equal to 13.64% (control 2, Figure 24). In this case, relative losses reduction is equal to 16.57% (Figure 25). If, in that condition of MAP and ambient temperature, 100% of consumers keep the packaging sealed until consumption, losses would be reduced to 8% (hyp 5, Figure 24), recording a relative losses reduction of 41.51%. Comparison of this relative reduction of 41.51% due to MAP at ambient temperature (black bar in Figure 25) with its equivalent at fridge temperature (28.4%, grey bar in Figure 24), revealed that the benefit of MAP is higher at ambient temperature than in the cold chain.

These results highlighted that the ideal storage condition to reduce a maximum the losses would be to use MAP technology for strawberries and that 100% of the consumers store their product in the fridge and 100% of them keep the packaging sealed (2.40%, hyp 3, Figure 24: i.e. about 74 % of losses reduction). But, on one side, cold chain has a high environmental impact that could hamper the global carbon footprint of the product if its use become systematic in the post-harvest chain of strawberries. The environmental benefit of losses reduction thanks to the systematic use of the cold chain should be evaluated and compared to the additional environmental load due to this overuse of the fridge. On the other side, some consumers will never put their strawberries in the fridge quite simply because they

consider that cold chain changes the taste of the product and they do not like this. Therefore, systematic use of cold chain seems not possible. It seems easier to educate the consumer to keep the packaging sealed until consumption time when MAP is used because MAP is beneficial for the product whatever the storage conditions (fridge or ambient temperature). In that case, the losses reduction that could be expect is 39.6% of losses (grey histogram; hyp 2, Figure 25), i.e. an absolute losses value of 5.6%.

Needless to say, there are some limitations to this analysis. The number of scenarios studied could have been increased. Other durations of scenarios could have been tested. In a same scenario, at the consumer level, the succession of high and low temperature of storage mimicking a consumer taking his strawberries out of the fridge some time before consumption could have been evaluated, which was not the case here. Similarly, at the distribution stage, other combination of temperature and duration market stall and storage room in the supermarket would have been interesting to test. In addition, the approach used here did not consider the case when consumer discard the total basket of strawberries purchased because he forgot it or he did not want to eat it anymore and finally the product is completely spoiled and discarded (wastage typically related to western consumer's way of life). This type of scenario which is not only related to the short shelf life of the product and its degradation could not be predict by our modelling approach and is thus not taken into account in our calculation of losses. Therefore, the percentage of losses recorded in the current situation, of 9.21% of losses (Figure 24), is underestimated.

3.2.4 Conclusions

In this paper, 132 post-harvest scenarios including the diversity of distributors' and consumers' practices have been simulated for the strawberries supply chain. Percentage of strawberries losses were calculated in each case in the objective of quantifying the benefit of MAP in the strawberries supply chain compared to the current standard situation (macro perforated pouches). It was found that, considering the current consumers' habits as regard strawberries storage and consumption at home, the use of MAP technology would decrease losses from 9.21 to 7.60 % as evaluated in the present work. Higher benefit would be expected by changing consumers' behaviours: indeed, 79 % of them remove the packaging just after purchase before product storage which limit the benefit of MAP and half of them stored

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strawberries at ambient temperature and not in the fridge. For instance, if the best storage conditions were maintained at household (i.e. all the consumers store it the fridge and under MAP), strawberries losses would be the lowest and equal to 2.4 % of losses. The work presented here highlighted well the interest of coupling food losses quantification to shelf life prediction. Even if a lot of hypothesis were done to develop the approach presented here, it illustrated well how it could provide valuable information on the real benefit of using one storage technology instead of another, including the practices of all stakeholders of the food chain. It could also help to identify the leverage actions to reduce amount of food losses in the post-harvest chain.

Acknowledgement

This work was conducted in the context of the Pack4Fresh project funded by the INRA-CIRAD Metaprogram GloFoodS and of the FP7-ERA-NET 618107 Eco Berries.

3.3 Concluding remarks

Thanks to the development of a modelling tool for the assessment of **food losses of strawberries at the consumer level**, we were able to quantify losses related to the 132 scenarios identified in this study. Losses were predicted in a commercial MAP (e.g. MAP achieve using a commercial packaging film) and in no MAP (using macro-perforated) packaging. Consumer level was the only stage of the postharvest chain treated focusing on the characterisation of losses related to product quality. This choice was made because of the rare information obtained on other postharvest stages.

In this purpose, it was assumed that the percentage of losses is directly proportional to the deterioration of the product. Therefore, a **linear relationship between the area under the deterioration curve and food losses reduction** was considered. It was found that in the current French population behaviour (i.e. where around 20% of the consumers keep the packaging and 40% store in the fridge), 9.21 % of losses is recorded in no MAP compared to 7.6% of losses in Commercial MAP which is a reduction of 17.8%. If changes in the consumer behaviour are considered in MAP condition, losses can be reduced from 9.21 % to a minimum of 2.4 % if all the consumers keep the packaging after purchase and store the product in the fridge recording a reduction of 74.4% compared to the current no MAP situation.

However, the **lack of data regarding the percentages of losses at the consumer level** forced us to **work with mean percentages between 2 and 30% of losses**. This range of losses was needed to be able to demonstrate clearly the methodology developed by linking product shelf life and food losses. Thus, **generated percentages of losses** in this study **are debatable and approximative**.

In future studies, the percentages of losses at the consumer level should be quantified by experimental tests in the laboratory or at household by weighting lost product for a known shelf life. Thus, the linear equation developed for predicting food losses related to the quality of the product still need to be validated experimentally. In addition, more research in this field is needed to a cover larger number of scenarios and consumer's behaviours. A method should also be developed to predict wastes generated at consumer level.

The same approach applied here to the consumer level should be also developed for the supermarket level to understand the relation between product shelf life at the supermarket and losses and wastes generated.

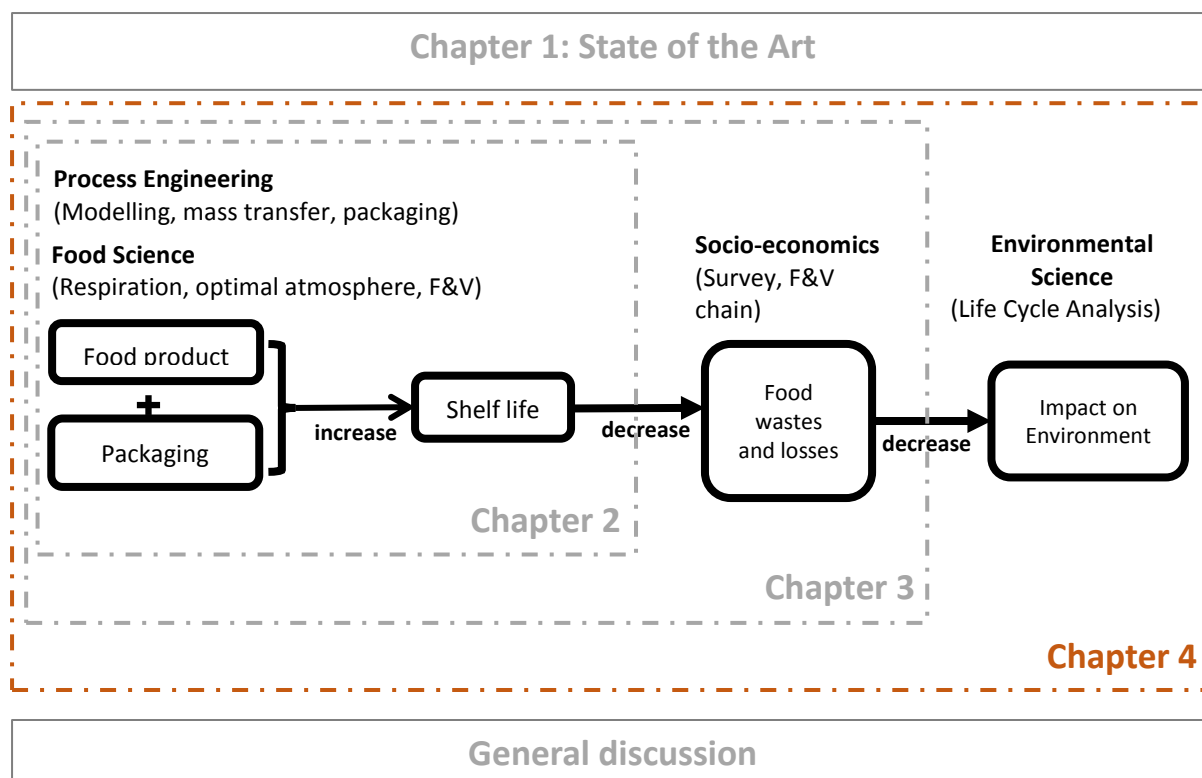
MAIN FINDINGS

- Losses were predicted in MAP and in no MAP (using macro-perforated) packaging at the consumer level
- A linear relationship between the area under the deterioration curve and food losses reduction was assumed
- The lack of data regarding the percentages of losses at the consumer level forced us to work with mean percentages between 2 and 30% of losses
- Percentages of losses used as input in this study needed to be further refined
- The same approach applied at the consumer level should be developed at the supermarket level

**Chapter 4: Evaluating the
environmental impact of the
food/packaging system**

Chapter 4: Evaluating the environmental impact of the food/packaging system

4.1 Introduction



The objective of this last chapter of the PhD is to evaluate the environmental impact of using modified atmosphere packaging (MAP) in the postharvest chain especially in comparison with the use of cold chain. More specially, the environmental benefit of using MAP, thanks to its positive impact on reduction of food losses, will be assessed. For this end, a life cycle analysis approach (LCA) will be used from harvesting till household level taking into account food losses and packaging (production, disposal and impact on the losses).

However, similarly to chapter 3, changing percentages of losses due to MAP will only be applied on consumer level. Consequently, variations in the environmental impacts will take place at the consumer level.

Will the environmental impact of using MAP on the food losses, at the consumer level be significant compared to the environmental impact of macro-perforated packaging?

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This article will present a comparative analysis of the environmental impact of the current situation (macro-perforated packaging) and the use of MAP packaging at the consumer level. Two different types of MAP will be considered: commercial MAP (DEF) and optimized MAP. The environmental impact of ambient and cold storage conditions for macro perforated packaging will be compared to ambient storage of MAP solutions (i.e. optimized and Commercial MAP).

4.2 Benefit of MAP at consumer's stage on the overall environmental impact of the postharvest chain of packed strawberries (Article 4)

Matar Céline^a, Hélias Arnaud^b, Gaucel Sébastien^a, Gontard Nathalie^a, Guilbert Stéphane^a & Guillard Valérie^{a, *}.

a, Joint Res. Unit Agro polymers Engineering & Emerging Technology,

b, Joint Res. Unit Environmental Lifecycle and Sustainability Assessment,

*UM - INRA- Supagro & CIRAD, 2 place Pierre Viala, Bat 31, 34060 Montpellier
cedex 01 France*

*valerie.guillard@umontpellier.fr

Abstract

Modified atmosphere packaging (MAP) is a packaging technology where gases composition surrounding the product are modified to increase product's shelf life and thus reduce its losses during storage. MAP could replace or at least, could reduce the extensive use of cold to store and preserve food with expected significant benefit on the global environmental impact of the food chain. In this work, life cycle assessment (LCA) is applied to assess this environmental benefit of using MAP as an alternative to the exclusive use of the cold chain. In this purpose, the environmental impact of conventional strawberries' storage conditions (macro perforated packaging put in ambient or cold condition) and of a new packaging solution (MAP) used at ambient temperature were compared. This study was conducted at the consumer level where impact of storage conditions and consumer's practices on food losses reduction have been well identified. LCA was applied on strawberries postharvest chain while considering step from harvesting till consumer level taking into account food losses and packaging production, disposal and its benefit, if any, on food losses reduction. It was found that optimized MAP at ambient temperature presents an important improvement compared to the macro perforated packaging stored in the fridge e.g. diminution about 20% of most environmental impacts.

Keywords

Modified atmosphere packaging, macro perforated packaging, reduction of losses and wastes, storage temperature, storage duration, environmental impact, carbon footprint

Nomenclature

Symbols	Definition	Units
Commercial MAP	MAP created using commercial packaging material (LDPE)	
Optimized MAP	MAP created using a film with ideal film permeabilities to O ₂ and CO ₂ .	
No MAP	Macro perforated packaging	
p	Type of the packaging	
s	Number of the scenario	
P	Population of scenarios studied	
I_s^p	Percentage of losses of the scenario s using the packaging p	%
$\int_{t=i}^{t=j} D_s^p$	Integral of the deterioration curve <i>D</i> for scenario s in the packaging p from t=i to t=j	dimensionless
i and j	Time at which the studied postharvest stage begins and ends respectively	day
a	Estimated parameters of the linear regression	dimensionless
b	Estimated parameters of the linear regression	dimensionless
$I_{smax}^{NO MAP}$	Maximal percentage of losses in no MAP packaging	%
$I_{smin}^{NO MAP}$	Minimum percentage of losses in no MAP packaging	%

4.2.1 Introduction

Over the last 10 years, scientists are putting tremendous efforts in developing sustainable solutions for fresh fruit and vegetables supply chain in order to reduce its negative environmental impact (Siracusa and Rosa, 2018). In fact, worldwide, 15% of the electricity consumed is used for refrigeration (Coulomb, 2008). The power used for refrigeration equipment comes from combustion of fossil fuels contributing greatly to ozone depletion and global warming (Maykot et al., 2004).

In developed countries, food packaging represents more than two-thirds of all packaging used (Pongrácz, 2007). For example, in the European fruit and vegetable sector, plastic is widely used as a primary, secondary and tertiary packaging for the distribution of the products (Albrecht et al., 2013). Around 40% of this plastic is disposed in landfills after only one use and it may take up to 1000 years to decompose,

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leaching potential pollutants into the soil and water (EU DG, 2011). Although packaging was initially implemented to protect food product and cold chain to maintain the quality of fresh fruit and vegetables, the amount of fresh fruit and vegetables losses and wastes are still very high reaching 40% of the total food losses and wastes (Gitz et al., 2014). These losses and wastes are creating an additional environmental burden. The global carbon footprint of food wastes, has been estimated at 3.3 Gtonnes of CO₂ equivalent in 2007 (Scialabba, 2013).

Modified atmosphere packaging (MAP) was identified as a promising packaging solution able to reduce food losses and wastes (Verghese et al., 2015). This technology is based on modifying the gases composition surrounding the packed product (e.g. in packaging headspace). In the case of respiring product, this modification results in the interplay between product respiration and gases (essentially for O₂ and CO₂) permeation through the film (Belay et al., 2016; Guillaume et al., 2010). In the packaging headspace, after a transitional phase where gases compositions are varying, a stationary phase is reached where gases compositions remain constant and should meet, by the end, the optimal gases concentration recommended for the product. These optimal gases composition are able to inhibit product respiration rate, prevent fermentation and senescence and in consequence increase product shelf life (Gontard and Guillaume, 2009; Kader et al., 1989; Oliveira et al., 2015). A recent study¹ quantified the benefit of MAP on food losses reduction in the postharvest chain of fresh produce focusing on household level (Matar et al, forthcoming). Results showed that a reduction up to 40% of the losses may be possible when MAP is established in the postharvest chain and appropriately used by all consumers at home. The environmental benefit of such food losses reductions still remained to characterize in comparison of conventional recommended storages conditions based on the use of cold chain and macro-perforated packaging (no MAP established).

Life cycle assessment (LCA) is one of the most widely used methodology for the evaluation of environmental impacts associated with a product, technology or activity based on the compilation of an inventory of material and energy inputs and outputs for each stage over a life cycle (ISO, 2006). Most recent studies in the postharvest chain of fresh fruit and vegetables focused on studying postharvest chain until supermarket

¹ Study conducted in Chapter 3 of this PhD entitled 'Predicting food losses due to MAP packaging'

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level such as Gunady et al. who assessed the environmental impact of fresh strawberries, romaine and lettuce in Australia (Gunady et al., 2012). Consumer level was not yet integrated as a part of the postharvest chain in LCA assessment for fresh fruit and vegetables. In addition, this study did not pay attention to the role of packaging.

Published LCA studies that considered packaging in their environmental assessment, took into account the production cost of the packaging material, cost of its end of life (mainly via incineration and sanitary landfill) (Girgenti et al., 2014) but never considered the positive impact of packaging on shelf life extension and corresponding food losses reduction achieved. This can be represented through the measurement of losses reduction throughout the postharvest chain. For this end, food losses should be considered as outputs of the postharvest system studied. Wikstrom et al. (2016), made a first attempt to consider the impact of the packaging on losses reduction of packed minced meat by comparing two packaging technologies: a lightweight tube made of plastic film and a tray packaging. It was found that the tube is a better environmental alternative even if the tray has a higher recycling rate and generate less food wastes compared to the tube revealed difficult to empty/clean (Wikström et al., 2016).

Up to know, to the best of our knowledge, LCA on a complete postharvest chain of fresh fruit and vegetables from packing till household level including, packaging production, disposal and impact on food losses at each step was not yet carried out. As an attempt to contribute towards further understanding of environmental impacts of this domain, the objective of this study is to measure the environmental benefit of using modified atmosphere packaging (MAP) in the postharvest chain. The LCA approach is applied in the present work to compare the environmental impact of conventional storage conditions (macro perforated packaging put in ambient or cold condition) and of a new packaging solution (MAP) used at ambient temperature, testing MAP as an alternative to the recommended use of the cold chain at the household level. Strawberries supply chain were chosen for this LCA analysis because they are highly perishable, thus requiring more energy and packaging for storage than other fruit and vegetables.

Firstly, a typical and representative postharvest chain of fresh strawberries will be reconstructed from harvesting till consumer level, considering packaging (use and disposal) and losses generated all over the chain. This postharvest chain will be used as a basis for the LCA. Secondly, the environmental impact of conventional storage conditions, e.g. macro perforated packaging with no modified atmosphere, stored in the fridge or ambient temperature, will be compared to improved storage condition, e.g. MAP stored at ambient temperature, considering the benefit of using MAP on the losses reduction at the consumer level. 2 types of MAP will be tested: a 'Commercial MAP' developed in chapter 1 of this PhD (i.e. using a commercial film packaging) and a fully 'Optimized MAP' packaging solution (i.e. supposing the use of an ideal film packaging) in order to quantify the maximal benefit that could be achieved for the food chain.

4.2.2 Materials and Methods

According to ISO 14044's framework (ISO, 2006), an LCA study consists of four steps:

- 1) Defining goal and scope
- 2) Life cycle Inventory (LCI): Modelling of product life cycle with environmental inputs and outputs (data collection).
- 3) Life cycle impact assessment (LCIA): Understanding the environmental impact relevance of all the inputs and outputs.
- 4) Interpretation of the results

4.2.2.1 *Goal and scope of the study*

4.2.2.1.1 *Goal of the study*

As indicated in the introduction, the first goal of the study is to conduct a LCA of the strawberries' postharvest chain taking into account simultaneously packaging (production and waste management), food losses (waste management) generated at each postharvest stage and the impact of the packaging on food losses at the consumer level.

The second goal is to test, at the consumer level, from an environmental point of view, if ambient storage in modified atmosphere packaging could decrease the overall environmental impact of the postharvest chain compared to conventional storage conditions, which are the use of macro perforated packaging in ambient or cold storage (consumer fridge).

4.2.2.1.2 Reference or construction of the postharvest chain stages (system description)

The reference postharvest chain of strawberries was reported in chapter 3 of this PhD work and is shown in Figure 26. The postharvest chain was composed of 10 steps: packing, precooling, transport 1, wholesalers, transport 2, central purchase, transport 3, supermarket, transport 4 and household. This postharvest chain was representative of the worst case for the supply chain of strawberries, e.g. a long distribution chain with the maximum of steps/stakeholders. It was considered thus as the most relevant for the study carried out here. Each step is characterized by its temperature (°C), duration (h: hours, ': minutes or d: days) and strawberries losses (%). The common steps for all scenarios are represented in grey color and the changing step is presented in black.

Only household stage is changing with 2 possible situations: best and worst situation characterized by short (1 day) and long (3 days) duration of storage respectively. For each situation, 4 scenarios were investigated. On one hand, 2 different conventional storage conditions, named 'Control 1' and 'Control 2' for storage in macro perforated packaging named 'No MAP' at ambient and low temperature respectively. On the other hand, 2 modified atmosphere packaging: 'Commercial MAP' and 'Optimized MAP' stored at ambient temperature. The 'Commercial MAP' represents the MAP created using a commercial available film able to establish, when correctly dimensioned (i.e. length and width of the pouch), concentration of oxygen and carbon dioxide close to the optimal ones in the headspace but not strictly in the range of the optimal ones. It is the case of LDPE (low density polyethylene) pouch used in previous work (Matar et al., 2018). This material has the suitable O_2 permeability to establish targeted oxygen concentration of 5% O_2 in the headspace. However, CO_2 permeability is too high to achieve the optimal carbon dioxide concentration equal to 15% for strawberries and able to inhibit microorganism's development (Sousa-gallagher and Mahajan, 2013). The MAP obtained in such condition is not fully optimized, thus called 'Commercial MAP' because only optimized on O_2 component. To represent an optimized MAP for both O_2 and CO_2 concentrations in the headspace, optimal MAP packaging permeabilities were estimated for 0.100 kg of strawberries using MAP modelling tool developed in Matar et al., 2018. The ideal film permeabilities using a film of 50 μm and a surface of 0.04 m^2 is equal to $4.023 \times 10^{-15} \text{ mol Pa}^{-1} \text{ m}^{-1} \text{ s}^{-1}$ for oxygen and $4.2362 \times$

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$10^{-15} \text{ mol Pa}^{-1} \text{ m}^{-1} \text{ s}^{-1}$ for carbon dioxide. In that latter case, called 'Optimized MAP', a significant higher impact on food losses reduction is expected.

The percentage of losses due to control scenario (i.e. macro perforated packaging called 'No MAP'), 'Optimized MAP' and 'Commercial MAP' was calculated using the modeling tool developed in chapter 3 of this PhD. The obtained percentages of losses for the 8 scenarios at household stage are presented in Figure 26.

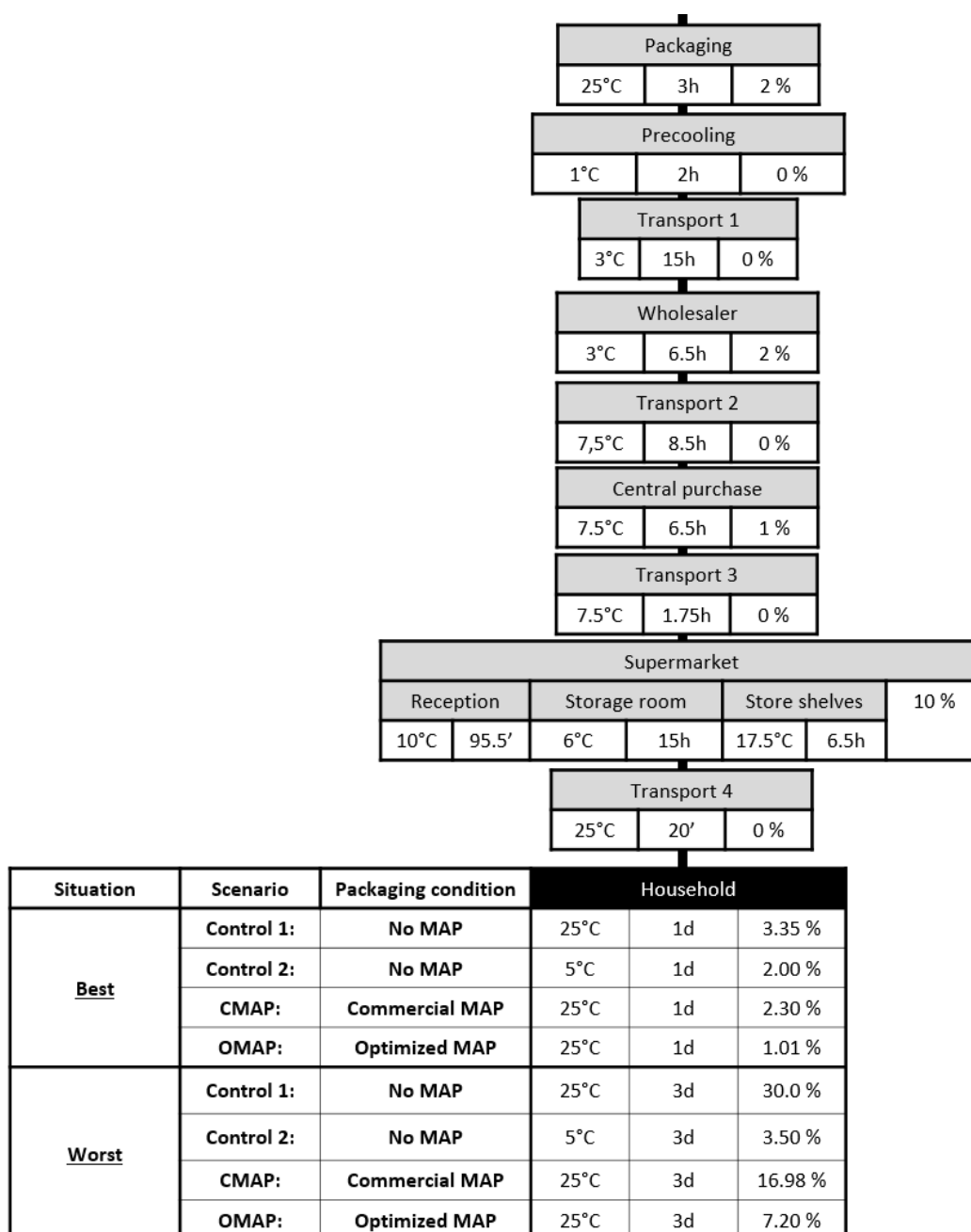


Figure 26: Scope of the study: Flow chart representing the postharvest stages taken into account in the environmental impact assessment. For each stage the temperature (°C), duration ('h,d) and percentages of strawberries' losses (%) are recorded. For household stage, the 8 scenarios studied are also detailed (4 for the best situation and 4 for the worst situations).

4.2.2.1.3 Functional unit

In the present study, the functional unit was defined as 1 kg of consumed strawberries that can be found at the end of the postharvest chain, e.g. eaten by the consumer.

4.2.2.1.4 Impact assessment method

The LCA was performed using SimaPro (version 8.5) with the with Eco invent 3.4, one of the most widely used and acknowledged LCA methods, developed by the center of environmental science of Leide, University ("SimaPro," 2018). The impact category indicators, included in this method, were climate change, ozone depletion, human toxicity, particulate matter, ionizing radiation HH, photochemical ozone formation, acidification, marine and terrestrial eutrophication, freshwater eco toxicity, land use, water resource depletion, mineral, fossil & renewable resource depletion.

4.2.2.1.5 Allocation method

The allocation is necessary when strawberries were sharing the material with other products. The allocation has been carried out on a mass basis relative to the total load inside the equipment. Thus, the allocation of the materials or energy consumption of 1 kg of product can be calculated as the ratio between the used quantity of energy/material and the total mass of product inside the equipment. This methodology was applied during:

- Transport between the supermarket and the household stage i.e. Transport 4. In France, the cost of one kilogram of strawberries is estimated equal to 7.20 euros when the average purchase budget for a French consumer is of 135 euros (FranceAgriMer, 2018; Martinez et al., 2017; Verdier, 2015). Thus, strawberries represent a ratio of $(7.20/135) 0.05$ of the total grocery purchase. This ratio was taken into account in the estimation of the environmental impact of 1kg of strawberries transported at Transport 4.
- For household stage, a study by the national institute of statistics and economic studies (Insee), showed that in France, 47% of supermarket purchase are fresh product stored in the fridge (Larochette and Sanchez-gonzalez, 2015). Consequently, among the 135 euros spent on supermarket shopping, 63.45 euros are spent for product stored in the fridge. Strawberries costing 7.20 euros will represent a ratio of $(7.20/63.45) 0.11$ of products stored in the fridge. This ratio was taken into account in the

estimation of the electricity needed for the household fridge to preserve 1 kg of strawberries.

Note that, the environmental impact of supermarket building, sealing machine production and storage containers construction are not taken into account in this study.

4.2.2.2 Life Cycle Inventory (data collection)

One of the most challenging tasks in an LCA analysis concerns the data gathering, it is the step that defines the precision and the limits of the analysis. In this section, the data of the input material and energy in each step per kg of strawberries was collected.

4.2.2.2.1 Assembling storage durations, temperatures and losses data

The source of data concerning the temperature, duration and % of losses gathered in Figure 26 is explained in details in chapter 3 of this PhD. A brief summary of data origin is presented hereafter:

For postharvest stages, storage conditions and corresponding losses from harvesting till transport 3:

A typical postharvest chain for strawberries was constructed based on interviews done with French wholesalers and based on literature reviews (Moras, 2001; Moras et al., 2003a, 2003b; Moras and Tamic, 2001; Vaysse et al., 2015). For each postharvest stage, the time and temperature of storage were recorded as well as the percentages of strawberries losses when available.

It was found that postharvest chain from harvesting until the arrival to the supermarket is composed of 7 different stages such as packaging, precooling, wholesaler, central purchase and 3 transport stages (Figure 26). For each mentioned stage, mean temperatures and mean storage duration were chosen to represent a mean typical storage scenario in the pre-supermarket stages. Transport duration between each step is rather long, mimicking the case where strawberries are grown far away from the wholesaler location. It was very difficult to estimate percentages of strawberries losses at these preliminary stages because of the unavailability and uncertainty of this data. To overcome this problem, percentages of losses found in the literature reviews were used.

For storage conditions and losses at supermarket level:

To build scenarios with realistic storage conditions at the supermarket level, a questionnaire was constructed to reproduce a typical circuit with indication of times and temperatures of storage, identify the locations of losses, and estimate them if any. The questionnaire was built and explained in details in chapter 3 of this PhD.

The results of the questionnaire showed that supermarket stage is mainly divided in three sub-stages: the reception, storage room and market stall (Table 4.1). As regard data related to storage conditions i.e. temperature and corresponding time; mean storage temperatures and mean duration were selected as for pre-supermarket stage to represent a mean scenario (from packing to transport 3).

Firstly, at the reception stage, the product is either refrigerated (2°C) or kept in ambient conditions (20°C) for a short duration of time varying from 5 minutes to 3 hours. Next, the product is stored at low temperature in the storage room (6°C) for a duration of 15h. Finally, in the market stall or shelves, products are stored in refrigerators at 17.5°C for 6.5 hours (Table 4.1).

Information about the percentages of losses and wastes at the distributor stage was never communicated by the interviewees. Therefore, the percentage of losses for strawberries recorded by ADEME (equal to 10% of the quantities distributed) was considered in the following (ADEME, 2016).

Due to the unavailability of detailed losses data and storage behavior from the packing till the supermarket, in the current study, it was not possible to explore the variation of food losses due to MAP technology at the supermarket.

For consumer level:

A survey conducted on a panelist of 846 consumers has permitted to decipher the role of consumer post-purchase habits on the shelf life of strawberries at households (chapter 3 of this PhD). Among many results, it has revealed that 14,5% of the consumers store the product for a maximum of 3 days, 24.5% for 2 days while 61% keeps it for a maximum of one day before consumption. Following that, the min and max duration chosen for the consumer stage was 1 and 3 days respectively.

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Another feature collected via the survey was that 57% of the consumers keep the strawberries at ambient temperature (25°C) while 43% of them keep the strawberries in the fridge (5°C). Therefore, these two conditions were kept as minimum and maximum of temperature at consumer stage (Figure 26).

Knowing that storing strawberries in the fridge in macro perforated packaging is the current recommended behavior by Ctifl (technological center of fruit and vegetables) (Christy Gilles and Catherine, 2017), conventional storage conditions considered here were strawberries packed in macro perforated packaging stored in the fridge (Control 1) and at ambient temperature (Control 2). The control situation was tested for a short duration of storage (1 d) and long duration (3 d) identified from the surveys and resulted in respectively best control 1,2 and worst control 1,2 scenarios (Figure 26). In order to test the environmental benefit of MAP at ambient temperature, 2 MAP scenarios are proposed: CMAP (Commercial MAP) and OMAP (Optimized MAP) at ambient temperature for best and worst situation i.e. 1 d or 3 d of storage.

Questions related to the percentage of strawberries wasted at the consumer level were asked during the interviews done with the wholesalers in the south of France and these data were compared to literature data on the topics (Gitz et al., 2014; Gustavsson and Stage, 2011). It was assumed that the consumer is not able to quantify by himself the percentage of losses that he generates and this question was not asked in the consumers' questionnaire. A range of 2-30% of losses is kept as representative of the min and max values for losses at this consumer stage. The method used to attribute the percentages of losses for each of the 8 scenarios at household level is explained in details in chapter 3 of this PhD and is briefly recalled hereafter:

In the following, we will consider that 2-30% of losses range corresponds to the damaged strawberries thrown by the consumer (pieces or whole strawberry) in the 1-3 days' consumption window mentioned in the surveys, and that this value is directly correlated to the level of deterioration predicted by the mathematical model. We therefore excluded the cases where the whole tray is thrown away for other reasons than problem of deterioration or because the max consumption time considered in this study is overcome. The % of losses corresponding to our scenarios analyzed corresponded to the cases where consumption of some part of the product occurred and therefore, is comprised in the range [2%,30%].

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It was assumed that the area under the deterioration curve, D , is proportional to the percentage of losses. Thus, the percentage of losses is considered linear to the integral of the deterioration curve D as follows:

$$I_s^p = a \int_{t=i}^{t=j} D_s^p + b \quad (47)$$

where p is the type of the packaging, s the number of the scenario tested in a population P of scenarios studied, I_s^p is the percentage of losses of the scenario s using the packaging p (%), $\int_{t=i}^{t=j} D_s^p$ is the integral of the deterioration curve D for scenario s in the packaging p from $t=i$ to $t=j$ (dimensionless), i and j representing the time at which the studied postharvest stage begins and ends respectively (day). a and b are the estimated parameters of the linear regression, a and b are dimensionless.

To calculate a and b values, in a population P of scenarios in no MAP, the minimum $I_{\min}^{\text{no MAP}}$ and maximum $I_{\max}^{\text{no MAP}}$ percentage of losses; identified in the previous surveys or interviews; are attributed to the scenario s_{\min} and s_{\max} having the smallest $\int_{t=i}^{t=j} D_{s_{\min}}^{\text{no MAP}}$ and biggest $\int_{t=i}^{t=j} D_{s_{\max}}^{\text{no MAP}}$ value of the deterioration integral. Having two data set for $(I_{\min}^{\text{no MAP}}, \int_{t=i}^{t=j} D_{s_{\min}}^{\text{no MAP}})$ and $(I_{\max}^{\text{no MAP}}, \int_{t=i}^{t=j} D_{s_{\max}}^{\text{no MAP}})$, the values of a and b can be calculated following a linear function of the form $y = ax + b$.

In this purpose, the maximal $I_{s_{\max}}^{\text{no MAP}}$ and minimal losses $I_{s_{\min}}^{\text{no MAP}}$ considered at consumer stage in no MAP conditions were respectively 2 and 30%. 2% was attributed to the smallest value of the deterioration integral calculated for scenario s_{\min} and 30% to the biggest value of the deterioration integral calculated for scenario s_{\max} . That means that in the best case (optimal storage conditions and moment of consumption), the consumer throws away only 2% of his strawberries while in the worst case, 30%. Using these two points and considering that losses are linearly proportional to the deterioration curve integral, as stated in Eq. (47), the two fitted parameters a and b could be calculated and were found equal to 3.53×10^{-04} and 1.10 respectively. In consequence, losses I_s^p corresponding to all other deterioration integrals ranging from the s_{\min} to s_{\max} values could be interpolated using Eq.(47).

4.2.2.2 Strawberries production and waste management

We consider strawberries cultivated in open field. European strawberries cultivation found in the database are used assuming that it represents the open field cultivation used in France. This cultivation considers all environmental impacts related to sowing, irrigation, vitamins and minerals intakes, pesticides and insecticides as well as machines used for soil inversion and irrigation. Bio waste i.e. biological waste is taken into account when a percentage of losses is identified at the studied stage. Biological waste is treated via incineration taken in charge by the municipality of the city.

4.2.2.2.3 Materials and energy use

4.2.2.2.3.1 Representation of cold storage

For Precooling, wholesalers, central purchase and supermarket (reception and storage room):

To reproduce the cold chain in refrigerated chamber and for simplification reasons, the size of the refrigerated chambers at the precooling, wholesalers, central purchase and supermarket (reception and storage room) are considered the same. It is assumed that the chamber used has a surface area of 67.3 m² as found in Eco invent data bases (Ecoinvent, 2016). Firstly, the maximal capacity of the chamber should be estimated in order to calculate the energy needed to refrigerate the goods. It was calculated assuming that only strawberries are stored in the chamber. To do this estimation, it was considered that each tray contains 0.5 kg of strawberries and has a top surface of 200 cm² (width 10 cm x length 20 cm) and that strawberries are stored on pallets containing 15 levels, each level has a surface of 1m². Therefore, each level can contain 50 trays of strawberries. Thus, one palette contains 750 trays of strawberries. In one refrigerated chamber, 20 palettes can be stored while keeping transits around the palettes to respect storage standards (Krishnakumar, 2017). Consequently, the maximal total number of trays that could be theoretically stored in the chamber is equal to 15000 representing 7,5 tons of strawberries. Note that this amount of strawberries is an artefact in the calculation and will only be used to determine the energy consumption due to cold storage.

After estimating the maximal amount of strawberries that could be stored in the refrigerated chamber, the required electrical power to cool the products is calculated using a decision support tool 'intarcon' (www.intarcon.com). This tool is able to estimate the amount of electricity needed to refrigerate a known quantity (here the

maximum capacity of the chamber) of goods taking into account the initial temperature and type of the good, the packaging surrounding the product (in this case plastic film) and the volume of the chamber. Then, the electrical power for all the stages containing refrigerated chambers, was re-calculated for one functional unit, from the global energy consumption calculated above (Table 12).

For refrigerated lorry during transport 1,2 and 3:

A lorry with a refrigeration machine for cooling products were taken from Eco invent data base (Ecoinvent, 2016). Transportation hours identified during surveys were represented in kilometers driven. In France, the maximal speed allowed for a lorry is of 90 km/h (FNTR, 2012). Carbon emission from refrigerated lorry is represented in Table 12.

For refrigerated Supermarket shelves:

At supermarket, an upright refrigerator is considered to store strawberries trays (Certification, 2011). This fridge has 7 levels of 15 m² each. A tray of strawberries containing 0.5 kg occupy 200cm². Considering that the fridge is filled with strawberries only and at its maximal capacity, the total number of strawberries' trays that could be stored in the fridge is equal to 42 representing 21 kg. The average electrical power needed for upright fridge display in that conditions (e.g. at its maximal capacity with 21 kg of strawberries stored) is equal to 20 kWh/m/d (Ligthart, 2007). The electrical energy needed for one functional unit was calculated and represented in Table 12.

For consumers' fridge:

At household, for control 1 and 2, products are stored at 5°C i.e. in the fridge (Figure 25). The mean electricity consumed by a household fridge is 354 kWh per year (Biglia et al., 2017). Only the amount of electricity needed to cool the strawberries is considered as explained in the allocation paragraph (§ 4.2.2.1.5). Electrical power for CMAP and OMAP scenario are indicated in Table 13.

4.2.2.2.3.2 Packing process

Product and waste management of the packaging

At the packing stage, the type of film used to pack the product is polyethylene (PE) and the tray used is made of PET (polyethylene terephthalate). The production of PET

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and PE granulate is considered as well as the formation of the tray through molding process and film production by extrusion. PE and PET waste management is considered in this LCA. In Table 12 are registered the weight of PE and PET used for one functional unit. Municipal solid waste incinerator (10%) and sanitary landfill (90%) are used to treat PET and PP.

To simplify the flow chart, PET and PP waste is only represented once in the flow chart, at the packing phase but is affected by the total weight of the plastic thrown along the postharvest chain (i.e. considering that all the quantity of packaging used will be wasted).

In this study, we assume that both control (1 and 2) and MAP (1 and 2) scenarios are made of trays and films with the same environmental impact.

Sealing machine

The sealing machine used to seal the PE film have a conveyer surface of 8375 cm². One tray of strawberries occupies 200 cm². Thus, the conveyer belt can contain 41 tray of strawberries per cycle. In addition, the power needed for this sealing machine is 6.3 kW for conducting 3 cycles in 1 minute (MPBS Industries, 2018). Thus, in one hour, 180 cycles are done sealing 7380 trays. Thus, power consumed to seal 1kg of strawberries is equal to 0.00854 kWh/5h (Table 12).

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Table 12: Inputs and outputs considered in this study from packaging to supermarket level for 1kg of strawberries

Stage	Input	Value/amount	Output	Values/amount
Packaging	Strawberries production	Quantity variable for each of the 8 scenarios	Bio waste	0.02 kg
	PE (polyethylene) granulate	18.3 g	PET waste	39.6 g
	Extrusion of PP	18.8 g	PP waste	18.3 g
	PET (polyethylene terephthalate) granulate	39.6g		
	Thermoforming of PET	39.8 g		
	Electricity for sealing machine	0.00854 kWh		
Precooling	Electricity for Cooling container	71000 kWh	-	-
Transport 1, 2, 3 and 4	Carbon emission from refrigerated lorry	3.17 kg CO ₂ /km	-	-
Wholesaler	Electricity for Refrigerated room	66800 kWh	Bio waste	0.02 kg
Central purchase	Electricity for Refrigerated room	56200 kWh	Bio waste	0.01 kg
supermarket	Electricity for Refrigeration at reception	49500 kWh	Bio waste	0.10 kg
	Electricity for Refrigeration at storage room	66800 kWh		
	Electricity for Refrigeration at store shelves	0.21 kWh		

Table 13: Inputs and outputs considered in this study for household level

Stage	Input	Value/amount	Output	Values/amount	
Household	CMAP: Best case	-	Bio waste	0.026 kg	
	OMAP: Worst case	-	Bio waste	0.28 kg	
	Control 1: Best case	Electricity for fridge	0.223 kwh	Bio waste	0.02 kg
	Control 2: Worst case	Electricity for fridge	0.669 kwh	Bio waste	0.035 kg

4.2.3 Results and discussions

The LCA calculations are based on the compilation of the amounts of materials and energy used and the emissions associated with processes. The latter are multiplied with characterization factors proportional to their power to cause environmental impact provided by Simapro.

4.2.3.1 Comparison between control and modified atmosphere packaging solutions at the consumer level

The environmental impact of strawberries stored in macro perforated packaging at ambient temperature (Control 1) for best (1 day) and worst (3 days) scenario was represented in Figure 27 and Figure 28 respectively through the black histograms. This Control 1 scenario will be used as a reference to be compared to Control 2, CMAP and OMAP; and is characterized by the highest percentage of food losses at the consumer level in the best (3.35%) and worst (30.0%) situation (see Figure 26).

Note that the environmental impact of MAP and no MAP production and disposal are considered the same for all the scenarios. In addition, the varying losses between the different scenarios are losses estimated at the consumer level and represents losses only due to the deterioration of products' quality. Thus, in this study; only a partial assessment of MAP benefit was done at the consumer level excluding wasted strawberries tray due to behavioral causes (strawberries not consumed on time, improperly stored or over purchase of the quantities needed).

Thus, in the following the objective is to evaluate the environmental benefit of using MAP at the consumer level and eventually measure the possibility to replace cold storage in macro perforated packaging by ambient storage in MAP packaging solutions at this stage (i.e. Optimized or Commercial MAP solutions).

Firstly, in order to evaluate the benefit of MAP compared to cold storage, for 1 d of storage at consumer level, the environmental impacts of Control 1,2 and CMAP were assessed. Figure 27 represents a relative comparison in percentage between Control 1 where strawberries are stored in macro perforated packaging in ambient conditions (black histogram), Control 2 scenarios where strawberries are stored in the fridge and in macro perforated packaging (grey histogram) and CMAP situation where the strawberries are stored in commercial modified atmosphere packaging at ambient temperature (striped histogram). Results shows that Control 1 and CMAP have

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practically the same environmental impact. Thus, in the case of commercial MAP applied during 1 day, the percentage of losses reduced to 2.30% due to MAP compared to 3.30 of losses in macro perforated packaging was not enough to reduce the environmental impact. However, a lower environmental impact of CMAP is recorded compared to control 2 (use of fridge) with a diminution in all categories due to the absence of fridge use in CMAP. But, for all the environmental categories, the difference between CMAP and Control 1 and 2 is lower than 20% considered as the minimum reduction needed to record a significant difference in the results (Jolliet et al., 2010).

Thus, strawberries stored for a short period of time, whatever the conditions, e.g. in the fridge or at ambient temperature with macro perforated packaging or in commercial modified atmosphere packaging at ambient temperature, will all have the same environmental impact. This can be partially explained by the close percentages of losses generated between CMAP scenario at ambient temperature (2,30% of food losses) (Figure 26) and using macro perforated packaging in the fridge Control 2 (2,00% of food losses) (Figure 26). Therefore, from an environmental point of view, for short period of time at household, MAP would not bring significant benefit compared to the no MAP stored in the fridge or at ambient temperature. Note that benefit of MAP at the supermarket was not evaluated, therefore not considered in this LCA while significant food losses reduction could have been reached at this stage.

Secondly, the environmental impact of the worst case scenario (long duration at the consumer level) for control 1,2 and CMAP was assessed. Figure 28 represents a relative comparison in percentage between Control 1 scenario where strawberries are stored in macro perforated packaging at ambient temperature (black histogram), Control 2 where strawberries are stored in the fridge and in macro perforated packaging (grey histogram) and CMAP situation where the strawberries are stored in commercial modified atmosphere packaging at ambient temperature (striped histogram). Results show a decrease of all the environmental impact for CMAP compared to control 1 scenario. Thus, for a long storage duration at ambient temperature the environmental impact of CMAP is lower than macro perforated packaging at the ambient temperature. This is due to the lower losses recorded in CMAP (16.98%) compared to control 1 (30%). However, the reduction of environmental impact is not enough to be significant.

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In addition, comparison of CMAP and Control 2 show higher environmental impact for CMAP in 4 categories: ozone depletion, land use, water resource depletion and mineral, fossil and renewable resources. A slight decrease between 2-17% for climate change, particulate matter, ionizing radiation, photochemical ozone formation, acidification, marine eutrophication and freshwater Eco toxicity. As for situation 1 (best situation), the achieved reduction of the environmental impact using CMAP in the worst situation is also negligible. In fact, the amount of losses generated in Control 2 (3.5%) are lower than in OMAP (16.98%) (see Figure 26- worst situation), it can be deduced that a high percentage of strawberries losses at ambient temperature will have the same environmental impact than the use of fridge in Control 2 with low percentages of food losses.

In other words, this study shows that MAP1 (Commercial MAP) could not reduce significantly the environmental impact of the post-harvest chain compared to the exclusive use of cold chain in the conditions investigated above. Note that these conditions are strongly restrictive: CMAP is used as an alternative to the use of cold chain and not in synergy with cold chain in this approach. And the effect of MAP on losses reduction is not taken into account at the supermarket level.

One of the reasons why MAP technology has a similar environmental impact than the cold chain, is the percentage of losses reduction obtained due to the proposed commercial MAP1 technology. In fact, CMAP was here established using an LDPE (low density polyethylene film) where only oxygen permeability was optimized, which can explain the quite high percentages of food losses recorded in MAP conditions. This can be improved by testing an optimized OMAP situation where film with optimal permeabilities for both oxygen and carbon dioxide is used to achieve the recommended oxygen and carbon dioxide composition for strawberries (5% O₂ and 15% CO₂) (Sousa-gallagher and Mahajan, 2013). The environmental impact of this Optimized MAP solution will be detailed in the next paragraph.

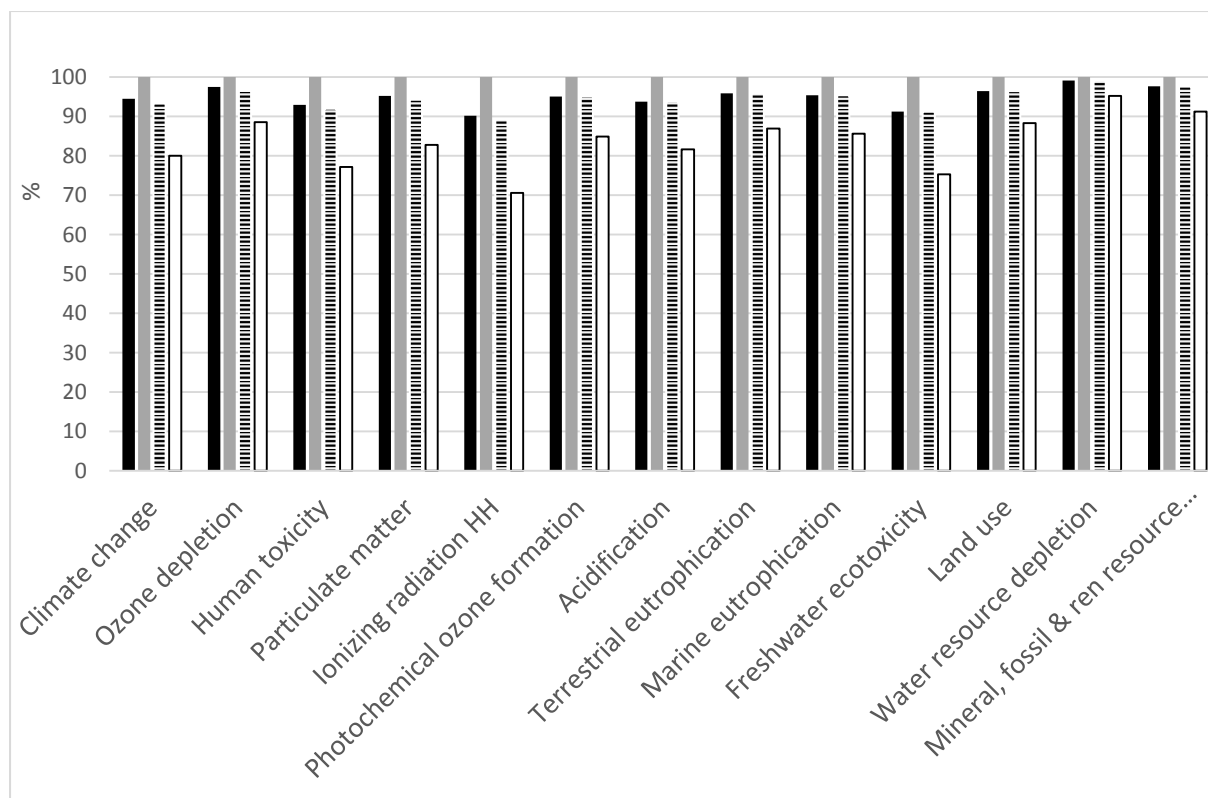


Figure 27: Relative comparison between control 1 (macro perforated packaging at ambient temperature), control 2 (the use of macro perforated packaging and cold storage for a short duration) in black, CMAP (the use of modified atmosphere packaging at ambient temperature for a short duration) in grey and optimized OMAP (the use of optimized modified atmosphere packaging at ambient temperature for a short duration) in white, (Raw values are shown in supplementary material 3).

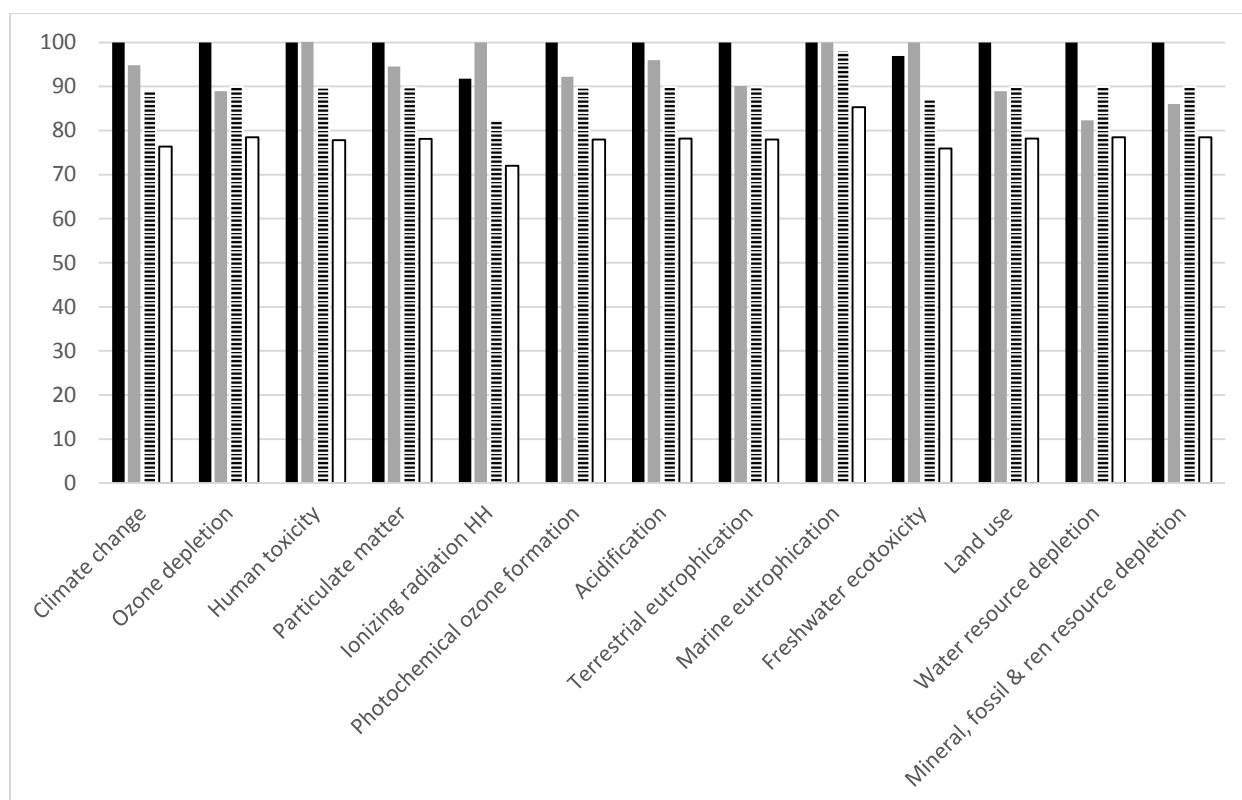


Figure 28: Relative comparison between control 1 (macro perforated packaging at ambient temperature), control 2 (the use of macro perforated packaging and cold storage for a long duration) in black, CMAP (the use of modified atmosphere packaging at ambient temperature for a long duration) in grey and optimized OMAP (the use of optimized modified atmosphere packaging at ambient temperature for a long duration) in white (Raw values are shown in supplementary material 3)

4.2.3.2 Potential of MAP technology optimization and its environmental impact: A focus on climate change.

In Figure 27, using optimized OMAP packaging in the best situation, shows a net diminution about 20 % and more for climate change, human toxicity, particulate matter, ionizing radiation HH, photochemical ozone formation and freshwater toxicity compared to Control 2. In Figure 28, using OMAP packaging in the worst situation, shows a diminution between 20-30% for climate change, human toxicity, ionizing radiation HH, acidification and freshwater toxicity compared to Control 2. Reductions equal to 20% are considered significant for climate change (Jolliet et al., 2010). These confirms the benefit that MAP, when optimized, could have on the reduction of the food/packaging system environmental impact even at consumer stage only.

For a clearly understanding of the concrete signification of carbon footprint reduction, a representation of the impact “Climate change” expressed in kg CO₂ eq, was done in term of equivalent of hours of storage in the fridge (Table 14). Results shows that a carbon footprint of 4.61 kg CO₂ eq represents 13.83 hours of storage in the fridge for

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strawberries stored in the fridge in macro perforated packaging during 1 day. Whereas for the same duration of storage, in optimized MAP at ambient temperature, the carbon footprint is equivalent to 10.8 hours of storage in the fridge. Thus, optimized OMAP during 1 days (best situation) has a lower carbon impact equivalent to a reduction of 3h of storage in the fridge. A similar comparison was done between Control 2 and optimized OMAP during 3 days (worst situation) of storage recording a difference of carbon footprint equivalent to 3,25h of storage in the fridge.

Thus, a reduction of the environmental impact is identified when MAP packaging is optimized. In both cases, long and short storage duration, and from an environmental impact balance only, it is preferable to store the product in optimized MAP at ambient temperature than in the fridge in macro perforated packaging even if losses at consumer stage are higher for MAP in ambient temperature condition. In optimized OMAP, for 3 days of storage, higher reduction i.e. 76% of losses reduction were recorded (from 30% to 7,2% of losses) (Table 13) against a reduction of 43% (from 30% to 16.98% of losses) for current CMAP when compared to the control 1 registering 30% of losses (Figure 26).

Table 14: Carbon footprint values expressed in kg CO₂ eq and hours of fridge storage for control 1,2 and optimized CMAP and OMAP cases study

Situation	Cases studied	Description of the cases	Losses (%)	Results of Climate change	
				Carbon footprint (kg CO ₂ eq)	Carbon footprint (hours of fridge storage)
Best	Control 2	5°C + Macro perforated packaging during 1d	2.00	4.61	13.83
	Optimized MAP 2	25°C + optimized OMAP during 1d	1.01	3.60	10.8
Worst	Control 2	5°C + Macro perforated packaging during 3d	3.50	5.33	16.15
	Optimized MAP 2	25°C + optimized OMAP during 3d	7.2	4.29	12.9

4.2.4 Conclusion

Life cycle assessment (LCA) was applied to postharvest chain of strawberries from harvesting till the consumer household considering generated food losses treatment, packaging production, disposal and benefit on food losses reduction, as never done before.

It was found that, at the consumer level, the environmental impact of macro perforated packaging was similar to MAP designed using commercial film. This result is valid for long and short duration of storage representing worst and best case scenarios. However, an optimisation of the MAP technology using ideal packaging at ambient temperature is a promising storage option, having a significant lower carbon footprint (20% lower) compared to macro perforated packaging stored in the fridge.

This work is a preliminary one in this domain and needs to be completed by further studies integrating the environmental impact of MAP at other postharvest stages such as supermarket level where losses are concentrated in one place and are easier to control than at the consumer level. Other packaging technologies with different environmental impacts can also be tested as an alternative to cold storage in macro perforated packaging such as biodegradable packaging, active packaging with oxygen scavenger or an initial flush of gases to establish quicker the optimal gases in the headspace.

Acknowledgement

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4.3 Concluding remarks

The postharvest chain of strawberries was characterized through LCA approach from packing till the household. As never done before, **food losses, packaging production, disposal and packaging usage benefit which is impact on the reduction of food losses**, were considered in this study.

The approach developed for assessing the environmental impact of modified atmosphere packaging at the consumer level showed that **no significant difference** exists between the Commercial MAP used at ambient temperature and the control, e.g. the macro-perforated packaging at ambient and cold storage which is currently used. However, **optimized MAP packaging, i.e. MAP with optimal equilibrium concentrations on both O₂ and CO₂, is able to decrease by 20% the environmental impact** compared to macro perforated packaging at ambient temperature.

A focus on carbon footprint showed that optimized MAP stored at ambient temperature is able to register a significant reduction of CO₂ emission (equivalent to 3h of fridge CO₂ emission), compared to macro perforated storage in the fridge for best and worst case situations i.e. short (1 day) and long (3 days) storage duration at the consumer level.

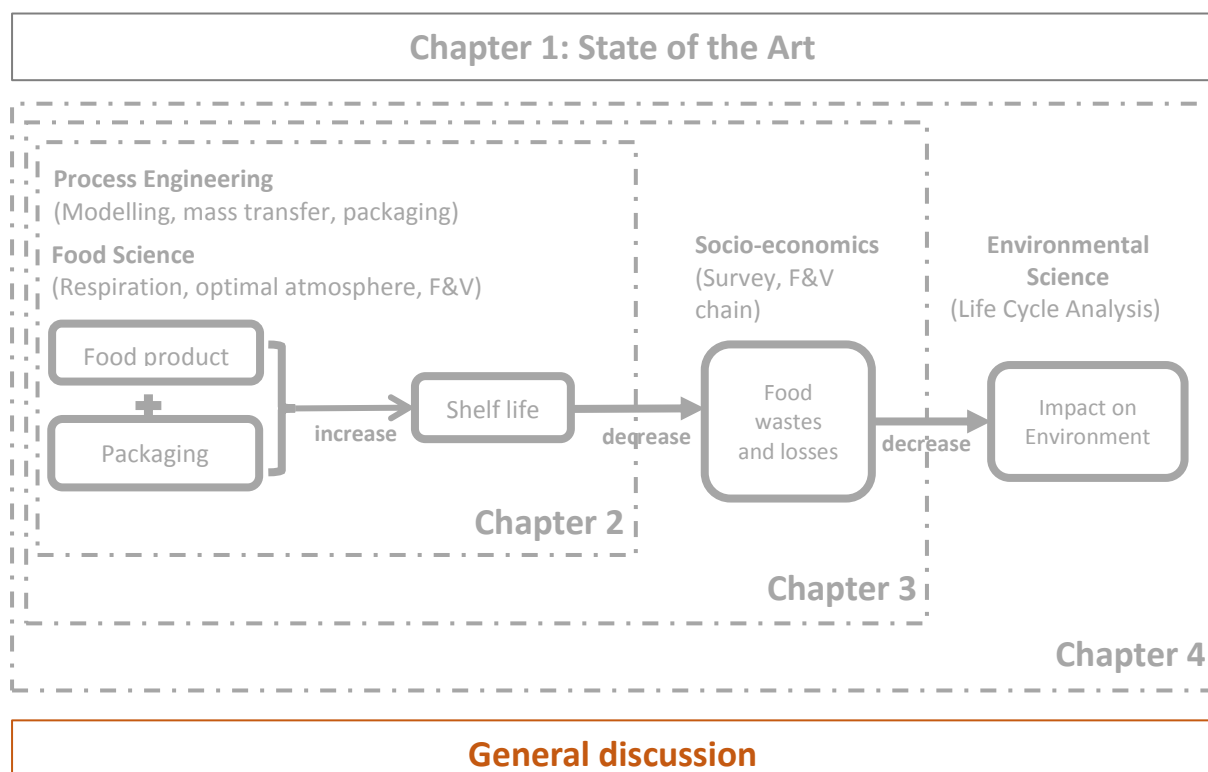
Further research on the effect of MAP in other postharvest stages such as **supermarket level** may enable to generate a higher positive impact of MAP on the environment. In fact, the advantage of the supermarket level will be the possibility to control easily large amount of losses concentrated in one place unlike of losses recorded at the consumer level.

MAIN FINDINGS

- Environmental impact of MAP benefit on strawberries losses at consumer level was quantified
- Optimized MAP packaging i.e. MAP with ideal film permeabilities and thus optimal gas concentration on both O₂ and CO₂ at equilibrium, is able to decrease by 20% the environmental impact compared to the control packaging, e.g. macro perforated packaging
- Further research on the effect of MAP in other postharvest stages such as supermarket level may enable to generate a higher positive impact of MAP on the environment

General discussion

General discussion



Context and objectives

Food losses and wastes reduction is an urgent issue to solve especially for the fresh fruit and vegetables sector representing around 40% of the food losses and wastes generated worldwide (Gitz et al., 2014). If wastes, referring to the discard of still edible foods at the distribution and consumer levels, a symptom of consumerist lifestyles of developed countries, are difficult to prevent using current food technologies, some losses could be avoided by setting up suitable food preservation strategies.

The current strategies used to reduce food losses is essentially based on the use of the cold chain which negative impacts on the environment are well identified. Modified atmosphere packaging (MAP) relying on the modification of the gases (principally O₂ and CO₂) composition surrounding the packed product can contribute to reduce fresh fruit and vegetables losses by increasing product shelf life, especially losses that are directly linked to problems of shelf life, deterioration and product quality loss during storage.

The possibility to predict gain of shelf life in MAP and its corresponding positive effect on the reduction of food losses could be a powerful tool for postharvest chain actors.

General discussion

Such type of predictive model is based on the understanding of the phenomena undergoing during postharvest storage in MAP such as effect of fluctuation of gases composition on product's deterioration, interaction with storage condition, in particular, temperature, and actor's behaviours in the postharvest chain. Such type of predictive model still needed to be developed at the beginning of this project, and in particular, the link between gain of shelf life and reduction of food losses.

Reduction of food losses is closely related to the reduction of the environmental impact of the food/packaging system as a whole. Reduction of food losses thanks to MAP technology could lead to significant benefit in terms of environmental impact reduction, potentially limiting the intensive usage of the cold chain. This environmental benefit remained to be quantified at the beginning of this thesis.

In this context, in the perspective to answer the general objective which is the development of an eco-design approach of the fresh food post-harvest steps, this PhD has focused more specifically on three main aspects which are:

- Development of a deterioration model integrated in a MAP modelling tool that permits to describe and predict the effect of gases on deterioration of the product.
- Losses predictions at household based on the prediction of food losses in link with stakeholders' behaviours, especially those of consumers.
- Environmental assessment of MAP system for a case study (strawberry, 'Charlotte' variety) and quantification of its benefit in terms of food losses reduction on environmental impact evaluated using classical LCA.

An original methodology to assess food shelf life

Setting up a full shelf life assessment including consumer acceptability

In this project, to go beyond the state of art, robust approach of food shelf life prediction for fresh product packed in MAP was first developed.

At the beginning of this PhD work, very few studies attempted to predict food shelf life under modified atmosphere packaging (MAP). Analysis of the scientific literature has highlighted the lack of unified, clear definition of shelf life and the lack of general methodology and modelling tools to assess and predict food shelf life (see chapter 1). As a result the first step was to define on which fundamental criteria, food shelf life is

General discussion

based on, and more specially, shelf life of strawberries, which is the model food used in the present work. In the literature, we identified that existing quality parameters are numerous and need to be all assessed at the same time to be representative of the overall product quality. In the present work, it was assumed that strawberry quality and thus their shelf life relies mainly on a visual assessment of their global deterioration by the different stakeholders of the food chain, especially by the distributors and consumers. This is based principally on a visual assessment made through the transparent packaging material. This was confirmed by the consumers' questionnaire carried out in the framework of this work: consumers evaluate strawberries' quality, by a large extend (80%), on a visual basis (see chapter 3). Therefore, a method based on the evaluation of the fruit surface deterioration (in %) was proposed and developed for the experimental assessment of product shelf life in MAP. This deterioration encompasses color change, texture softening and microorganism's development such as molds. The construction and validation of this method is explained in chapter 2.2

Such type of visual assessment based on surfaced deterioration was never carried out before. It was proved to be more accurate than the assessment of number of spoiled fruits that was generally applied by Riad et al., (2015), Aday et al., (2013) and Hertog et al., (1999) as described in chapter 2.2.

Prediction of the deterioration rate was a first step but in order to predict a product's shelf life, it was necessary to also determine what is the maximal acceptable deterioration, D_{acc} , by the consumers. To take into account the consumer acceptability of the product, a maximal acceptable deterioration D_{acc} was identified after asking 30 untrained panel if they were ready to buy the product or not. It was found that when the surface deterioration of the strawberries reached 13%, the consumer was no longer willing to buy the product.

The intersection of the deterioration curve and the maximal acceptable deterioration D_{acc} has permitted, in this work, to identify product's shelf life in various conditions of storage (MAP/ no MAP and various temperature conditions). This approach could be applied to many other fresh products which quality relies on visual assessment. It represents a significant breakthrough in the field of food science.

Modelling product shelf life in MAP system

System of equations

Deep analysis of the literature showed that so far there is a lack of MAP modeling tools able to predict shelf life in MAP. In general, mass transfer of gases (O_2 and CO_2) in MAP system are predicted independently of the intrinsic quality of the product.

In the core of this PhD, an upgraded MAP modeling tool was developed combining gases prediction in the headspace of the packed product and their impact on product's deterioration as a function of time. The main upgrade concerned the model of food deterioration that was developed based on the experimental assessment of food deterioration as summarized in the previous §. It was assumed that this deterioration depends on the level of CO_2 into the headspace and the storage temperature. This assumption was based on main findings of the literature dealing with the development of molds and more specially that of *Botrytis* that is limited by increasing levels of CO_2 and even completely inhibited by a % of $CO_2 > 30\%$. CO_2 was considered as an inhibiting element of the deterioration and the model of deterioration built as a model of predictive microbiology: a primary model which is a logistic function describing deterioration rate as a function of time, and a secondary model which is an inhibition function, describing the effect of CO_2 on the maximal deterioration rate.

The MAP system considered in the modelling approach and all equations used are summarized in Figure 29. Main hypothesis and development are summarized hereafter:

Gases transfers are described by Fick first law to represent the permeation through the film (Eq. (a)). Michaelis and Menten law was used to represent the respiration of the product (Eq. (b)). The general model coupling gases transfers and respiration was improved to take into account the metabolic deviation of the product, (Eq. (c)), that is proportional to the level of deterioration which is predicted, as mentioned above, by a logistic function (Eq. (d)). The differential equation for O_2 and CO_2 variation in the headspace are represented in (Eq. [A]).

Determination of the maximal deterioration rate, D_{acc} , subtended by the consumer when he buys his strawberries permitted to use the model of food deterioration to

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predict shelf life assuming that this shelf life is directly linked to the level of deterioration up to a certain limit (13%) above which the product would be not bought anymore (Eq. [B]).

The effect of temperature represented by Arrhenius law (Eq. (e)) and taken into account via film permeability P_{CO_2} or P_{O_2} , maximal respiration rate $R_{O_{2max}}$, deterioration rate k_D and β_{O_2} or β_{CO_2} representing the rate of CO_2 production or O_2 consumption due to deterioration.

δ_{CO_2} described in the deterioration model (Eq. (d)) depend on the quantity of CO_2 predicted in the mass balance (Eq. [A]). Coupling gases mass balance and product deterioration is done at this level.

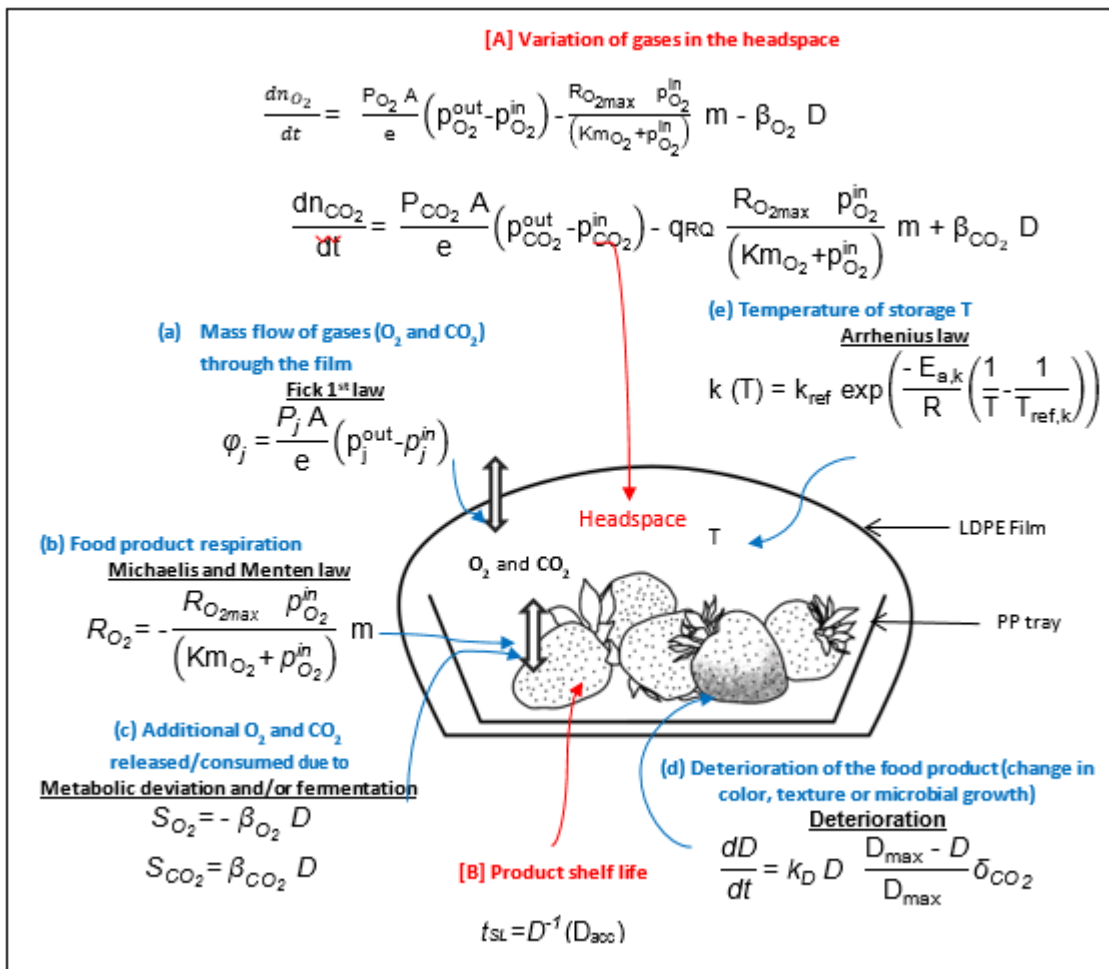


Figure 29: Schematic representation and equations used to model mass transfer and associated reactions (food product deterioration) in the food packaging system (abbreviations are listed in the nomenclature of chapter 2.2)

General discussion

The differential equations for gases transfer and product's deterioration were coupled in one system of equations, enabling to take into account the effect of gases and consumer acceptability in the prediction of product shelf life which was never done before this PhD work.

The outputs of the models are: the prediction of O₂ and CO₂ in the headspace (Eq. [A]), deterioration of the product (Eq. (d)) and product shelf life in days (Eq. [A]). A gain of shelf life thanks to MAP technology can be estimated by comparing MAP and no MAP deterioration curves.

This model was solved via MATLAB using ode15s solver and is able to conduct one simulation in less than 2 min. 30 Input parameters are needed among them, 18 are for describing mass transfer phenomena, 6 deterioration parameters, 6 for the geometry and the initial conditions of the system.

Model validation on strawberry 'Charlotte' packed in MAP

Model validation was done in 2 steps. First gases transfer and deterioration evolution were assessed in isothermal conditions at 5, 10 and 20°C then using a temperature profile mimicking realistic postharvest storage conditions. 'Charlotte' was the variety of strawberries studied (chapter 2.3). 100 g of strawberries were packed in LDPE (low density polyethylene) pouches, which size was preliminary calculated using the MAP modelling tool in order to obtain at equilibrium, an internal atmosphere closed to the optimal one for O₂ (5% O₂). Indeed, experimental MAP set up was here done by choosing an easily available, commercial film LDPE. LDPE pouch, with a surface of 0.04 m² and thickness of 50 µm had the most adequate O₂ permeabilities able to establish oxygen concentrations in the headspace of the product close to the optimal ones for strawberries i.e. 5 %O₂. However, optimal CO₂ concentration (15%), able to inhibit microorganisms, was not established in the headspace using LDPE film due to its too high CO₂ permeability. Therefore, the MAP established for carrying out the validation is called in the following, 'commercial MAP', e.g. meaning that modified atmosphere is established in that case using a commercial but non-fully optimal film.

Overall, 130 trays of strawberries were needed to validate the model.

The model was able to predict the variation of gases in the headspace and the evolution of product deterioration in % in all cases. The hypothesis and the parameters

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used to represent the model were thus validated. A gain of 0.33 days of shelf life in commercial MAP compared to the control, macro-perforated packaging where no modified atmosphere is this established, was obtained both by the experiment and the prediction in the simplified and non-optimal storage conditions investigated here (see chapter 2.3.).

Potentialities for the upgraded modeling tool

Once validated, the model could be used for numerical exploration of different storage conditions (modified atmosphere and temperature conditions).

Indeed, in the condition of the experimental validation, the MAP set up was not fully optimized in terms of atmosphere composition at equilibrium. Moreover, temperature conditions were not optimized either. Much more benefit of MAP in terms of increase of shelf life is then expected by using optimized storage conditions.

Confirming that, the model permitted to estimate that, by changing only temperature during storage at household (5°C instead of 20°C), a shelf life of 1.68 could be achieved instead of 0.33 days (chapter 2.3, Figure 21).

The model could be also used to explore the benefit of changing the nature of the packaging, for instance by considering a packaging with ideal permeabilities P to O_2 and CO_2 (named in the following 'optimized MAP'). In this case preliminary calculations have proved that for 100 g of strawberries packed in a pouch of 0.04 m², the suitable permeabilities would be $PO_2 = 4.0 \times 10^{-15}$ mol/m.s.Pa and $PCO_2 = 4.2 \times 10^{-15}$ mol/m.s.Pa. Figure 30 represents for a given temperature profile (Figure 30 (a)), the deterioration curves obtained in macro perforated packaging (Figure 30 (b), grey curve), in Commercial MAP (Figure 30 (b), black line) and in optimized MAP (Figure 30 (b), black dotted line) with ideal permeabilities. The intersection of the maximal acceptable deterioration with the deterioration curves showed that the gain of shelf life is equal to 0.88 day in optimized MAP (between grey and black dotted curve) multiplying by 2.6 the shelf life estimated in Commercial MAP using LDPE film equal to 0.33 day (grey and black full line). Thus, MAP technology is revealed as promising packaging solution to considerably increase product shelf life when a film with the optimal permeabilities for oxygen and carbon dioxide is used. To have a higher shelf life, the couple time and temperature could be optimized. For instance, if we only

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change the consumer storage temperature from 20°C to 5°C the shelf life estimated will increase from 1.68 day gained in Commercial MAP to 2.76 days gained in Optimized MAP (which is an increase of x1.6) (figure not shown).

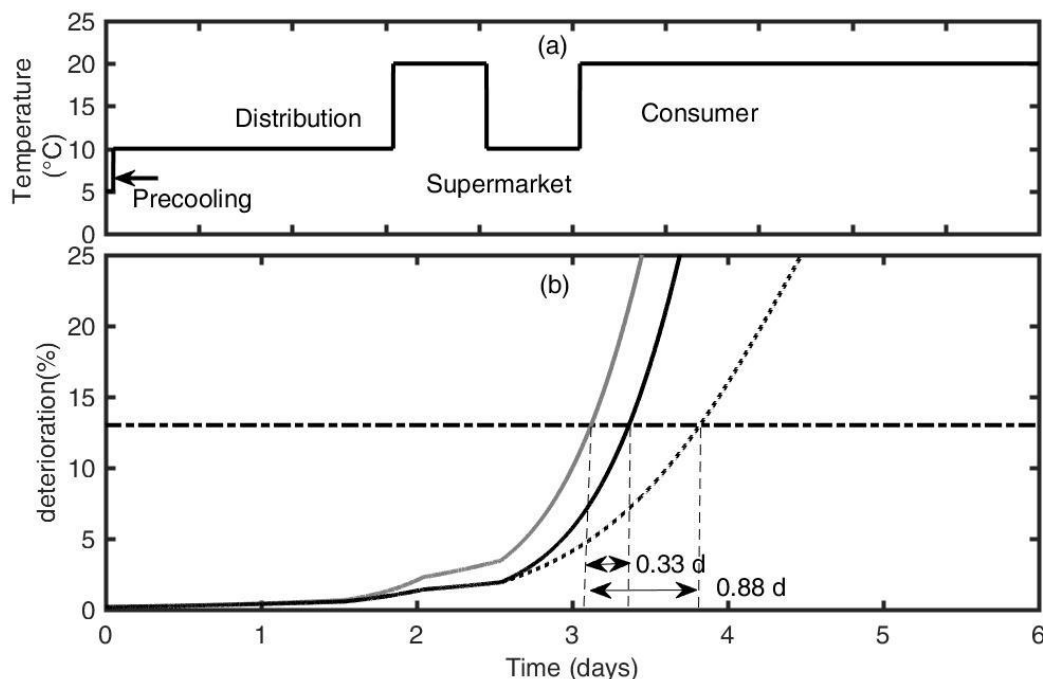


Figure 30: Estimation of shelf life gain for a predefined temperature profile (a), using no MAP (grey curve), Commercial MAP (black curve), optimized MAP (dotted black curve) curves and their intersection with the maximal acceptable deterioration (-.-.)

In order to apply this model to other strawberries varieties or food product, some parameters need to be adapted. For instance, during this PhD, the developed MAP modeling tool was tested on strawberries variety 'Sonata' grown in Norway. The superposition of experimental assessment of the deterioration and the upgraded MAP modelling tool showed that the model need to be adjusted to the new product. In fact, the major variation was the change of initial product deterioration D_{ini} , that affected deterioration prediction and thus shelf life estimation.

In consequence, for a successful application to another product, initial deterioration parameter should be re-estimated prior to any prediction. This will take time and it is costly. Complementary parameters are needed such as optimal gases composition and respiration characteristics and hopefully, some of them are available in the literature such as optimal gases composition for instance. For example, Kader et al (1988), identified and gathered optimal gases composition for a large number of fruit and vegetables (Zagory and Kader, 1988). However, for respiration rates, data are

scattered in the literature. For this end, a database called '@web' (<http://pfl.grignon.inra.fr/atWeb/>) was initiated at INRA in order to assemble these data and be afterwards used as input for the MAP modelling tool. During this PhD, I also contributed in increasing this database with respiration rate and optimal gases composition data of fruit and vegetables found in the literature.

Linking product deterioration to a percentage of losses at consumer stage

The model for shelf life prediction being developed and successfully validated, it was then used to predict food losses reduction for strawberries in MAP. In this approach, it was assumed that food losses were directly proportional to the deterioration level predicted by the model developed. Therefore, the work done in this PhD exclusively focuses on food losses at household excluding wastes (voluntary losses) that are not directly link to product shelf life (Figure 31). The first step to link product deterioration to food losses was to obtained reliable estimation of these losses at the different post-harvest stages.

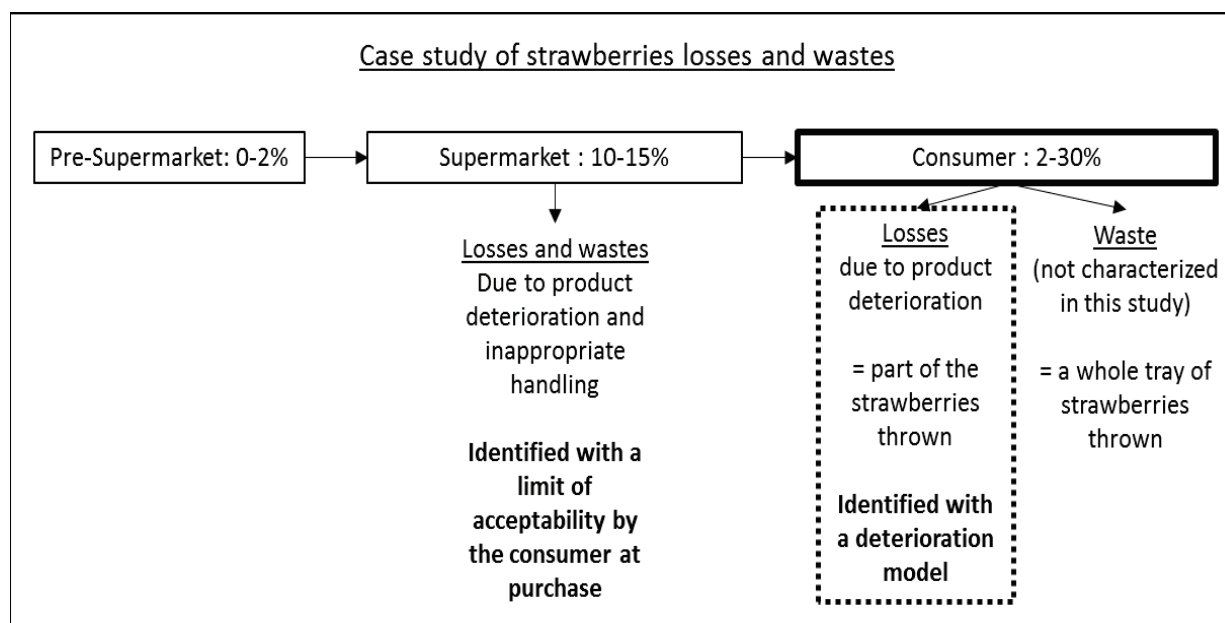


Figure 31: Losses and wastes in the postharvest chain of strawberries. The dotted frame represents the section of the postharvest chain losses that will be quantified in this study

A mapping of food losses in the post-harvest stage of strawberries

Despite the high **awareness claimed by the consumers** toward food losses and wastes in France, the range of losses identified at this level was between 2 and 30%. Undoubtedly, difference exists between consumer's actions and what they claim for doing. It should be also noted that, the definition behind the range of losses (2-30%) taken as reference in this study is not clear (Figure 31). In other words, it is not very well known what these percentages of losses represents. This is an interesting area of research for future works that will contribute to validate these percentages or measure more precisely losses related to behavior of the consumer and how to cover a wider number of scenarios. Meanwhile, the approach developed in this model can be applied testing other percentage of losses.

A breakthrough in the prediction of food losses at consumer stage

Literature search revealed the absence of mathematical models able to link product quality in MAP to a percentage of food losses, while considering postharvest actors' behavior such as supermarket, wholesaler or the consumer. In this study, we decided to focus on consumer level because of the availability/accessibility of data/information regarding this stage unlike other postharvest stage (for instance, supermarket, wholesalers). Indeed, the consumer survey performed in the framework of this work permitted to obtain relevant an exploitable information while the distributor survey was less successful.

In this work, we proposed to link the developed deterioration model (in chapter 2) to a percentage of losses at the consumer level. This was done by setting the hypothesis that the integral of the deterioration curve is proportional to a percentage of food losses at household. Note that this model is able to quantify the losses exclusively related to product quality i.e. product deterioration (Figure 31). At the household stage, the maximal acceptable deterioration of 13% is not valid anymore because it represents consumer's behavior at purchase at the supermarket stage. We assume that once packed strawberries are bought (for packed strawberries that are below the threshold value of 13% of deterioration at the supermarket), the consumers discarded only deteriorated surfaces and consume the others.

In order to predict food losses reduction at household in the most realistic way, typical postharvest scenarios were investigated. To reconstruct these typical postharvest

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chain scenarios i.e. to identify temperatures, durations of storage and % of losses in each stage of the postharvest chain in France, surveys were sent to 89 wholesalers and 846 consumers (collaboration with UMR MOISA). The range of losses found at the consumer level (2-30%) is very uncertain and will be only used as guidelines i.e. calibrations points for setting up the link between deterioration and generated losses.

From information obtained from consumer and distributor surveys, 132 post-harvest scenarios were built. They considered the diversity of behavior at distribution and consumer stage i.e. temperature of storage (ambient temperature or in the fridge), duration of storage (for 1 or 3 days). Exploring all these scenarios and their occurrence in the post-harvest chain, it was found that in the current storage conditions, in France, the percentages of losses recorded at household using conventional macro-perforated packaging would be equal to 9.21%. Note that these losses correspond only to product that is consumed but which spoiled parts are discarded. Product that are entirely thrown away because they have been forgotten in the back of the fridge, etc. are not considered in this approach. Due to uncertainties on the range of food losses 2-30% found for consumer steps, the percentage of losses estimated (9.21%) should be interpreted carefully and only used as an example.

Alternative to the conventional macro-perforated packaging is to use MAP. Simulating a MAP storage (commercial MAP used at this stage) all along the postharvest chain while taking into account consumer storage habits, i.e. that 21.4 % only keep the packaging integrity until consumption, the others removing the packaging losing thus benefit of MAP at household stage, and that 42.8 % of consumers store in the fridge, reduced the percentage of losses by 17.8%. Moreover, if we convinced all the consumers to keep the packaging at ambient storage conditions, we can hope a reduction of around 40% of the initial losses. Thus, the developed methodology which was based on the link between product quality and food losses was able to quantify losses related to product quality loss at the consumer level and estimate the impact of consumer behavior on the changing quality and its repercussion on the losses.

Remaining challenges of the quantification of losses in the postharvest chain

The approach developed at consumer level linking food losses and product deterioration should also be developed at other stages of the postharvest chain. For instance, the supermarket is an interesting step to work on, having the second highest

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amount of losses in the postharvest chain (about 10%) after the consumer level (up to 30%). In addition, at the supermarket level, the losses are concentrated at one stage and are easier to control than at the consumer level. To attribute percentages of losses and wastes to scenarios at the supermarket level, we can use the maximal acceptable deterioration ($D_{acc} = 13\%$) developed in this study as a limit. When the product exceeds the D_{acc} i.e. when more than 13% of strawberries surface is deteriorated, the consumer won't buy the product anymore and it will be entirely thrown away and thus wasted. In our case study among the 24 scenarios investigated for the supermarket step, only 2 resulted into product waste for conventional packaging and only 1 for Commercial MAP. If the 2/24 scenarios correspond to the maximal of waste at supermarket step, i.e. 10%, we can thus consider that by applying MAP we reduce this waste by a factor 2 (2/24 to 1/24), therefore waste at supermarket when MAP is used would be equal to 5%. However, more scenarios at the supermarket level need to be explored for a better identification of waste reduction at this stage. This need to be addressed in a further work.

The consumer surveys revealed that 79% of consumers removed the packaging just after purchase because they think that it is preferable for the storage of strawberries. This a nonsense when MAP is applied because in that case, the packaging integrity must be kept to ensure that the suitable atmosphere conditions are maintained in the close surrounding of the product until its consumption. One of the remaining difficulties is in **the ability to change consumers' habits and** storage behaviors. Currently, consumers may not be aware of the importance of keeping the packaging. In addition, according to a qualitative study done by CTIFL on 15 consumers between 25 and 45 years old, it was found that the French consumers are reluctant to packed fresh fruits and vegetables fearing product stifling in the plastic or suspecting the intention of hiding a product of lower quality (Baros and Hongre, 2017). Thus, awareness campaign toward public at large need to be done before launching the MAP technology in the postharvest chain even if 60% of the consumers thinks that they have a good knowledge of strawberries storage and preservation.

Moreover, the establishment of MAP technology in complement to the cold chain in the postharvest chain can generate an additional cost impacting the final **production cost**. In that case, the MAP technology should be cost-effective on the reduction of food losses and wastes, either wise, the distributor will not be interested in investing

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in this technology. It is still not known which minimum percentage of losses reduction MAP technology should reduce to be worthwhile for the distributor.

Last but not least, the **environmental impact** of MAP technology should also be taken into account before being established. MAP packaging would be preferable compared to cold storage but this benefit remains to be really quantified. In fact, the cold used in the industries, refrigerated transport and retailers all together represent 40% of total CO₂ emission and hydrofluorocarbons related to refrigerant fluid (Joassard, 2017). Thus, even if storing at low temperature is more effective in the reduction of losses, it is less interesting on the environmental point of view. To optimize the use of MAP packaging, a good compromise should be found between the environmental impact of the packaging used and the amount of food losses and wastes reduced due to this packaging. In fact, It was demonstrated by William et al. (2010), that it can be environmentally motivated to increase the environmental impact of packaging, if necessary, when packaging design helps to reduce food losses (Wikstrom and Williams, 2010).

Despite the numerous hypotheses set, we believe that the method presented in this PhD work can assist in the progress towards a more comprehensive understanding on how MAP could quantitatively reduce food losses at the consumer level.

Environmental impact of MAP in the postharvest chain

A focus on the environmental impact of MAP at the consumer level

Literature review showed that so far analysis of the environmental impact of postharvest chain of fresh fruit and vegetables were focusing only on stages going from production till the supermarket level without considering consumer level and the full role of the packaging in the postharvest chain, i.e. its usage benefits in terms of food losses reduction. The packaging used along the supply chain has an environmental negative impact due to its production and disposal but help to keep the quality of the packed product leading to a reduction of food losses that is an indirect, environmental benefit. This latter is never considered in LCA analysis.

In this purpose, the environmental impact of the case study used in this work (Strawberry packed in Commercial MAP or conventional packaging) was evaluated by

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applying a life cycle analysis approach (LCA). This LCA will take into account postharvest stage from packaging till consumer level considering food losses generated along the postharvest chain and packaging: production, disposal and effect on food losses reduction. Benefit of MAP on reduction of food losses will be considered at the consumer level only, because it is only at this stage that the link between product quality and losses was studied in details in the framework of that work.

The objective of this LCA was to measure, at the consumer level, the environmental impact of MAP (optimized and commercial MAP) technology compared to macro-perforated packaging through losses variation. 'Commercial MAP' refers to the MAP packaging designed in chapter 2.3 (adequate permeabilities for O₂ via a commercialized film) and optimized MAP refer to the ideal MAP packaging enabling us to reach optimal O₂ and CO₂ concentration. MAP packaging technologies were tested at ambient temperature and compared to macro perforated packaging in the fridge and at ambient temperature. It was assumed that macro-perforated packaging, commercial MAP and optimized MAP have the same environmental impact for packaging production and disposal. The percentage of losses generated due to the packaging is the only varying parameter between those three packaging technologies.

It was found that, at the consumer level, there was no significant difference between the environmental impact of the current commercial MAP used at ambient temperature and macro perforated packaging stored at ambient temperature or in the fridge. This means, that even if the use of cold chain permits to significantly reduces food losses in macro perforated packaging, the environmental benefit of these losses reduction was masked by the environmental cost of the cold chain system. In the case of commercial MAP, the usage benefit was too low to have a significant effect on the environmental balance. Considering now optimized MAP packaging at ambient temperature, it is a promising solution able to reduce by 20% the environmental impact compared to macro-perforated packaging stored in the fridge. This benefit is rather related to the reduction of cold chain use than the reduction of food losses which are, on the contrary even higher in the case of optimized MAP packaging at ambient temperature than in no MAP in the fridge.

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The low environmental benefit obtained for 'Commercial MAP' here could be related to the fact that only losses reduction was measured at the consumer level answering partly the global objective aiming at measuring the environmental impact of MAP in all the postharvest chain. To continue the approach started, environmental impact of MAP in all the postharvest chain, considered reduction of losses at each step must be evaluated.

Remaining postharvest stages to be explored

In addition to the consumer level, the impact of MAP technology can also be considered at the supermarket level. As proposed in the previous paragraph of this general discussion, we can suppose that MAP reduce by 2 the losses at the supermarket stage.

Applying this hypothesis on the worst situation studied in chapter 3 i.e. storage duration of 3 days at household, the environmental impact of MAP when losses reduction is considered in both supermarket and consumer levels can be evaluated.

Figure 32 show the environmental impact obtained at ambient temperature for macro perforated packaging (black histogram), for Commercial MAP applied with losses reduction considered at the consumer level only (black hatched histogram) and for Commercial MAP applied with losses reduction considered at both supermarket and consumer level (blue hatched histogram).

Results show that, considering the benefit of MAP (Commercial MAP) at both supermarket and consumer level (blue hatched histogram), will decrease by 10% the environmental impact compared to the case where benefit of MAP is considered at the consumer level only (black hatched histogram). Moreover, a 20% reduction is registered for MAP with benefit at the supermarket and consumer levels (blue hatched histogram) when compared to the macro perforated packaging (black histogram). Thus, considering benefit of MAP at both supermarket and consumer level, even if this commercial MAP is imperfect and non-optimized for CO₂, would be sufficient to register a significant improvement in LCA results compared to macro perforated packaging.

This quick assessment need to be confirmed by complementary tests on other scenarios but it well illustrated the necessity of considering the impact of MAP on the

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losses reduction at all steps of the postharvest chain in order to measure a more accurate impact of MAP technology.

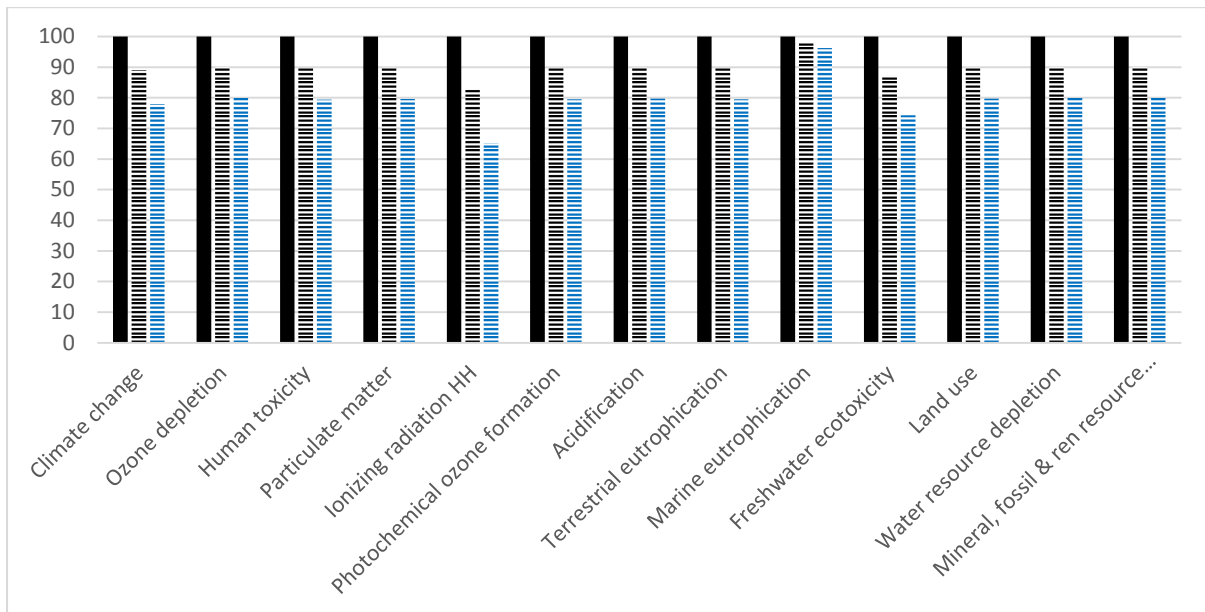
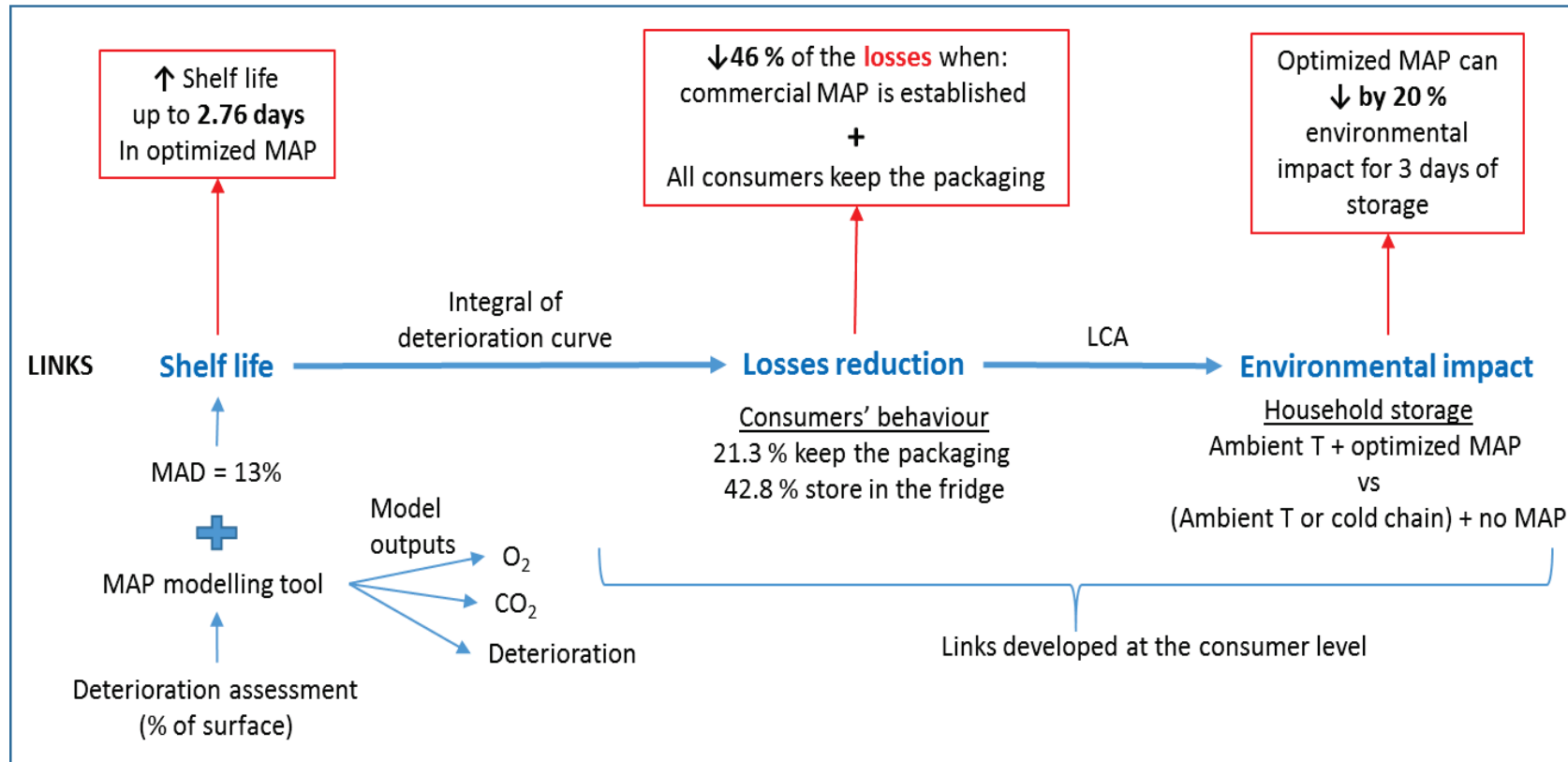


Figure 32: Environmental impact of postharvest chain when macro perforated packaging is used (black histogram), when effect of Commercial MAP is considered at consumer level (black hatched histogram) and when the effect of Commercial MAP is considered at the supermarket and consumer level simultaneously (blue hatched histogram).

Take Home Message

Main findings



Conclusions and prospects

Conclusions and prospects

Conclusion

The literature search carried out within this PhD work highlighted the lack of quantifying methods for product shelf life assessment in modified atmosphere packaging (MAP) and the absence of a clear representation of the link between product shelf life and a corresponding percentage of food losses and wastes. In addition, no study takes yet into account the environmental impact of the packaging on the reduction of food losses and wastes.

In this study, a novel methodology was developed which is able to assess product deterioration, as a function of time with a relatively high accuracy. Strawberries was taken as a model food.

The numerous experiments carried out enabled to developed a model for predicting product deterioration which is influenced by gases composition in the headspace, and temperature. The intersection of this deterioration model with the maximal acceptable deterioration by the consumer determined the shelf life at supermarket step, i.e. the time after which the product is not any more bought by the consumer and thus discarded. The model was validated by steps of increasing complexity. First in isothermal temperature of storage followed by a temperature profile representing postharvest chain storage. To the best of our knowledge, so far in the literature, no such complete model predicting product quality and shelf life in MAP was published before.

To go further in the approach, a quantitative link was built between product deterioration and the recorded percentages of losses, at the consumer level. This quantification approach was used to estimate the reduced amount of losses recorded in the postharvest chain of strawberries stored in modified atmosphere packaging (MPA) technology compared to conventional macro perforated packaging while considering French consumers' practices for this product. Results highlighted a reduction of 40% of the losses when the product is packed in MAP and if all consumers keep the packaging's integrity before consumption.

Conclusions and prospects

Last but not least, the environmental impact of the use of Commercial and Optimized MAP in ambient temperature was compared to the use of macro perforated packaging at ambient temperature and in the fridge. This comparison includes the environmental impact of the losses, at the consumer level, resulting from each packaging conditions. It was found that optimized MAP solution stored at ambient temperature is able to reduce by 20 % the environmental impact compared to macro-perforated packaging stored in the fridge.

Prospects

The following prospects has been identified in order to continue progressing towards a complete understanding and representation of the links between product shelf life, food losses and wastes and their resulting environmental impact.

- The MAP model proposed in this PhD predicting product shelf life and gases composition in the headspace can be improved. An additional differential equation representing relative humidity can be coupled to this model to represent the transpiration of the respiring product and water permeation through the film. Examples of these models are developed in the literature by (Sousa-Gallagher et al., 2013). This improvement can help the user to correctly choose a film packaging by avoiding dehydration of the product and water condensation at the product or packaging surfaces which can lead to undesirable evolution, e.g. development of microorganisms at food level or modification of permeability at packaging level.
- Currently, at the consumer level, the link established between product deterioration and percentages of losses recorded represent only the eaten strawberries (losses) without taking into account strawberries thrown without consumption (wastes). Wasted strawberries should be added to the model. One possible way is by taking into account additional scenarios in which consumers throw a whole tray of strawberries. These scenarios can be identified through surveys at the consumer level, where questions related to the amount and frequency and storage conditions of thrown strawberries trays are asked.

Conclusions and prospects

and afterwards a condition can be set in the modeling tool, where 100% of losses will be attributed to baskets that are totally thrown.

- In this study, consumers' behavior was studied in relation to the percentage of losses. Some scenarios were not tested such as the removal of the strawberries from the fridge a short time before consumption.
A similar analysis can be done at the supermarket level: only a limited range of scenario was explored. A detailed study of supermarket storages behaviors should be done to achieve this goal.
- The estimated percentages of losses (10% for supermarket level, 2-30% for consumer level) recorded for the French population are not enough precise and thus satisfactory. A validation of these losses is still needed. This can be done by weighting the losses generated at the supermarket or at the consumer level for a known product shelf life.
- Concerning environmental impact evaluation, the approach developed in this study can be used to compare other packaging options such as active MAP packaging, bio based packaging with different environmental impact in order to identify the most effective packaging option in reducing simultaneously food losses and the overall environmental impact of the system. It can be also used to identify which environmental impact of the packaging technology could be afforded to significantly decrease the food losses for an equivalent environmental balance of the whole system?

Supplementary materials

Supplementary material 1: Design of the experimental MAP system

The basic modelling tool i.e. the system of Eqs. (27) and (28)(3) of chapter 2.3 was used to design the experimental MAP system. Based on a mass balance of moles of O₂ and CO₂ in the packaging headspace, this model combines gas permeation through the film and fruits' respiration. It predicted as outputs, O₂ and CO₂ molar fractions in percentage as a function of time in the headspace. Required input parameters are summarized in Table 2.3.3, chapter 2.3 with indication of their origin (experimental or literature data) such as information about the geometry (volume, surface of the pack, thickness), the film (permeabilities) and the product (respiration characteristics).

Using as target the recommended gases concentration for better food preservation, this model was used to dimension the system, i.e., pouch's dimensions, knowing all other parameters such as mass of fruit, permeability of the film, respiration characteristics, etc. (Table 2.3.3, chapter 2.3)

For strawberries, it is recommended to achieve an internal atmosphere in the range of 5-10 % for O₂ and 15-20 % for CO₂ to obtain a significant increase of the product shelf life (Cantwell, 2001; Sousa-Gallagher et al., 2013). A non-perforated pouch of LDPE was used to pack about 100 g of strawberries '*Charlotte*'. LDPE was chosen as one of the most permeable, non-micro-perforated, commercial, oil-based material. All other parameters being known; the basic modelling tool was then used to set up the dimensions of the LDPE pouch accordingly to the defined targets. Considering measured values for LDPE permeability of $9.57 \pm 0.43 \times 10^{-16}$ and $47.85 \pm 0.43 \times 10^{-16}$ mol Pa⁻¹ m⁻¹ s⁻¹ respectively for O₂ and CO₂ at 25 °C, it permitted to define that an exchange surface area of 0.04012 m², corresponding to a pouch of dimensions 0.03 × 0.15 × 0.11 m would be suitable to pack 100 g of strawberries and achieve an atmosphere of 5.12 %O₂ and 3.21 %CO₂, the closest possible to the targeted atmosphere. It should be noted that this atmosphere is fully optimal for O₂ but not for CO₂. Indeed, to have a CO₂ concentration that meet the recommended value, we

Supplementary materials

should have had a film with a CO₂ permeability of $0.9 \times 10^{-15} \text{ mol Pa}^{-1} \text{ m}^{-1} \text{ s}^{-1}$ at 25 °C, that means a selectivity i.e. a ratio of P_{CO₂} to P_{O₂} around 1 considering a P_{O₂} value of about $1 \times 10^{-15} \text{ mol Pa}^{-1} \text{ m}^{-1} \text{ s}^{-1}$. This could not be achieved, except by using micro-perforated film, because all oil-based commercial films have a selectivity of 4. However, perforated film need to be manufactured according to a specific packed product and could not be done in the framework of this study. Therefore, in our experiment, by using the proposed designed MAP system, O₂ content would be, at 20 °C, close to the recommended one while the CO₂ concentration would be below.

Once the MAP system was designed, experimental assessment could be set up in order to quantify and model shelf life extension of strawberries.

References

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Sousa-gallagher, M.J., Mahajan, P. V., 2013. Integrative mathematical modelling for MAP design of fresh-produce: Theoretical analysis and experimental validation. Food Control 29, 444–450. <https://doi.org/10.1016/j.foodcont.2012.05.072>

Supplementary material 2: Surveys at the supermarket and Consumer level

2.1 Survey done at the Supermarket level

Strawberries distribution

Hello,

This survey is about the distribution of French strawberries

All the team thank you in advance for any given information:

This questionnaire contains 57 questions

Your profile:

Question 1: Do you work in store?

Please select one of the following answers

- Yes
- No

Question 2: If you don't work in store, in which type of structure related to the distribution sector you work?

Please select one of the following answers

- Centrale purchase
- Warehouse
- Transport company
- Others:

Question 3: What is your current job in store?

Please select one of the following answers

- Director

- Manager of fruit and vegetables department
- Crewman of fruits and vegetables department
- Purchase/Supply
- Storage/Warehouseman
- Other

Please comment your choice here:

.....

Question 4: What is the postal code of your workplace:

Please write the answer here:

Your answer should be between 01000 and 99999. Only an integer can be written.

Question 5: what is your current job in the strawberries distribution?

Please select one answer and write a comment if possible:

- Buyer

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- Transporter
- Warehouseman
- Other:

Please comment your choice here:

.....

Store characteristics:

Question 6: What is the size of your store (in m²)?

Please write the answer here: m²

Question 7: What are the opening and closing hours of the store?

If it opens at 9:30 am, put 9 am

If it closes at 9:30 pm, put 21 pm

Please write the answer here:

Opening time:

Closing time:

Question 8: Can you give us the data about the annual turnover of fruit and vegetables department and/or the strawberries in particular.

Please select one of the following answers

- Yes
- No

Question 9: What is the annual turnover of fruit and vegetables department in your store?

For fruit and vegetables department:

For strawberries only:

Question 10: In your store, strawberry's season is mainly from March till July?

Please select one of the following answers

- Yes
- No

If not, please indicate the period of strawberry's season:

Please write your answer here:

Month of the beginning of the season (from 1 to 12):

Month of the end of the season (from 1 to 12):

Organization of fruit and vegetables department

Question 11: Indicate the number of persons other than you working on:

Put 0 if none of the employees work in this department

Put 1 if 1 person work full time i.e. 35h/week all year long

Put 0.5 if one person works part time on this department (if the person is working on two departments at the same time, 6 months on this department or 15 days per month etc...)

Please write the answer here:

Fruit and vegetables department:

Strawberries:

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Question 12: Is the team working on fruit and vegetables department trained on the specificity of fruit and vegetables usage?

Please select one of these answers and add in the comment the training undertaken

- Yes to fruit and vegetables in general but not to strawberries in particular
- Yes with a special training for strawberries handling
- No
- I don't know

Please add your comment here:

Purchase process

Question 13: How are mainly strawberries purchase organized?

Please choose one or more answer and add a comment if needed:

- You are the one buying the strawberries and the delivery of the goods is done by the supplier
- You use a central purchase and the delivery of the goods is done by the supplier
- You use a central purchase and the delivery pass through a warehouse
- Other

Question 14: Are the following constraints for strawberries purchase respected?

Please choose the appropriate answer for each element:

Yes Maybe No

The timeframe for delivery

The transport conditions (temperature of the lorry, transport duration and prior storage)

Freshness of the strawberries

Question 15: Is there a record book related to strawberries purchase (characteristics and quantities)?

Please select one of these following answers:

- Yes
- No
- I don't know

If yes, do they specify which packaging to use:

- Yes
- No
- I don't know

Question 16: Are the strawberries orders':

Please select one of the following answers and add a comment if possible

- Provided before harvesting
- independently of the harvest
- Other

Please add your comment here:

Question 17: How do you participate yourself to strawberries ordering?

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Please select one of these answers and add a comment if possible

- You fix the content of the order
- You fix the quantity, but you cannot choose the product
- You transmit information regarding stock situation and do not have information on the product nor the quantity ordered
- You do not participate at all to the ordering process
- Other

Please add your comment here:

Question 18: How many times the supplying is done during strawberries season?

Please select one of the following answers and explain why in the comment if possible

- Weekly
- 2 times/Week
- 3 times/Week
- 4 times/Week
- 5 times/Week
- 6 times/Week
- Other

Please add your comment here:

Question 19: Do you have a monitoring the quantity of strawberries ordered?

Please select one of these answers

- Yes
- No

If Yes, indicate the type of tool:

Please write your answer here:

Question 20: During strawberries season, what is the quantity of strawberries usually ordered:

Please write your answer here:

Per order:

Per week:

Per month:

Per day:

Reception process

Question 21: If you pass by a wholesaler, what is the delivery time between the launching of the order and its reception at the store

Please add in the comment any useful comment on that delivery time

Please select one of these answers:

- Less than one day
- 1 day
- Between 1 and 2 days
- More than 2 days
- I don't know

Please add your comment here:

Question 22: If you are directly delivered by the supplier, what is the delivery time between the launching of the order and its reception at the store

Please add in the comment any useful comment on that delivery time

Please select one of these answers:

Supplementary materials

- Less than one day
- 1 day
- Between 1 and 2 days
- More than 2 days
- I don't know

Please add your comment here:

Question 23: If the suppling pass through a logistic platform how is organized the reception of strawberries?

Please select one of these propositions and add a comment if necessary:

- The reception is done only in the platform without your intervention
- The reception is done first at the platform (verification of the product, quantities) then in store (verifying quantities at arrival)
- Other

Please add your comment here: ...

Question 24: Is the employees at the reception of fruit and vegetables trained for identifying any major non-conformity

Please select one of these answers:

- Yes
- No
- I don't know

Question 25: how do you participate yourself at the reception of the order (in the verification process):

Please select one of the following answers:

- You verify the product by yourself

- You delegate the verification of the product to a collaborator

- The verification is done by a team trained and dedicated to fresh product.

Question 26: If you delegate the reception to an employee in your team, is he trained to the identification of fruit and vegetables main non-conformities

Please select one of the following answers:

- Yes
- No
- I don't know

Question 27: How the check-up or control is done on the reception?

Please select one of the following answers and add a comment if possible:

- On all the order
- On a random sample of a pallet ordered
- On a random sample of a cage ordered
- On a random sample of a tray ordered
- I don't know
- Other

Please add your comment here

Question 28: Is there a communication system/ management to treat the non-conformity at the reception to avoid keeping the product on hold

Please select one of the propositions

- Yes
- No
- I don't know

Supplementary materials

If Yes, please indicate the type of the system:

Please write your answer here: ...

Question 29: Are the rejection criteria indicated in a record book?

Please select one of the propositions and add any supplementary information in the comment:

- Yes
- No
- I don't know

Please add your comment here: ...

Question 30: For which reasons, rejections of products occur?

Please selected one or more answer if needed and add a comment:

- Error in the product (inadequate format or type of packaging)
- Error in the quantities
- Error in the quality (freshness, open packaging etc..)
- Other

Question 31: What are the errors related to the quality of the strawberries leading to a rejection of the product?

Please choose one or more answer and leave a comment if needed:

- Open packaging, defective packaging
- Water at the bottom of the packages
- Unripen strawberries
- Over ripen strawberries

- Dehydration
- Spoilage
- Other

Question 32: In case of a defect, what is the minimal thrown quantity?

Please select one of these answers

- The cage
- The pallet
- The order
- Other

Question 33: Do you have a tool to assess the quantity of strawberries rejected (ordered but refused at the reception)

- Yes
- No

If Yes, please indicate the type of tool

Please write your answer here:

If Yes, can you please indicate the quantity of strawberries rejected during strawberries high season?

Per order:

Per week:

Per month:

Per year:

Storage process

Question 34: How much time a new arrival of strawberries stays on the reception before being sent to the storage room?

Please select one of these propositions

- Between 0 and 1 hour

Supplementary materials

- Between 1 and 2 hours
- Between 2 and 3 hours
- Other

Question 35: Concerning the storage, are the strawberries stored in cold chambers?

Please select one of these questions

- Yes
- No

Question 36: Please indicate the strawberries' storage temperature (in °C)

Please write your answer here: °C

Question 37: how much time a new arrival of strawberries is kept in the stock before being sent to store shelves:

Please select one of these answers

- None (the product is directly transported from the lorry to the store shelves)
- Less than one day
- One day or more

If less than one day, please indicate the number of hours possible

Please write your answer here:

If more than one day, indicate the number of hours possible

Please write your answer here:

Question 40: Is there an inventory of strawberries stock done every day at the same hour and scheduled in the agenda

Please select one of these propositions

- Yes
- No

- I don't know

Please add your comment here if needed:

....

Management of store shelves

Process

Question 41: What is the most privileged practice for strawberries

	Number of supplies per day	Quantity of strawberries on the shelves during the high season (April/Mai) (number of trays)	Quantity of strawberries on the shelves during the low season (june/july) (number of trays)
Limited stock on the shelves and regular supply			
Maximal stock on the shelves and less frequent supply			
Other			

Question 42: How often the damaged product are removed from the shelves?

Please select one of the following answers

- 1 time per day
- 2 times per day
- 3 times per day

Supplementary materials

- Other

Question 43: In average, from march till July, what is the temperature of fruit and vegetables shelves?

Please indicate your answer here: °C

Question 44: Are they arrangements planned for fruit and vegetables shelves to better preserve the product?

Please select one of these answers

- Yes
- No

Please describe these arrangements

Please choose one or more of the following suggestions and comment them

- To avoid thermal chocks:
- To avoid dehydration:
- To limit product manipulation:

Question 45: According to your experience, is there a need for new arrangements to preserve fruits and vegetables?

Please indicate your experience in the comment section below (about preservation of fruit and vegetables, difficulties, arrangements needed and why etc...)

Please select one of these answers

- Yes
- No
- I don't know

Please write your comment here:

Question 46: What happens to the unsold products?

Please select one of these answers

- Stored on the shelves
- Thrown
- Put back in the storage room
- Processed and sold in another form (ready to eat fruits salads, freshly cut fruits etc...)
- Other

Please add a comment here:

Question 47: Do you have a tool to assess the lost quantities (Rotten or damaged strawberries, unsold and not possible to keep for the next day)

Please select one of the answers

- Yes
- No

If Yes, indicate the type of tool:

Please write here your answer:

Lost volumes

Question 48: Can you indicate the value of the annual strawberries losses in your store?

- Yes per year
- Yes but for another period
- No

Question 49: Please indicate the periodicity used:

Please choose one of these propositions:

Supplementary materials

- Day
- Week
- Month
- Year (season)

Question 50: what is the values of losses for strawberries?

Please write your answer here

Lost sales revenue (in thousands of euros):

.....

Percentage of losses related to strawberries sales revenue:

Sales:

Process:

Question 51: In average, during how many days strawberries can be found in the store shelves in the high season?

- 7/7
- 6/7
- 5/7
- 4/7
- 3/7
- 2/7
- 1/7

Question 52: Is there a regular monitoring of the sales on the shelves?

Please explain why in the comment

Please select one of these answers

- Yes
- No

If Yes, please indicate the frequency:

Please write your answer here:
(number of times per day)

Question 53: Do you conduct surveys at the consumer level to identify their strawberry's needs?

Please indicate any precision on the surveys conducted (objectives, reasons)

Please select one of these propositions

- Yes, survey about strawberry's quality
- Yes, survey about strawberry's quantity
- Yes, survey about strawberry's quality and quantity
- Yes, but survey related to other aspects of the strawberries
- none

Please write your comment here:

Volumes:

Question 54: What is the quantity of strawberries sold during the season?

	Per day	Per week	Per month
Weight in kg			
Weight in tons			
Number of trays			

Supplementary materials

Number of cages			
Number of pallets			
I don't know			

Question 55: Please classify the different formats of strawberries trays from the most sold to the less sold

Number the boxes according to your preferences from 1 to 4

Please choose at least one element

- 250 g
- 500g
- 1 kg
- Other

If Other, please indicate the weight (in g):
.....

Question 56: How much do you estimate the participation of the strawberries in the sales revenue of the fruit and vegetables department.

Please write your answer here: (in % of sales revenues of Fruit and vegetables)

Question 57: How much do you estimate the margin realized due to strawberries sold during the high season

Please indicate your answer here:
(in % of sales revenues)

Strawberries shelf life and packaging:

Question 58: Do you think that a packaging able to increase strawberries shelf life is useful? Please explain why in the comment

- Yes, of course
- Yes, maybe
- No

Please write your comment here:

Question 59: What is the minimal additional shelf life duration is needed?

Please write your answer here: (in days)

Question 60: Do you think there will be changes in the management of strawberries if a gain of one day in the shelf life is established? Please explain why in the comment

- Yes
- No
- I don't know

2.2 Survey done at the Consumer level

Introductory mail to the questionnaire:

Hello, in the framework of a study on the consumer behavior towards strawberries consumption, we are looking for consumers to answer this questionnaire. This question will take about 15 min. We guaranty the anonymous participation of consumers and the confidentiality of the answers.

The questionnaire is available through the following link:

<http://www.supagro.fr/enquetes20/index.php/152142/lang-fr>

We thank you in advance for your participation.

Full questionnaire in English

Hello, this questionnaire is about strawberries purchase habits. It will take you 15 min to complete it. This survey is completely anonymous.

Thank you for your participation. This questionnaire contains 22 questions.

Your profile:

Question 1: Did you buy strawberries the last couple of months? Yes No

Question 2: What is your gender? Male Female

Question 3: How old are you? Please select one of the following answers

- Between 20 and 34-year-old
- Between 35 and 49-year-old
- Between 50 and 64-year-old
- More than 64-year-old

Question 4: What is your socio professional category? Please select one or more answer

- Farmer
- Retailer/ Artisan/ Company director
- Senior manager/ Intellectual profession
- Intermediate profession
- Employee
- Worker
- Retired person
- Inactive and other person without professional activity
- Student

Strawberries purchase

Question 5: How many times do you buy strawberries during strawberries season?
Please select one or more answer

- Once per week

Supplementary materials

- More than once per week
- Once per month and less
- 2 or 3 times per month

Question 6: What is the usual quantity of strawberries that you buy? Please select one of these answers

- 250 g
- 500 g
- 750 g
- 1kg
- more than one kg

Question 7: Please select your main point of purchase: Please select one of these answers

- At the market
- From the producer
- In specialized store for fruit and vegetables
- In the supermarket
- In the hypermarket
- In mini-market
- Others

Question 8: When you buy strawberries, what do you in order to make your choice:

	Never	Rarely (1 time over/5 or less)	Sometimes (1 time over/3 to 1 time/4)	Often (at least 1/2)	Always	Without answer
I look at the color	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I look at the size	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I smell the strawberries	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I taste one of the strawberries	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I look at the cultivation mode	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I look at the product origin	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I look at the variety	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I look under the tray	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I look at the packaging	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Question 9: How much time do you keep the purchased strawberries at home before eating them? Please select one of these answers

- I eat them directly during the day of purchase
- 1 day
- 2 days

Supplementary materials

- 3 days
- 4 days
- 5 days
- 6 days
- 7 days or more

Strawberries' usage after purchase

Question 10: For each statement, please indicate the corresponding frequency of usage after strawberries' purchase

	Never	Rarely (1 time over/5 or less)	Sometimes (1 time over/3 to 1 time/4)	Often (at least 1/2)	Always	Without answer
At purchase, i verify the absence of rotten strawberries	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I consume the strawberries directly after purchase	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I put the strawberries in the refrigerator vegetables' drawer to preserve them before consumption	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I change strawberries packaging to preserve them	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I remove the outer packaging (plastic film) to preserve the strawberries	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I put the strawberries on the kitchen worktop or in a storage cupboard before consumption	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I freeze the strawberries to preserve them	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I sort the strawberries directly after purchase	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I sort the strawberries before consumption	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
If some of the strawberries are rotten, i discard all the tray of strawberries	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I only discard the rotten strawberries	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I remove the rotten parts of the strawberries and i consume the rest	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I wash the strawberries directly after purchase	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Supplementary materials

I wash the strawberries before consumption	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
At home, i eat the whole strawberry, right after being washed	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
At home, i eat nearly the whole strawberries, after removing the peduncle	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
At home, i eat the strawberries cut into pieces	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
At home, i eat the strawberries in cakes, jams or coulis.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
At home, i eat the strawberries at any time	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
At home, ay eat strawberries for dessert or as an afternoon snack.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Question 11: In your opinion, how much time after the purchase, strawberries will keep the same gustatory qualities?

→ If they are stored at ambient temperature:

Please select one of the following answers

- less than one day
- 1 day
- 2 days
- 3 days
- 4 days
- 5 days
- 6 days
- 7 days or more

Question 12: In your opinion, how much time after the purchase, strawberries will keep the same gustatory qualities?

→ If they are stored in the fridge

Please select one of the following answers

- less than one day
- 1 day
- 2 days
- 3 days
- 4 days
- 5 days
- 6 days
- 7 days or more

Question 13: In your opinion, how long it takes for half of the strawberries to be physically deteriorated (Spoilage development, texture softening)

→ If they are stored in the fridge

Please select one of the following answers

- less than one day
- 1 day
- 2 days

Supplementary materials

- 3 days
- 4 days
- 5 days
- 6 days
- 7 days or more

If Yes, which ones?

.....

Question 14: In your opinion, how long it takes for half of the strawberries to be physically deteriorated (Spoilage development, texture softening)

→ If they are stored at ambient temperature

Please select one of the following answers

- less than one day
- 1 day
- 2 days
- 3 days
- 4 days
- 5 days
- 6 days
- 7 days or more

Question 15: If the storage duration of the strawberries can be increased, will it affect your consumption habits?

- Yes
- No

If Yes, how?

.....

Question 16: Do you know some strawberries varieties?

- Yes
- No

Supplementary materials

Consumer awareness to wastage

assumptions, according to a scale from 1 to

4:

Question 17: Can you give us your degree of agreement for the following

	1. I do not agree at all	2. I rather disagree	3. I neither agree nor disagree	4. I rather agree	5. I absolutely agree
I will be ashamed to throw food in front of someone	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I will be very affected if I see somebody throwing edible food	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Making sure that I manage my grocery shopping in order to waste less is one of my priorities	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
If I forgotten to eat a product and it is already expired, I will feel very guilty	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Within my own circle, wasting food is very badly seen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I have ethical problems concerning food wastes when it comes to hungry people	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I have moral issues toward my family concerning food waste	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Familiarities and expertise

Question 18: Can you give us your degree of agreement for the following assumptions, according to a scale from 1 to 4:

	1. I do not agree at all	2. I rather disagree	3. I neither agree nor disagree	4. I rather agree	5. I absolutely agree	1. I do not agree at all
I know quite much about strawberries	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I know how to pick/choose the strawberries	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I know how to store the strawberries	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I know how to use and cook the strawberries	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Size of the household

Question 19: What is the size of your household?

- 1 person (You)
- 2 persons
- 3 persons
- 4 persons
- more than 4 persons

2.3 Interview devoted to cooperatives in the south of France

Below are listed the questions asked to the cooperatives located in the south of France to get information on the postharvest stages of strawberries as well as storage time and temperature and percentages of losses at each stage.

1. What are the most common postharvest stages by which passes a tray of strawberries? Please indicate the stages between the packing till the arrival to the consumer level
2. What are the quantities of strawberries packed per tray and the materials used to pack them?
3. Please indicate the temperature of storage at each postharvest stage
4. Please indicate the duration of storage at each postharvest stage
5. What are the losses in kilogram or percentage recorded at each stage?

Supplementary material 3: LCA raw values

Tables assembling the raw data of the environmental impacts.

Table 15: Values of all impact categories for Control 1,2 , CMAP, OMAP stored during 1 day (Best situation)

Impact category	Unit	Control 1 : Best case	Control 2 : Best case	CMAP : Best case	OMAP: Best case
Climate change	kg CO ₂ eq	4.35529569	4,60966473	4,30540374	3.688379267
Ozone depletion	kg CFC- 11 eq	6.6809E-06	6,8504E-06	6,613E-06	6.06975E-06
Human toxicity,	CTUh	2.1058E-06	2,2644E-06	2,0836E-06	1.74803E-06
Particulate matter	kg PM2.5 eq	3.7983E-07	0,00268328	0,00252906	0.002222679
Ionizing radiation HH	kBq U235 eq	0.00255562	14,2000883	12,6841497	10.0208203
Photochemical ozone formation	kg NMVOC eq	12.8143593	0,0145785	0,01386028	0.012375073
Acidification	molc H+ eq	2.308E-05	0,0277789	0,02604771	0.0226805
Terrestrial eutrophication	molc N eq	0.01400646	0,05929021	0,05685911	0.051556638
Marine eutrophication	kg N eq	0.02631924	0,00694036	0,00661896	0.005943327
Freshwater ecotoxicity	CTUe	0.05745866	264,063362	240,900579	198.8749473
Land use	kg C deficit	0.00128329	10,9523738	10,560479	9.670354627
Water resource depletion	m3 water eq	0.00668862	0,22058783	0,21877851	0.210108621
Mineral, fossil & ren resource depletion	kg Sb eq	243.392588	0,0010236	0,00099965	0.000934495

Supplementary materials

Table 16: Values of all impact categories for Control 1,2 , CMAP, OMAP stored during 3 day (Worst situation)

Impact category	Unit	Control 1: worst case	Control 2 : Worst case	CMAP: Worst case	OMAP : Worst case
Climate change	kg CO ₂ eq	5.62160083	5,33202276	5,00294069	4.291148902
Ozone depletion	kg CFC- 11 eq	8.4049E-06	7,4723E-06	7,5626E-06	6.59358E-06
Human toxicity	CTUh	2.6683E-06	2,6784E-06	2,3935E-06	2.07729E-06
Particulate matter	kg PM2.5 eq	4.8105E-07	0,00305197	0,0029003	0.002521477
Ionizing radiation HH	kBq U235 eq	0.00322956	17,5609055	14,5046031	12.646947
Photochemical ozone formation	kg NMVOC eq	16.1192014	0,01634081	0,01590396	0.013818518
Acidification	molc H+ eq	2.9034E-05	0,03186413	0,02984389	0.025970135
Terrestrial eutrophication	molc N eq	0.01771654	0,06546631	0,0652414	0.05668781
Marine eutrophication	kg N eq	0.03321079	0,00773754	0,00759287	0.006599053
Freshwater ecotoxicity	CTUe	0.07267582	316,426246	275,741234	240.1885763
Land use	kg C deficit	0.00162696	11,9752225	12,1010438	10.52899606
Water resource depletion	m3 water eq	0.00845665	0,22880533	0,25017088	0.218136973
Mineral, fossil & ren resource depletion	kg Sb eq	306.642143	0,00109324	0,00114322	0.000996716

Summary in French

Summary in French

Contexte et objectives

La réduction des pertes et gaspillages des fruits et légumes frais est un problème urgent à résoudre vu qu'ils représentent environ 40% des pertes et gaspillages à l'échelle mondiale (Gitz et al., 2014). Si le gaspillage, faisant référence à l'élimination volontaire de produits alimentaires encore consommable, est difficile à prévenir ; les pertes quant à elles peuvent être évitées en mettant en place une stratégie adéquate de conservation du produit.

La stratégie actuelle pour réduire les pertes et gaspillages est essentiellement basée sur l'utilisation de la chaîne du froid dont l'impact négatif sur l'environnement est déjà connu. L'emballage sous atmosphère modifiée (EAM) se basant sur la modification des concentrations de gaz, principalement O₂ et CO₂, dans l'espace de tête peut contribuer à la réduction des pertes de fruits et légumes frais en augmentant leur durée de vie, surtout pour les pertes directement liées à un problème de durée de vie, de détérioration et de pertes de la qualité durant le stockage.

La possibilité de prédire le gain de durée de vie en EAM et son effet sur la réduction des pertes peut être un outil puissant pour les acteurs de la chaîne post-récolte. Ce genre de modèle de prédiction est basé sur la compréhension des phénomènes ayant lieu durant les étapes post-récolte en EAM, comme l'effet de la fluctuation de gaz sur la détérioration du produit, l'interaction avec les conditions de stockage, particulièrement la température et le comportement des acteurs dans la chaîne post-récolte. Ces modèles de prédiction seront développés au cours de cette thèse ainsi que le lien entre gain de durée de vie et la réduction des pertes.

De plus, la réduction des pertes est fortement liée à la réduction de l'impact environnemental du système 'produit emballé'. La réduction des pertes suite à l'utilisation de l'EAM peut entraîner une réduction significative de l'impact environnemental, pouvant potentiellement réduire l'utilisation de la chaîne du froid. Ce bénéfice environnemental sera quantifié durant cette thèse.

Dans ce contexte, dans le but de répondre à l'objectif général de développer une approche d'écoconception pour la conservation des fruits et légumes frais dans la chaîne post-récolte, cette thèse est axée sur trois grands aspects :

Summary in French

- Le développement d'un modèle de détérioration intégré dans un outil de modélisation EAM qui permet de décrire et prédire l'effet des gaz sur la détérioration du produit
- La prédiction des pertes chez le consommateur en tenant compte de son comportement (conditions de stockage)
- L'analyse de l'impact environnemental du system EAM via une analyse de cycle de vie (ACV) en prenant le cas d'étude 'fraises de la variété Charlotte' et la quantification du bénéfice environnemental en terme de réduction des pertes.

Une méthode innovante pour le suivi de la durée de vie du produit

Mise en place d'une méthode complète de suivi de la durée de vie en tenant compte de l'acceptabilité du consommateur

Au cours de ce projet, pour aller au-delà de l'état de l'art, une approche robuste de prédiction de la durée de vie des produits frais emballés est d'abord nécessaire.

Au début de ce travail de thèse, très peu d'études portaient sur la prédiction de la durée de vie des produits en EAM. L'analyse scientifique de la littérature a démontré le manque d'une définition claire de la durée de vie et le manque d'une méthode générale et outil de modélisation dans le but de suivre et prédire la durée de vie de produit frais (cf Chapitre 1). Par conséquent, durant cette thèse, la première étape est de définir sur quels critères fondamentaux la durée de vie est basée, et plus particulièrement, la durée de vie des fraises, choisies comme le produit alimentaire modèle dans cette étude. Les indicateurs de qualité identifiés dans la littérature sont nombreux et ont besoin d'être mesurés en même temps pour être représentatifs de la qualité globale. Dans cette étude, il a été considéré que la qualité des fraises et leur durée de vie sont basées essentiellement sur un suivi visuel de leur détérioration globale par différents acteurs de la chaîne post-récolte, surtout les distributeurs et les consommateurs. L'analyse visuelle est faite à travers le matériau plastique d'emballage transparent. Le choix de ce paramètre est appuyé par les résultats du questionnaire d'enquête fait dans le cadre de cette étude où plus de 80% des consommateurs évaluent la qualité des fraises visuellement (voir Chapitre 3).

Summary in French

C'est pourquoi, une méthode basée sur l'évaluation de la surface de détérioration du fruit (en %) a été proposée et développée pour le suivi expérimental de la durée de vie du produit en EAM. Cette détérioration prend en compte le changement de couleur, de texture et le développement de microorganismes comme les moisissures. La construction et la validation de la méthode sont expliquées dans le Chapitre 2.2.

Ce genre de suivi visuel de la qualité basé sur une surface détériorée n'a jamais été réalisé auparavant. Cette méthode s'est montrée plus précise que le suivi du nombre de fruits détériorés habituellement appliqué par Riad et al., 2015, Aday et al., 2013 et Hertog et al., 1999 comme décrite dans le Chapitre 2.2.

La prédiction de la vitesse de détérioration était une première étape, mais pour pouvoir prédire la durée de vie du produit, il était nécessaire aussi de déterminer la détérioration maximale acceptée par le consommateur ' D_{acc} '. Pour prendre cela en compte, une détérioration maximale acceptable par le consommateur a été identifiée en demandant à 30 consommateurs non entraînés s'ils sont prêts à acheter le produit ou pas. Il s'avère que lorsque la surface de détérioration des fraises atteint les 13%, le consommateur ne voulait plus acheter le produit.

L'intersection entre la courbe de détérioration et la détérioration maximale acceptable D_{acc} , a permis, au cours de ce travail, d'identifier la durée de vie du produit dans de multiples conditions de stockage (EAM, sans EAM et des températures variables). Cette approche peut être appliquée à d'autres fruits frais dont la qualité se base sur un suivi visuel. Cette méthode présente un avancement dans le domaine des sciences alimentaires.

Modélisation de la durée de vie du produit en EAM

Mise en équation

Une analyse approfondie de la littérature a montré un manque d'outil de modélisation en EAM capable de prédire la durée de vie du produit en EAM. En général, le transfert de gaz (O_2 et CO_2) dans le système EAM est prédit indépendamment de la qualité intrinsèque du produit emballé. Les modèles de prédiction utilisés pour décrire ces deux phénomènes ont été identifiés.

Summary in French

Dans le cadre de cette thèse, un outil de modélisation d'EAM a été développé combinant la prédiction de gaz dans l'espace de tête du produit emballé et leur impact sur la qualité du produit en fonction du temps.

La principale nouveauté concerne le développement d'un modèle de détérioration du produit basé sur le suivi expérimental de la détérioration du produit comme résumé dans le paragraphe précédent. Nous avons considéré que cette détérioration dépend du niveau de CO₂ dans l'espace de tête et de la température. Cette hypothèse est basée sur des recherches bibliographiques concernant le développement de champignons plus spécifiquement botrytis, limité par des concentrations élevées de CO₂ et est totalement inhibées lorsque le % de CO₂ atteint plus de 30%. Le CO₂ a été considéré comme un élément inhibiteur de la détérioration et aussi comme un modèle de détérioration conçu à l'image des modèles de prédiction microbiologique : modèle primaire qui dépend du temps (fonction logistique) et modèle secondaire (modèle d'inhibition). Le system EAM considéré dans l'approche de modélisation ainsi que toutes les équations utilisées sont résumées dans la Figure 33. Les principales hypothèses et développement sont les suivants :

Le transfert de gaz est décrit par la première loi de Fick pour représenter la perméabilité à travers l'emballage (Eq. (a)). La loi de Michaelis et Menten a été utilisée pour représenter la respiration du produit (Eq. (b)). Le modèle général de couplage des transferts de gaz et de la respiration a été amélioré pour prendre en compte la déviation métabolique du produit (Eq. (c)), qui est proportionnelle au niveau de détérioration prédit par une fonction logistique (Eq. (d)). Les équations différentielles représentant la variation de l'O₂ et le CO₂ dans l'espace de tête sont représentées dans l'(Eq. [A]).

La détermination de la détérioration maximale D_{acc} , acceptée par le consommateur lors de l'achat du produit a permis d'utiliser le modèle de prédiction de la détérioration en assumant que la durée de vie du produit est directement liée au niveau de détérioration jusqu'à une certaine limite (13%) au-dessus de laquelle le produit n'est plus acheté (Eq. [B]).

L'effet de la température est représenté par la loi d'Arrhenius (Eq. (e)) et est pris en compte à travers la perméabilité du film P_{CO_2} ou P_{O_2} , l'intensité respiratoire maximale

Summary in French

R_{O_2max} , la vitesse de détérioration k_D et β_{O_2} ou β_{CO_2} représentant la vitesse de production du CO_2 ou de consommation d' O_2 due à la détérioration.

δ_{CO_2} , représentée dans le modèle de détérioration (Eq. (d)) dépend de la quantité de CO_2 prédite dans le bilan de matière (Eq. [A]). Le couplage des bilans de matières de gaz et de la détérioration du produit se fait à ce niveau.

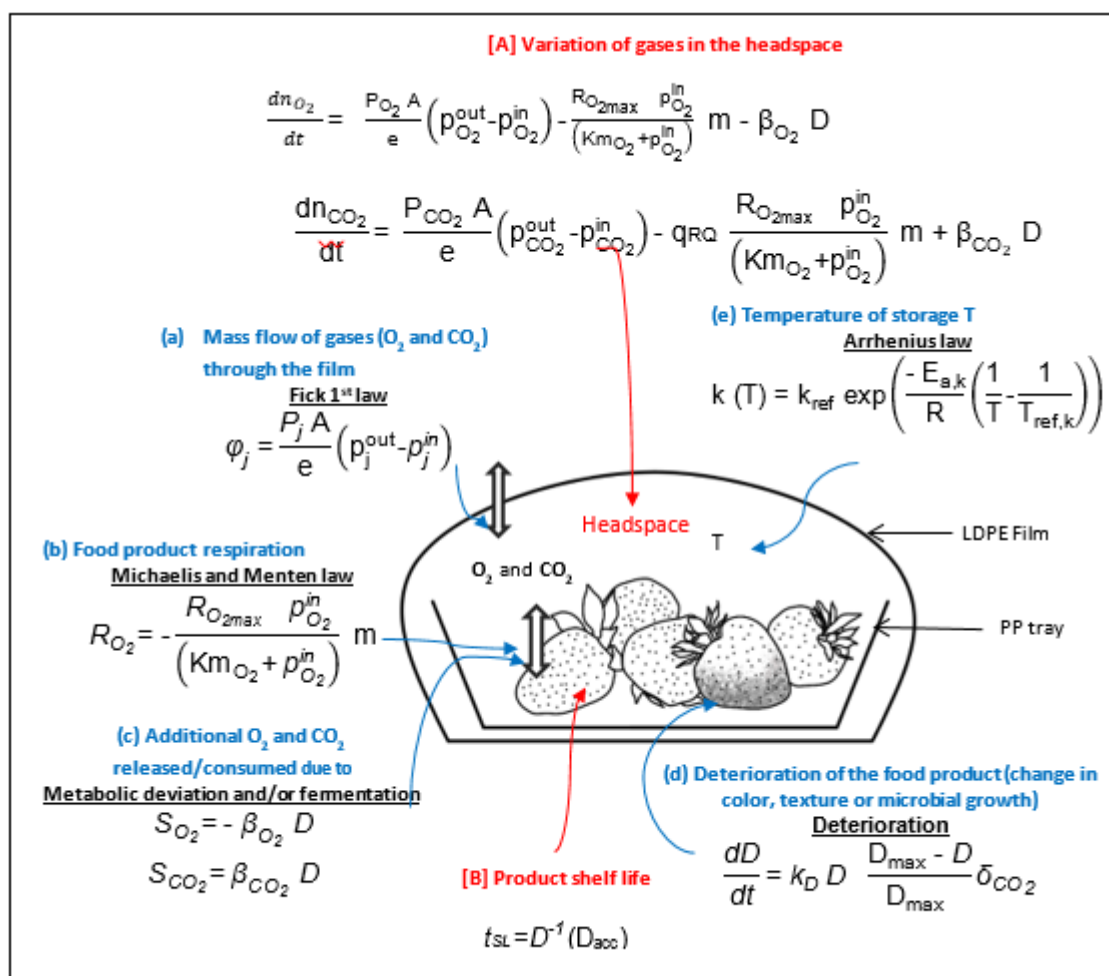


Figure 33: Représentation schématique et équations utilisées pour représenter les transferts de matière et réactions associées (détérioration du produit) dans le système produit emballé (les abréviations sont listées dans la nomenclature du Chapitre 2.2)

Les équations différentielles, concernant le transfert de gaz et la détérioration de produit ont été couplées dans un seul système d'équation capable de prendre en compte l'effet des gaz et l'acceptabilité du consommateur lors de la prédiction de la durée de vie du produit, estimation jamais mesuré avant ce travail de thèse.

Les sorties du modèle sont : la prédiction de l' O_2 et du CO_2 dans l'espace de tête (Eq. [A]), la détérioration du produit (Eq. (d)) et la prédiction de la durée de vie en jours

Summary in French

(Eq. [A]). Un gain de durée de vie en EAM peut alors être estimé en comparant les courbes obtenues en EAM et sans EAM.

Ce modèle a été résolu via MATLAB en utilisant le solveur ode15s capable de faire une simulation en moins de 2 minutes. 30 paramètres d'entrée sont nécessaires parmi lesquels, 18 décrivent les phénomènes de transferts de matière, 6 paramètres liés à la détérioration et 6 pour la géométrie et les conditions initiales du système.

Validation du modèle sur les fraises 'Charlotte' conservée en EAM

La validation du modèle est faite en 2 temps. D'abord, le transfert de gaz et l'évolution de la détérioration ont été suivis en isotherme à 5, 10 et 20°C et ensuite en utilisant un profil de température reproduisant des conditions réalistes de stockage dans la chaîne post-récolte. 'Charlotte' était la variété de fraises utilisée (Chapitre 2.3).

100g de fraises ont été emballées en utilisant du PEBD (Polyéthylène basse densité) peut être amélioré et optimisé. Le PEBD, avec une surface de 0.04 m² et une épaisseur de 50 µm, avait la perméabilité optimale à l'oxygène capable d'atteindre la concentration optimale en O₂ dans l'espace de tête du produit emballé (dans ce cas, 5%O₂ – 15%CO₂ conseillés pour les fraises). En effet, la mise en place du MAP a été faite en choisissant un film commercialisé, facilement disponible. Le PEBD avait les perméabilités à l'O₂ les plus adéquates. Cependant, la concentration en CO₂ conseillée (15% CO₂), un autre gaz essentiel pour l'inhibition de microorganismes dans l'espace de tête, n'a pas été atteinte en utilisant le PEBD à cause de sa perméabilité très élevée au CO₂.

Au total, 130 barquettes de fraises ont été utilisées pour valider le modèle.

Le modèle était capable de prédire la variation de gaz dans l'espace de tête et l'évolution de la détérioration du produit en %. Les hypothèses et paramètres utilisés pour représenter le modèle ont donc été validés. Dans les conditions de temps et températures utilisés, Un gain de durée de vie de 0.33 jours en EAM a été identifié comparé à l'utilisation de l'emballage macro-perforé (voir Chapitre 2.3).

Potentiels utilisations de l'outil de prédiction développé

Une fois validé, le modèle peut être utilisé pour des explorations numériques pour différentes conditions de stockage (EAM et conditions de températures).

Summary in French

Les conditions expérimentales utilisées pour valider le modèle, ne permettaient pas d'obtenir un EAM entièrement optimisé en termes de composition de gaz à l'équilibre. De plus, les conditions de températures n'ont pas été optimisées non plus. Un bénéfice largement plus grand est attendu en termes de gain de durée de vie du produit en appliquant les conditions optimales de stockage.

Pour appuyer ceci, le modèle est capable de prédire, en changeant la température de stockage chez le consommateur (5°C au lieu de 20°C), une durée de vie de 1.68 jours au lieu de 0.33 jours (Chapitre 2.3 Figure 21).

Le modèle peut aussi être utilisé pour explorer le bénéfice du changement du matériau d'emballage, par exemple en considérant un emballage avec des perméabilités idéales P à l' O_2 et au CO_2 . Dans ce cas-là, des calculs préliminaires ont montré que pour emballer 100g de fraises dans un emballage d'une surface de 0.04 m^2 , les perméabilités idéales seront $PO_2 = 4.02e^{-15} \text{ mol/m.s.Pa}$ and $PCO_2 = 4.23e^{-15} \text{ mol/m.s.Pa}$. La Figure 34 représente pour un certain profil de température (Figure 34(a)), les courbes de détériorations obtenues en emballage macro-perforé (Figure 34 (b), courbe grise), en EAM commercial en utilisant le PEBD (Figure 34 (b), courbe noire) et EAM optimisé avec les perméabilités de film idéal (Figure 34 (b), courbe noire pointillée)

L'intersection entre la détérioration maximale acceptable et les courbes de détérioration montre qu'un gain de durée de vie égale à 0.88 jours est estimé en utilisant l'EAM optimisé, ce qui multiplie par 2.6 la durée de vie estimée en utilisant l'EAM commerciale qui est égale à 0.33 jours.

Donc, l'EAM se révèle comme une technologie prometteuse d'emballage qui permet d'augmenter considérablement la durée de vie du produit lorsqu'un film de perméabilités optimal à l'oxygène et au dioxyde de carbone est utilisé. Pour atteindre des gains de durées de vie encore plus grande, le couple temps température peut être optimisé. Par exemple, si nous changeons uniquement les conditions de stockage chez le consommateur de 20°C à 5°C, la durée de vie estimée augmentera de 1.68 jours en EAM commercial à 2.76 jours en EAM optimisé (ce qui représente une augmentation de 1.6) (figure non représentée).

Summary in French

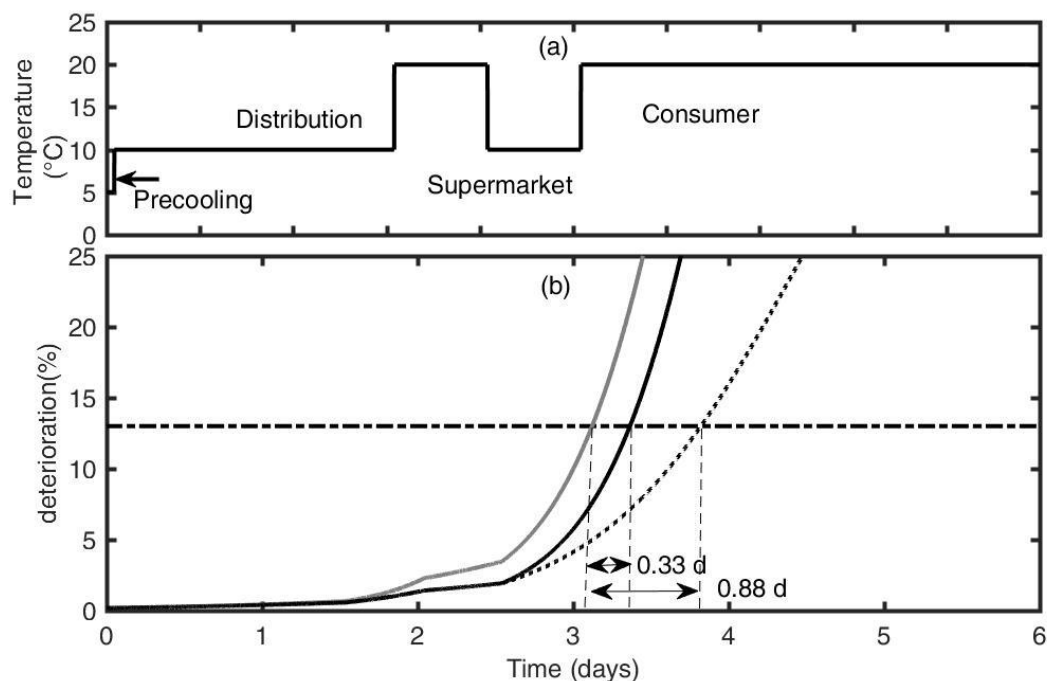


Figure 34: Estimation du gain de durée de vie pour un profil de température donné (a), en utilisant les courbes sans EAM (courbe grise), avec l'EAM non optimisé (courbe noire), avec l'EAM optimisé (courbe noire pointillée) et leur intersection avec la détérioration maximale acceptée (-.-.).

Cependant, pour pouvoir appliquer ce modèle à d'autres fruits ou produits, quelques paramètres doivent être adaptés. Par exemple, durant cette thèse, l'outil de modélisation a été testé sur des fraises 'Sonata' cultivée en Norvège. La superposition des valeurs expérimentales de détérioration et des courbes de prédiction de la détérioration ont montré que le modèle a besoin d'être adapté au nouveau produit. En effet, la variation majeure était la détérioration initiale D_{ini} , qui affecte la courbe de prédiction de la détérioration et donc l'estimation de la durée de vie. Par conséquent, pour une application réussie à d'autres produits, la détérioration initiale est un paramètre qui doit être réestimé. Ceci coûtera en temps et en argent.

Des paramètres complémentaires sont nécessaires comme la composition optimale de gaz, les caractéristiques respiratoires du produit qui sont en partie disponible dans la littérature comme par exemple les compositions de gaz optimales. Par exemple, Kader et al (1988), ont identifié et rassemblé les compositions de gaz optimales pour un grand nombre de fruits et légumes (Zagory and Kader, 1988). Cependant, concernant les intensités respiratoires, les données sont éparpillées dans la littérature. Pour cela, une base de données '@web' (<http://pfl.grignon.inra.fr/atWeb/>) a été initiée dans le but de rassembler ces données et pour ensuite être utilisées comme données

d'entrée au modèle de prédiction en EAM. Pendant cette thèse, j'ai aussi contribué à augmenter cette base de données en rassemblant des données portant sur l'intensité respiratoire et les conditions optimales de stockage des fruits et légumes trouvées dans la littérature.

Lien entre la détérioration du produit et le pourcentage de perte chez le consommateur

Le modèle de prédiction de la durée de vie développé et validé avec succès, a été ensuite lié à une prédiction de la réduction des pertes et gaspillages de fraises en EAM. Dans cette approche, il a été considéré que les pertes sont directement proportionnelles au niveau de détérioration prédit par le modèle développé. C'est pourquoi, le travail effectué durant cette thèse porte sur les pertes (volontaires) chez le consommateur qui sont directement liées à la durée de vie du produit (Figure 35). La première étape, pour pouvoir lier la détérioration du produit aux pertes et gaspillages, est l'obtention de valeurs fiables de ces pertes aux différentes étapes de la chaîne post-récolte.

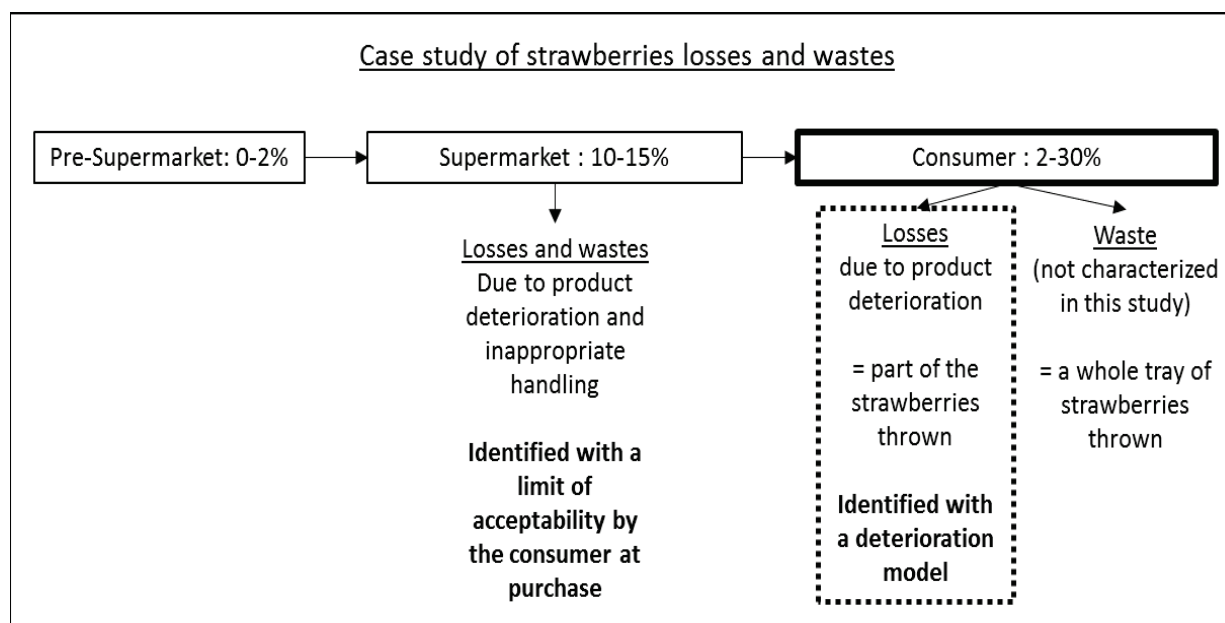


Figure 35: Pertes et gaspillages dans la chaîne post-récolte des fraises. La zone pointillée représente la section des pertes au niveau de la chaîne post-récolte qui sera quantifiée dans cette étude.

Un mapping des pertes dans la chaîne post-récolte des fraises

Malgré la forte sensibilisation que réclament les consommateurs envers les pertes et gaspillages en France, la marge des pertes identifiée à ce niveau est entre 2 et 30%. Sans doute des différences existent entre les comportements des consommateurs et ce qu'ils réclament de faire. À noter aussi que la définition de cette marge des pertes (2-30%) prise comme référence dans cette étude n'est pas claire (Figure 35). En d'autres termes, on ne sait pas exactement ce que ces pourcentages de perte représentent. C'est une piste intéressante de recherche à creuser et qui contribuera à valider ces pourcentages de perte ou permettra de mesurer plus précisément les pertes liées au comportement du consommateur et contribuera à couvrir un plus grand nombre de scénarii. Entre temps, l'approche développée dans ce modèle pourra être utilisée en testant d'autres pourcentages de perte.

Une avancée dans la prédiction des pertes chez le consommateur

L'étude bibliographique a montré l'absence de modèles mathématiques capable de lier la qualité du produit en EAM à un pourcentage de perte, tout en considérant les comportements des acteurs de la chaîne post-récolte comme les distributeurs et les consommateurs. Dans cette étude, nous avons décidé de nous focaliser sur l'étape consommateur vu la disponibilité des données concernant cette étape contrairement aux autres étapes de la chaîne (comme les centrales d'achat, les distributeurs). L'enquête consommateur réalisée au cours de cette étude a permis d'obtenir des données exploitables alors que l'enquête distributeur a été moins réussie.

Dans ce travail, nous proposons de lier le modèle de détérioration développée (Chapitre 2) à un pourcentage de perte au niveau du consommateur. Ceci est possible en émettant une hypothèse considérant que l'intégrale de la courbe de détérioration est proportionnelle à un pourcentage de pertes chez le consommateur. À noter que ce modèle est capable de quantifier les pertes liées exclusivement à la qualité du produit c.à.d. la détérioration du produit (Figure 35). Chez le consommateur, la détérioration maximale acceptable de 13% n'est plus valide car elle représente le comportement du consommateur à l'achat du produit en grande surface. Il a été considéré que lorsque les fraises emballées sont achetées, le consommateur élimine les parties abimées et consomme le reste.

Summary in French

Dans le but de prédire la réduction des pertes chez le consommateur dans les conditions les plus réalistes, des scénarii typiques de chaînes post-récolte ont été examinés. Pour reconstruire ces scénarii c.à.d. identifier les températures, durée de stockage et % de perte à chaque étape de la chaîne post-récolte en France, des enquêtes ont été envoyées à 89 distributeurs et 846 consommateurs (collaboration avec UMR MOISA). La marge des pertes identifiée au niveau du consommateur (2-30%) est très incertaine et sera utilisée comme directive c.à.d. comme point de calibration pour la mise en place du lien entre la détérioration et les pertes générées.

Des informations obtenues par enquêtes chez le consommateur et les distributeurs, 132 scénarios de chaînes post-récolte ont été construits. Ils considèrent la diversité des comportements des distributeurs et consommateurs c.à.d. les températures de stockage (ambiante ou au frais), durée de stockage (1 ou 3 jours). L'exploration de ces scénarii et leurs probabilité d'occurrences dans la chaîne post-récolte a montré que, dans les conditions actuelles de stockage, en France, le pourcentage de perte enregistré chez le consommateur en utilisant l'emballage macro perforé est de 9.21%. Ces pertes correspondent aux produits consommés et dont une partie est jetée. Les produits entièrement jetés, car ils ont été oubliés dans le réfrigérateur, ne sont pas considérés dans cette approche. À cause de l'incertitude, au niveau de la marge des pertes identifié (2-30%) à l'étape consommateur, le pourcentage de perte estimé (9.21%) doit être interprété avec précaution et seulement utilisé à titre d'exemple.

L'EAM est une alternative à l'utilisation de l'emballage macro perforé. La simulation du stockage en EAM tout au long de la chaîne post-récolte en considérant les comportements du consommateur, c.à.d. 21.4 % des consommateurs qui gardent l'emballage jusqu'à la consommation alors que les autres enlèvent l'emballage engendre une perte du bénéfice de l'EAM chez le consommateur. Et 42.8 % des consommateurs qui gardent le produit au frigo, réduit le pourcentage de perte de 17.8%. De plus, si on réussit à convaincre tous les consommateurs de garder l'emballage à température ambiante de stockage, nous pouvons espérer une réduction des pertes allant jusqu'à 40% des pertes initiales en emballage macro perforé.

Ainsi, la méthodologie développée basée, sur le lien entre qualité du produit et pertes correspondantes, a été capable de quantifier les pertes liées à la qualité du produit

chez le consommateur et d'estimer aussi l'impact du comportement du consommateur sur le changement de la qualité et sa répercussion sur les pertes.

Challenges restant pour la quantification des pertes dans la chaîne post-récolte

L'approche développée chez le consommateur liant les pertes à la détérioration du produit doit aussi être développée au niveau des autres étapes de la chaîne. Par exemple, l'étape distributeur est intéressante à étudier, vu qu'elle concentre le second plus haut pourcentage de pertes (10%) après l'étape consommateur (30%). De plus, à l'étape distributeur, les pertes sont concentrées à un seul endroit et sont plus facile à contrôler que l'étape consommateur. Pour attribuer des pourcentages de pertes et gaspillages à l'étape distributeur, nous pouvons utiliser comme limite la détérioration maximale acceptable ($D_{acc} = 13\%$) identifiée au cours de cette thèse. Lorsque le produit dépasse les 13% de détérioration c.à.d. quand plus de 13% de la surface de fraises sont détériorés, le consommateur n'achètera plus le produit et il sera entièrement jetée et donc gaspillée. Dans notre cas, parmi les 24 scénarios identifiés au niveau du distributeur, seuls 2 scénarii mènent au gaspillage des fraises en emballage macro perforé et 1 scénario en EAM. Si 2/24 scénarii correspondent aux pertes maximales à l'étape distributeur, c.à.d. 10%, nous pouvons considérer qu'en utilisant l'EAM, on peut réduire ces pertes d'un facteur de 2 (2/24 à 1/24). Ainsi, les pertes et gaspillages au niveau du distributeur quand l'EAM est utilisé est égale à 10%. Cependant, plus de scénarii à l'étape distributeur doivent être explorés pour mieux identifier la réduction des pertes à cette étape. Cela mérite de faire l'objet de prochaines études.

L'enquête consommateur a montré que 79% des consommateurs enlèvent l'emballage juste après l'achat du produit car ils pensent qu'il est meilleur pour le stockage des fraises. Ceci n'est pas le cas lorsque l'EAM est appliqué car dans ce cas, l'emballage doit être garder pour s'assurer que l'atmosphère optimale autour du produit jusqu'à la consommation. Une des difficultés de l'application de l'EAM est le changement du comportement du consommateur, de leurs habitudes de stockage. Actuellement, les consommateurs ne semblent pas conscients de l'importance de garder l'emballage. Une campagne de sensibilisation du public doit être effectuée avant d'utiliser l'EAM dans la chaîne post-récolte.

De plus, l'utilisation de l'EAM en complément de la chaîne du froid peut générer des coûts additionnels impactant le coût de production. Dans ce cas, l'EAM doit être rentable au niveau de la réduction des pertes et gaspillages. Dans le cas contraire, le distributeur ne sera pas intéressé pour investir dans cette technologie. On ne sait toujours pas quel minimum de réduction des pourcentages de pertes en EAM doit être atteint pour être rentable pour le distributeur.

Enfin, l'impact environnemental de l'EAM doit être aussi pris en compte. L'EAM sera préférablement comparé à la chaîne du froid mais son bénéfice reste à quantifier. En effet, le froid utilisé dans les industries, les transports réfrigérés et les distributeurs représentent à eux seuls 40% des émissions de CO₂ et hydrofluorocarbones liés à l'utilisation de réfrigérants (Joassard, 2017). Ainsi, même si le stockage à basse température est plus intéressant au niveau de la réduction des pertes, son impact environnemental est plus élevé. Pour optimiser l'utilisation de l'EAM, un bon compromis doit être trouvé entre l'impact environnemental de l'emballage utilisé et la quantité des pertes et gaspillages réduite par l'emballage.

Malgré les multiples hypothèses, la méthode présentée au cours de cette thèse a aidé dans la compréhension du lien entre l'EAM et la réduction des pertes chez le consommateur.

L'impact environnemental de l'EAM dans la chaîne post-récolte

Un focus sur l'impact environnemental de l'EAM chez le consommateur

L'analyse bibliographique a montré que les études de l'impact environnementales de la chaîne post-récolte des fruits et légumes frais se concentraient uniquement sur les étapes allant de la production jusqu'à l'étape distributeur sans considérer l'étape consommateur et sans tenir compte entièrement du rôle de l'emballage c.à.d. son impact sur la réduction des pertes. L'emballage utilisé tout au long de la chaîne post-récolte a un impact environnemental négatif due à sa production et la gestion de sa fin de vie mais il aide aussi à conserver la qualité du produit emballé entraînant une réduction des pertes, qui se traduit par un bénéfice environnemental indirect. L'impact

Summary in French

de cette réduction des pertes n'a pas encore été considéré en analyse de cycle de vie (ACV) jusqu'à présent.

Pour ce faire, l'impact environnemental des fraises sous EAM ou emballé en emballage macro-perforé a été évalué en appliquant une ACV. Cette ACV prendra en compte les chaînes post-récoltes allant de la récolte jusqu'au consommateur en considérant les pertes générées tout au long de la chaîne et l'emballage : sa production, sa fin de vie et son effet sur la réduction des pertes. Le bénéfice du MAP sur la réduction des pertes sera considéré chez le consommateur uniquement, car c'est au niveau de cette étape que le lien entre la qualité du produit et les pertes a été établi dans le cadre de cette étude.

L'objectif de l'ACV était de mesurer chez le consommateur, l'impact environnemental de l'EAM (commercial et optimisé) comparé à l'emballage macro-perforé en analysant les variations de pertes engendrées par les différents emballages. Un 'EAM commercial' faisant référence à l'EAM mis au point dans le Chapitre 2.3 (perméabilité idéale pour l'O₂ en utilisant un film commercialisé) et 'EAM Optimisé' faisant référence à l'emballage avec des perméabilités idéales pour l'O₂ et le CO₂. Les technologies EAM seront testées à température ambiante et comparées à l'emballage macro-perforé mis au frigo et à température ambiante. Il a été considéré que l'emballage macro perforé, l'EAM commercial et l'EAM optimisé ayant le même impact environnemental pour leur production et fin de vie. Le pourcentage de pertes dû à l'emballage est la seule variation entre les trois technologies d'emballages étudiées.

Il en résulte que chez le consommateur, pas de différence significative entre l'impact environnemental de l'EAM commercial utilisé à température ambiante et l'emballage macro perforé conservé à température ambiante ou dans le frigo. Donc, même si le froid permet de réduire significativement les pertes en emballage macro perforé, le bénéfice environnemental est masqué par le coût environnemental de l'utilisation de la chaîne du froid. Dans le cas de l'EAM commercial, le bénéfice sur la réduction des pertes était très faible pour avoir un impact significatif sur la balance environnementale. Cependant, l'EAM Optimisé utilisé à température ambiante, s'est avéré être une solution prometteuse capable de réduire de 20% l'impact environnemental comparé à l'emballage macro perforé conservé au frigo. Ce bénéfice

est plutôt lié à la réduction de l'utilisation de la chaîne du froid qu'à la réduction des pertes qui est au contraire plus élevée dans le cas de l'EAM Optimisé à température ambiante que l'emballage macro perforé conservé au frigo.

Le faible bénéfice environnemental obtenu en EAM commercial peut être lié au fait que la réduction des pertes a été uniquement mesurée chez le consommateur répondant partiellement à l'objectif global étant celui de mesurer l'impact environnemental de toute la chaîne post-récolte. Pour continuer cette approche, l'impact environnemental de l'EAM au niveau de toutes les étapes de la chaîne post-récolte doit être pris en compte en considérant la réduction des pertes à chaque étape.

Etapes de la chaîne post-récolte à explorer

En plus de l'étape consommateur, l'impact de l'EAM peut aussi être considéré à l'étape distributeur. Comme proposé dans le paragraphe précédent, on peut supposer que l'EAM divise par 2 les pertes à l'étape distributeur.

En appliquant cette hypothèse sur le pire scénario étudié dans le Chapitre 3, c.à.d. une durée de stockage de 3 jours chez le consommateur, l'impact environnemental de l'EAM en considérant les pertes au niveau des 2 étapes consommateur et distributeur peut être évalué.

La Figure 36 représente l'impact environnemental obtenu à température ambiante en utilisant l'emballage macro perforé (histogramme noir), l'EAM commercial considérant son impact sur les pertes chez le consommateur (histogramme noir hachuré) et l'EAM commercial en considérant son impact sur les pertes au niveau du distributeur et du consommateur en même temps (histogramme bleu hachuré).

Les résultats montrent qu'en considérant le bénéfice de l'EAM au niveau des 2 étapes distributeur et consommateur, l'impact environnemental est réduit de 10% comparé dans le cas où l'impact de l'EAM est uniquement considéré à l'étape consommateur. De plus, 20% de réduction sont enregistrés pour l'EAM lorsque son bénéfice est pris en compte chez le distributeur et le consommateur comparé à l'emballage macro perforé (histogramme noir). Donc, considérant l'effet de l'EAM au niveau des 2 étapes distributeur et consommateur, même si cet emballage n'est pas totalement optimisé pour le CO₂, peut être suffisant pour enregistrer une amélioration de l'impact environnemental comparé à l'emballage macro perforé.

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Cette rapide analyse a besoin d'être confirmée par des tests complémentaires sur d'autres scénarii, mais elle permet de mettre en valeur la nécessité de considérer l'impact environnemental de l'EAM sur la réduction des pertes à toutes les étapes de la chaîne post-récolte pour mesurer de façon plus précise l'impact de l'EAM.

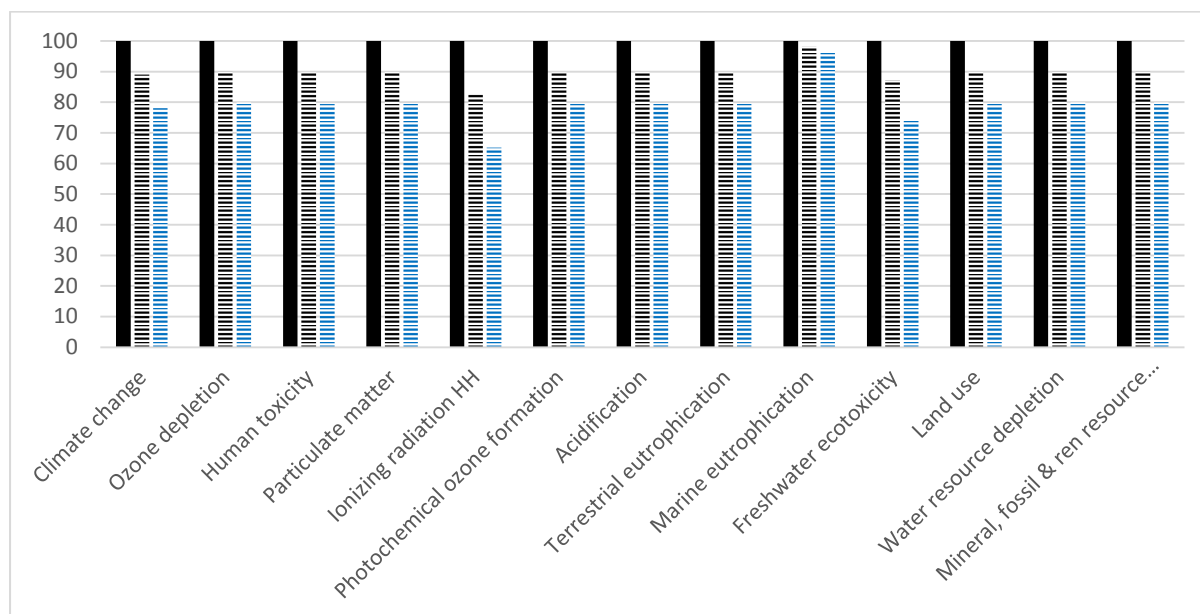


Figure 36: Impact environnemental de la chaîne post-récolte en utilisant l'emballage macro perforé (histogramme noir), l'EAM non optimisé pris en compte au niveau du consommateur (histogramme noir hachuré) et l'EAM non optimisé pris en compte au niveau du supermarché et du consommateur en même temps (histogramme bleu hachuré).

Conclusion

L'analyse bibliographique au cours de cette thèse a mis en évidence le manque de méthode de quantification de la durée de vie des produits en EAM et l'absence de représentation claire du lien entre la durée de vie du produit et les pertes correspondantes. De plus, à ce jour, aucune étude n'a pris en compte l'impact environnemental de la réduction des pertes et gaspillages.

Au cours de cette étude, une nouvelle méthodologie a été développée capable de suivre la détérioration du produit en fonction du temps. Les fraises étaient le fruit modèle de l'étude.

Les multiples expérimentations qui ont été réalisées, nous ont permis de développer un modèle de prédiction de la détérioration du produit qui dépend de la composition de gaz autour du produit et de la température. L'intersection entre la courbe de

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détérioration et la détérioration maximale acceptable détermine la durée de vie du produit.

Pour aller plus loin dans l'approche, un lien quantitatif entre la détérioration du produit et le pourcentage de perte a été construit à l'étape consommateur. Cette approche quantitative a été utilisée pour estimer la réduction des pertes dans la chaîne post-récolte des fraises en EAM comparée à l'emballage macro perforé en considérant le comportement du consommateur français. Les résultats démontrent qu'une réduction de 40% des pertes si le produit est emballé en EAM et si tous les consommateurs gardent l'emballage jusqu'à la consommation.

Finalement, l'impact environnemental de l'utilisation de l'EAM Commercial et l'EAM Optimisé à température ambiante a été comparé à l'utilisation de l'emballage macro perforé à température ambiante et au frigo. Cette comparaison inclut l'impact environnemental des pertes chez le consommateur pour chaque emballage utilisé. Il s'avère que l'EAM Optimisé, conservé à température ambiante, est capable de réduire de 20% l'impact environnemental comparé à l'emballage macro perforé, conservé au froid.

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