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Postharvest Biology and Technology 177 (2021) 111521

Contents lists available at ScienceDirect

Postharvest Biology and Technology

journal homepage: www.elsevier.com/locate/postharvbio

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ARTICLE INFO

Keywords:
Packaging
Equilibrium modified atmosphere
Food losses
Life cycle assessment
Environmental impact

ABSTRACT

Life cycle assessment (LCA) was used to address the environmental benefit of using Equilibrium Modified Atmosphere Packaging (EMAP) at ambient temperature as an alternative to the use of conventional macro perforated packaging (MPP) and refrigeration in the strawberries' farm to fork system. In this purpose, the environmental impact of strawberries' storage conditions at household in macro perforated packaging put in ambient or cold condition were compared with that of EMAP used at ambient temperature. LCA was applied from production till consumer level taking into account food losses at each step as well as packaging production, disposal and usage benefit, if any, i.e. food losses reduction. Our findings confirmed that for highly perishable product, the production step is the main driver of environmental impacts. As such, the technology of preservation that permits to minimize losses leads to the lowest environmental impact in spite of its direct impacts. For short storage at household, well optimized EMAP system is a valuable alternative to MPP for both low and ambient temperatures while for long storage duration (3d), EMAP at ambient temperature could not substitute for MPP at refrigeration temperature. Finally, sensitivity analysis of results to the food losses parameters at both supermarket and household has revealed that conclusions regarding the best packaging strategy are highly sensitive to these parameters. The main conclusions of this study are that (i) EMAP could be, in several conditions, a valuable option compared to standard packaging strategies, (ii) it is needed to inform consumers on packaging functions in order to preserve EMAP benefit until consumption and (iii) better knowledge of food losses among the supply chain is needed to assess environmental impacts more precisely.

1. Introduction

High perishability of fresh fruit and vegetable requires in general the intensive use of refrigeration for their distribution all long the post-harvest chain. At global level, 15 % of the electricity consumed is used for refrigeration (Coulomb, 2008). The power used for refrigeration equipment comes principally from combustion of fossil resources contributing greatly to environmental burdens as ozone depletion and climate change (James and James, 2010; Maykot et al., 2004). In addition to refrigeration, plastic packaging, commonly used to protect fresh products generates important end-of-life issues such as detrimental persistence of plastic particles in our environment that our societies have failed to solve up to now (Geyer et al., 2017). Although packaging and cold chain maintain the quality of fresh fruit and vegetables, it is thus particularly relevant to optimize the use of these two technologies as "their just necessary" in order to achieve the lowest impact while maximizing their usage benefits, e.g. food waste and losses reduction. However, in spite of extensive use of these technologies of preservation, the amount of fresh fruit and vegetables losses and wastes are still very high reaching 40 % - 46 % of the total food losses and wastes (Caldeira et al., 2019; Gitz et al., 2014). The production and management of these losses and wastes create an additional environmental burden (Scherhaufer et al., 2018). The global carbon footprint of food wastes, has been estimated at 3.3 Gigatonnes of CO_2 equivalent in 2007 (FAO, 2014).

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https://doi.org/10.1016/j.postharvbio.2021.111521
Received 18 November 2020; Received in revised form 19 February 2021; Accepted 26 February 2021
Available online 18 March 2021
0925-5214/

Faced with this situation, over the last 10 years, scientists have put tremendous efforts in developing sustainable solutions for fresh fruit and vegetables farm to fork systems. Identified as a key lever for action (Angellier-coussy et al., 2013; Wikström et al., 2019, 2016), packaging is gaining more and more attention with notably some efforts to reinforce its positive role in food preservation in order to decrease the environmental burden of the material production and after-use disposal. Equilibrium Modified Atmosphere Packaging (EMAP) was identified as a promising solution able to maintain quality, increase shelf life and reduce food losses and wastes (Guillard et al., 2018; Mangaraj et al., 2009; Verghese et al., 2015). This technology is based on modifying the gases composition surrounding the 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 O_2 and CO_2) permeation through the film (Guillaume et al., 2010; Mangaraj et al., 2009) and does not require any gas injection at the packaging step. 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 limit product respiration rate, prevent fermentation and senescence and in consequence increase product shelf life (Guillaume et al., 2010; Kader et al., 1989; Oliveira et al., 2015). In spite of evidence of interest of EMAP for preserving fresh produce, this technology is rarely used in the postharvest chain except for some dedicated application (e.g. fresh cut salads for instance). Producers may be reluctant to use a technology where benefit is not clearly quantified in terms of shelf life gain and losses reduction. In this purpose, a recent study has quantified the benefit of using EMAP on the reduction of fresh strawberry losses at household (Matar et al., 2020, 2018). Results showed that a reduction up to 40 % of the losses may be possible when EMAP is established in the postharvest chain and appropriately used by all consumers at home. However, the environmental benefit of such food losses reductions due to EMAP still remained to be characterized in comparison of conventional recommended storages conditions based on the use of cold chain and macro-perforated packaging (no EMAP established).

Life Cycle Assessment (LCA) appears very useful to perform a complete analysis of the environmental impact of the food/packaging couple. However, most of LCA analysis have been focused on packaging only excluding the product inside the package (Abejón et al., 2020; Levi et al., 2011; Molina-Besch et al., 2018; Singh et al., 2006; Williams and Wikström, 2011). Indeed, common practice is to focus on packaging's direct impact such as for example in the recent LCA study comparing eco-efficiency of different bio-based packaging (Changwichan, 2018) focusing on production and end-of-life options, without paying attention to its indirect environmental impact. Packaging's indirect environmental impact is the usage benefit that packaging has on the food product's life cycle and on the resulting reduction of food waste and losses (Guillard et al., 2018). Over the last 10 years, some groups of authors called for the indirect environmental impact of packaging to be included in LCA analysis (Wikström and Williams, 2010; Williams and Wikström, 2011). Williams and Wikström (2011) first tried to consider the impact of the packaging on losses reduction. They linked the change of the total environmental impact to the achieved reduction of food losses and applied their model on 5 food items but, due to lack of data between nature of the packaging and losses reduction, they stayed on a theoretical basis. However, they demonstrated that the packaging that reduces food waste can be an important tool to reduce the total environmental impact, even if there is an increase in impact from the packaging itself. Since this first attempt, several works have been made to include food waste in food/packaging LCAs (Conte et al., 2015; Dilkes-Hoffman et al., 2018; Mario et al., 2017). However, it remains unclear in these studies to what extent the authors consider the interrelationship between food chain and packaging chain and the usage benefit of packaging for the reduction of food losses (Molina-Besch et al., 2018). For instance, Dilkes-Hoffman et al. (2018) used arbitrary values such as 6 % of beef waste reduction thanks to barrier packaging without considering specific numerical relationship that described how increased shelf life could be translated into reduced food wastage.

As an attempt to contribute towards further understanding of environmental impacts of packaging indirect impact, the objective of this study is to measure the environmental benefit of using EMAP in the postharvest chain of strawberries in comparison with conventional practices that rely mainly on refrigeration and microperforated film. This work focuses principally on the usage benefit that an optimized EMAP solution could have for packed strawberries at household, considering consumers' common storage practices for this highly perishable product for which EMAP could significantly improve the shelf life (Matar et al., 2018). To the best of our knowledge, it is the first full environmental assessment of a fruit farm to fork system that will try to decipher the environmental impact of packaging, cold chain and food losses and the balance between the three. This paper does not address any technical, economic or social considerations related to the implementation of EMAP. Indeed, although important, they are outside the scope of this study. To do such analysis, a typical long-circuit distribution scenario was chosen for the packed strawberries (Matar et al., 2018). For each step from production till consumer level, refrigeration (temperature and duration), type of packaging and losses generated were calculated using previously validated mathematical model (Matar et al., 2020, 2018). The current farm to fork system was used as a reference scenario for the LCA (macro perforated packaging with no modified atmosphere). Two different EMAP modalities were modelled: a standard, commercial EMAP ($EMAP_{STD}$) achieved using a commercial packaging film and an optimized EMAP ($EMAP_{OPT}$) obtained using an optimized, non-commercial, film packaging, in order to quantify the maximal benefit that could be achieved for the food chain. Eight environmental assessments were done considering the different packaging solutions, storage conditions and duration at household.

The paper is structured as follows: Section 2 presents the LCA methodology so as the characteristics of packaging strategies assessed in this study; Section 3 presents and discuss the main results and Section 4 provides the main conclusions of this work.

2. Materials and methods

2.1. Functional unit, system boundaries and scenarios

The functional unit was defined as 1 kg of strawberries eaten by the consumer from farm to fork, i.e. including the whole supply chain and consumer stage. In this paper, all operations until the supermarket gate are defined as parts of the supply chain. Consumer stage includes transportation between supermarket and household and storage at household (Fig. 1). Eight scenarios are assessed according to three packaging possibilities and storage conditions at household stage (duration and temperature). Two storage durations at household were considered corresponding to main consumer habits after purchase as previously determined (Matar et al., 2020): the best (1 d storage) and the worst (3 d storage) situation. For each situation, 4 scenarios were investigated varying temperature (5 or 25 °C) and type of packaging (MPP, $EMAP_{STD}$ and $EMAP_{OPT}$ for microperforated, standard EMAP and optimized EMAP respectively). Therefore, two different conventional storage conditions, named '$MPP_{25\,°C}$' and '$MPP_{5\,°C}$' for storage in Macro Perforated Packaging (MPP) at ambient (25 °C) and low (5 °C) temperature respectively were investigated and 2 EMAP: '$EMAP_{STD,\,25\,°C}$' and '$EMAP_{OPT,\,25\,°C}$' both stored at ambient temperature. The environmental impacts of $EMAP_{STD}$ and $EMAP_{OPT}$ at temperature of 5 °C were not evaluated here, given that the purpose of this study was to evaluate to what extend EMAP strategies can substitute the use of cold chain to ensure strawberry preservation.

The standard EMAP ($EMAP_{STD}$) represents the EMAP created using a commercial available film (LDPE (low density polyethylene) pouch used

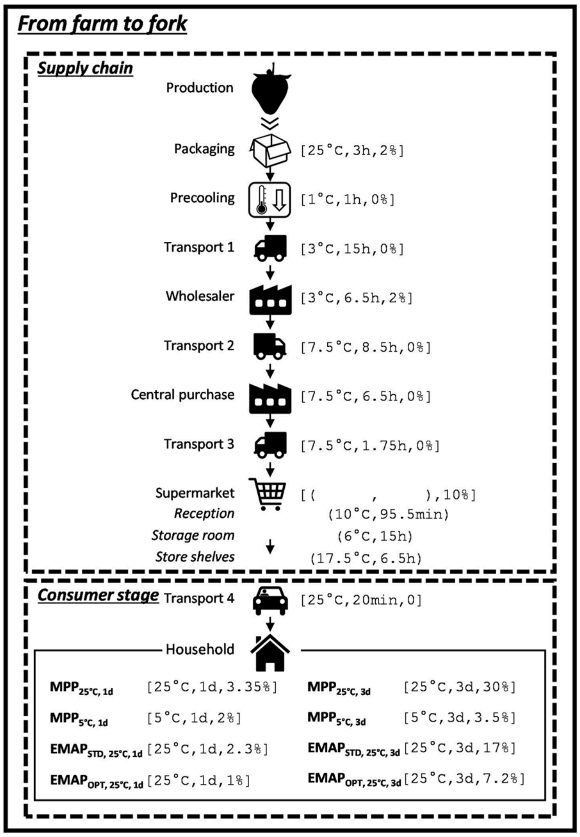

Fig. 1. Flow chart of the system. For each stage the temperature (°C), duration (min: minute, h: hour, d: day) and percentages of strawberries' losses (%) calculated in the present work are recorded. For household stage, the 8 scenarios studied are also detailed (4 for the best (1 d) situation and 4 for the worst (3 d) situation).

in previous work (Matar et al., 2018). This packaging makes it possible to decrease O_2 concentrations in headspace, but not to increase enough CO_2 concentration at its optimal value which equals to 15 % for strawberries (Sousa-Gallagher and Mahajan, 2013). This material has the suitable O_2 permeability to achieve the target concentration of 5 % O_2 in headspace but not the right CO_2 permeability. $EMAP_{STD}$ is thus a sub-optimal EMAP. The optimized EMAP, $EMAP_{OPT}$, is a theoretical EMAP system in which both optimal O_2 and CO_2 concentration in headspace would be achieved. This $EMAP_{OPT}$ has been dimensioned with the EMAP modelling tool developed in Matar et al. (2018). Even if this $EMAP_{OPT}$ could not be applied in practice because of lack of suitable commercial film, it is the theoretical system that would permit, in theory, to achieve the highest food losses reduction. It was thus considered as the optimal situation. It must be highlighted at this stage that EMAP does not require any additional gas flushing during the packaging step. Therefore, packaging machine and related inputs (e.g. electricity consumption, etc) are the same between conventional packaging (MPP) and standardized and optimized EMAP systems.

For each of the eight scenarios of Fig. 1, the percentage of losses was calculated using the modelling tool of Matar et al. (2020). This model represents the evolution of product quality based on a multi-criteria degradation assessment in EMAP conditions. Three phenomena are considered: change of colour, texture softening and microorganism development. The percentage of deteriorated fruit surface evaluated by visual inspection depends on the storage temperature and on headspace CO_2 concentration and is modelled using a logistic equation (Eq. 1). When EMAP is used, intended effect is a slowing down of strawberry respiration through O2 limitation and related texture softening and colour change, and limitation of microorganism growth (principally *Botrytis cinerea*) through CO_2 increase.

$$\frac{dD}{dt} = k_D(T)D\left(1 - \frac{D}{D_{max}}\right)\delta_{CO2} \tag{1}$$

where D is the percentage of surface deterioration (%) at time t (s), D_{max} is the maximum percentage of deterioration (%), $k_D(T)$ represents the deterioration rate constant (s^{-1}) which is dependent on temperature T and δ_{CO2} a dimensionless weighting parameter representing the inhibiting effect of carbon dioxide on the deterioration rate. Eq. (1) allows to calculate the % of damaged products as a function of time, temperature but also packaging condition, through headspace concentration effect, δ_{CO2} (Matar et al., 2018).

At each time, strawberry instantaneous losses were assumed to be related to the deterioration of the fruit, through a linear relationship. Consequently, the % of losses, i.e. the cumulated losses, were linearly dependent on the integral of the predicted deterioration, from Eq. 1, i.e. the area under the deterioration curve (Fig. 2). This % of losses was calculated as follows:

$$l_s^p = a\int_{t=i}^{t=j} D_s^p(t)\, dt + b \tag{2}$$

where p is the type of the packaging, s the scenario tested, l_s^p is the percentage of losses of the scenario s using the packaging p (%), i and j representing the time at which the studied postharvest stage begins and ends respectively (day). a and b (dimensionless) are the estimated parameters of the linear function.

2.2. Life cycle inventory

The modelling of the process chain has been done from information collected in Matar et al. (2020). For the background data, ecoinvent 3.5 cut off system model has been used. A brief summary of data origin is presented hereafter.

2.2.1. Strawberries supply chain

Strawberries were considered grown open-field in Spain, and sold in the South of France, to mimic the case where strawberries are grown far away from the wholesaler location which is a sub-optimal, long circuit of distribution for the environmental assessment. A typical supply chain for strawberries was constructed based on interviews done with French wholesalers and based on literature reviews as described elsewhere (Matar et al., 2020) (Fig. 1). Mean temperatures and mean storage durations were chosen to represent a standard storage scenario in the pre-supermarket stages. Percentages of losses for the pre-supermarket stage come from questionnaires (Matar et al., 2020) and has been validated by comparison with literature data on the topics (Gitz et al., 2014; Gustavsson and Stage, 2011a).

2.2.1.1. Strawberries production. Spanish strawberries production in macro tunnel from ecoinvent database were used for this study ("Strawberry {ES}| strawberry production, open field, macro tunnel"). This cultivation considers all environmental impacts related to agricultural operations, fertilizers and pesticides production and use and machines used for soil inversion and irrigation too.

2.2.1.2. Packaging process. 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 and PE granulate is considered as well as the formation of the tray through moulding process and film production by extrusion. PE and PET waste management is considered in this LCA. Table A1 (Supplementary material) presents the weight of PE and PET used for one functional unit. In this study, we assume that both control (1 and 2) and EMAP (1 and 2) scenarios are made of trays and films with the same environmental impact.

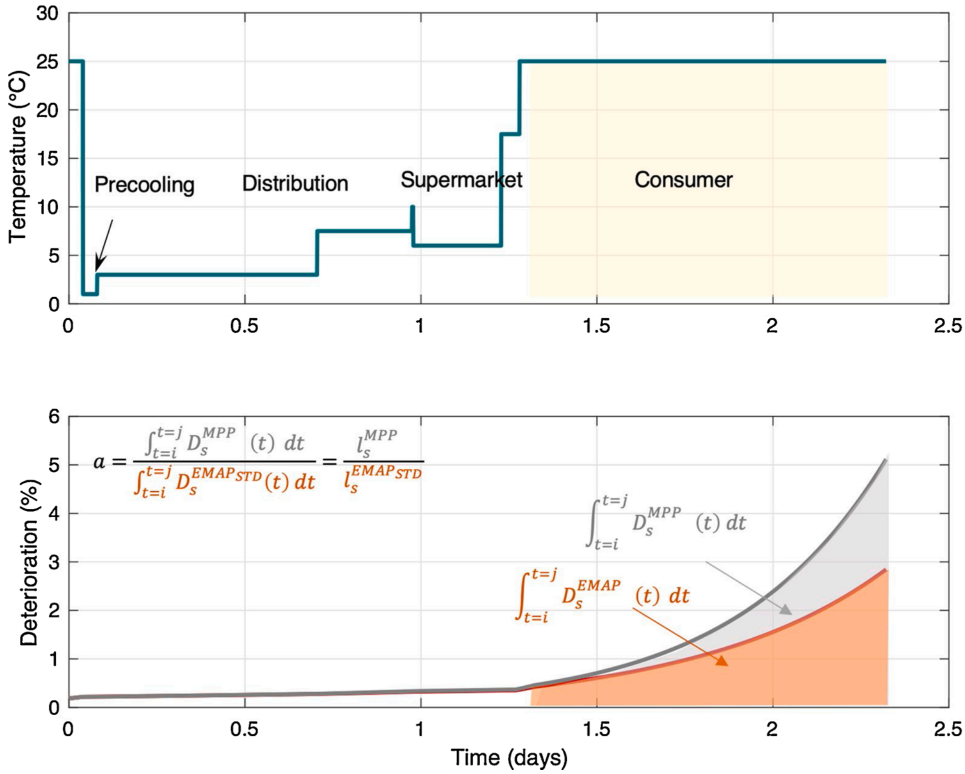

Fig. 2. Principle of the prediction of the % of strawberry losses at household level based on estimation of the % of deterioration. Example given for the two different scenarios at household EMAP $_{\mathrm{STD},\ 25\ °C,\ 1\ d}$ and MPP$_{25\ °C,\ 1\ d}$.

The sealing machine used to seal the PE film have a conveyer surface of 8375 cm^2. One tray of strawberries occupies 200 cm^2. 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 min (MPBS Industries, 2018). Thus, in one hour, 180 cycles are done sealing 7380 trays. Thus, power consumed to seal 1 kg of strawberries is equal to 0.00854 kW h 5h^{-1} (Table A1 – Supplementary material). The environmental impact related to the construction of the sealing machine itself and storage containers were not taken into account in this study.

2.2.1.3. Supermarket stage. Data from the questionnaire of Matar et al. (2020) were used to describe the typical circuit of strawberries at the supermarket with durations and temperatures of storage, the locations of losses, and estimate them if any. The results showed that supermarket stage is divided in three main sub-stages: the reception, storage room and store shelves. 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 min to 3 h. Next, the product is stored at low temperature in the storage room (6 °C) for a duration on average of 15 h. Finally, in the market stall or shelves, products are stored at an average temperature of 17.5 °C for 6.5 h, considering a mix of supermarkets with refrigerated shelves and non-refrigerated shelves. Information about the percentages of losses and wastes at the distributor stage was never communicated by the interviewees even if it was explicitly demanded, probably because of confidentiality of this data. Distributors clearly did not want to disclose such sensitive information. Therefore, the percentage of losses for strawberries recorded by ADEME (2016) equals to 10 % is used for the whole supermarket stage, without assignations to sub-stages. Technical flows considered for the supermarket stage are presented in Table A1 (Supplementary material). The environmental impact of supermarket building is not taken into account in this study.

2.2.1.4. Cold chain and electricity consumption. The energy consumption was estimated using a tool provided by Intelligence Energy Europe (ICE-E) (Evans, 2013). This simulation tool was developed to identify the energy-saving potential of cold store equipment and technologies on the basis of datasets from 294 cold stores, mostly from EU countries. Each dataset included the temperature of the store, the area and volume of the store, food throughput and energy usage per year.

2.2.1.4.1. Precooling, wholesalers, central purchase and supermarket (reception and storage substeps). The refrigerated chambers at the precooling, wholesalers, central purchase and supermarket (reception and storage room) are considered the same and the infrastructure of the ecoinvent dataset “Cold room based on: Operation, reefer, cooling {GLO}| 40-foot, high-cube, R134a as refrigerant” is used (Ecoinvent, 2016). Energy used for strawberries storages have been determined as follows. The maximal capacity of the chamber (67.4 m^3), its dimensions (12 × 2.35 × 2.39 m) and its temperature (6 °C) is estimated in order to calculate the energy needed to refrigerate the goods. It is assumed that only strawberries are stored in the chamber, with a loading of approximately 50 % to keep transits around the palettes to respect storage standards (Krishnakumar, 2017). Each tray containing 0.5 kg of strawberries is assumed to have a volume of 2000 cm^3 (10 × 20 × 10 cm), corresponding to a theoretical maximal load of 7,5 t of strawberries in the chamber. A volume allocation was performed to ascribe the corresponding energy consumption to the volume necessary to store the functional unit of strawberries, considering both the real volume occupied by the trays and the loading rate of 50 %.

2.2.1.4.2. Supermarket shelves. The electricity consumptions other than for refrigeration at supermarket level are determined as follows. A relation linking the energy use with the store surface (Tassou et al., 2011), and an average supermarket surface of 5 329 m^2 (Leclerc, 2017), provides the average electricity consumption of a supermarket (545 kW h m^{-2} y^{-1}, with 71 % of the whole electricity consumption used for activities other than cold production). From this value, considering that the half of the store is occupied by the product shelves and a tray of strawberries containing 0.5 kg occupy 200 cm^2, a consumption of 0.016 kW h per kilogram of strawberries is found.

2.2.2. Consumer stage

2.2.2.1. Strawberries losses at household. A survey conducted on a panelist of 846 consumers has permitted to pinpoint the role of post-purchase habits (Matar et al., 2020). Strawberries are generally stored between 1 and 3 d before consumption (1 d: 61 %, 2 d: 24.5 %, 3 d: 12.5 %). So, we define the two storage periods for the scenarios from these lower and upper limits. 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, recommended behaviour by the CTIFL (the French technological institute for fruit and vegetables) (Christy and Catherine, 2017). Therefore, these two conditions were kept as minimum and maximum of temperature at this stage.

A range of 2–30 % of losses at household was considered based on previous work (Matar et al., 2020). Thorough cross-checking of scientific literature has revealed that the lower value of 2 % of losses at the consumer level is coherent with the value generally admitted as the inedible fraction of fresh fruit which would vary from 2 to 6 %, depending on the reference (De Laurentiis et al., 2018). The upper limit of 30 % is coming from the following references: on average 29 % of the mass of fresh fruit or vegetables (FFVs) purchased by households in the EU28 in 2010 was wasted (De Laurentiis et al., 2018), 15–30 % of FFVs purchases by mass are discarded by consumers according to (Gustavsson and Stage, 2011b). In this work, the 2–30 % range for strawberry losses at household were assumed to be only damaged strawberries thrown by the consumer (pieces or whole strawberry) in the consumption timeframe of 1–3 d; 2 % would be the best-case scenario with only unavoidable losses corresponding to inedible component and 30 % would be the worst-case scenario, i.e. one third of the product is discarded due to unsuitable quality (e.g. apparent spoilage, softening, browning, etc.).

To evaluate losses for the different scenario studied at household, Eq. 2 needs first calibrated. In this purpose, the maximal and minimal losses were attributed to the smallest and the biggest values of the deterioration integral for the standard storage condition: i.e. 2 % for $\int_{t=i}^{t=i+1\ d} D^{MPP}_{5\ ^{\circ}C}(t)\, dt$ and 30 % for $\int_{t=i}^{t=i+3\ d} D^{MPP}_{25\ ^{\circ}C}(t)\, dt$. The a and b values are thus determined equal to 3.53×10^{-04} and 1.10 respectively and others scenario losses were determined by interpolation with Eq. (2).

2.2.2.2. Consumers' fridge. At household, when a refrigeration is performed (Fig. 1), a mean electricity consumption value of 354 kW h per year is used (Biglia et al., 2017) and this value is allocated to strawberries as detailed below (see 2.2.6). Household stage inventory is detailed in Table A1 (Supplementary material).

2.2.3. Transports from farm to fork

Among the supply chain, refrigerated lorry was considered for transport 1, 2 and 3. The lorry with a refrigeration machine for cooling products were taken from ecoinvent ("Transport, freight, lorry with refrigeration machine, cooling {GLO}| market for | Cut-off, S"). Transportation hours identified during surveys were converted in kilometres driven assuming a speed of 67.4 km h^{-1} (CNR, 2015) (Table A1 – Supplementary material).

At consumer step (transport 4), we considered a 20 min' drive in a passenger car taken from ecoinvent ("Transport, passenger car {RER}| market for | Cut-off, S"), assuming a speed of 67.4 km h^{-1} (CNR, 2015).

2.2.4. Waste management from farm to fork

Wastes corresponding to strawberry losses at the different stages from farm to fork are managed according to current practices for non-recycled municipal solid waste in France (incineration 46 %, landfill 31 % and composting 23 % (Commissariat général au développement durable, 2009)).

Packaging waste are managed according to French situation (recycling 23 %, landfill 34 % and incineration 43 % (PlasticsEurope, 2018)).

2.2.5. Allocations

For multioutput steps, the environmental burdens are split up according to economic allocations. This approach is applied for the transport by car from the supermarket to the household stage (Transport 4). In France, the cost of one kilogram of strawberries is estimated equal to 7.20 euros, when the average cost of a supermarket basket is 135 euros (FranceAgriMer, 2018; Martinez et al., 2017; Verdier, 2015). Consequently, 5.3 % of the transport impact are allocated to strawberries. Fridge used at household stage must also be allocated to its content. The French national institute of statistics and economic studies (Insee) showed that 47 % of supermarket purchase (63.45 euros) are fresh product stored in the fridge (Larochette and Sanchez-gonzalez, 2015). The allocation factor for strawberries at this step is therefore 11.3 %.

2.3. Impact assessment method

Environmental impacts were assessed with the Environmental Footprint method version 2.0 implemented in Simapro software (v9.0.0.48). This method has been selected as recommended by the European union for product environmental footprint (Fazio et al., 2018). The impact categories considered were: acidification terrestrial and freshwater, cancer human health effects, climate change, ecotoxicity freshwater, eutrophication marine and freshwater, eutrophication terrestrial, ionizing radiation (human health), land use, non-cancer human health effects, ozone depletion, photochemical ozone formation, resource use – energy carrier, resources use – mineral and metals, respiratory inorganics and water scarcity.

2.4. Uncertainty analysis

A Monte-Carlo approach was used to assess uncertainties on data and food losses parameter from farm to fork. Environmental impacts of the scenarios were calculated 1000 times. For each run, a random value of each parameter, within a define range, is considered. Considered stages of the farm to fork system and values for the food losses are reported in Table 1. Distributions are considered uniform for this parameter. Pairwise comparisons were performed. It allows us to determine for each comparison the percentage of occurrence for which one scenario best perform compared to the other.

First uncertainty analysis was performed considering EMAP benefit at consumer's level only. A similar efficiency was assumed for all EMAP technologies and benchmark at the supermarket level, i.e. 10 % of food losses, based on a report from (ADEME, 2016). Range of uncertainties for the inputs parameters considered (duration, temperature and losses) are given in Table 1.

Second uncertainty analysis was performed on the combination of consumer and distribution steps: i.e. benefit of EMAP to reduce food loss at household was combined with benefit at supermarket level. It was not possible to precisely determine the impact of EMAP on strawberry loss reduction at supermarket level following questionnaires and interviews of distributors made by Matar et al. (2020). Indeed, distributors did not want to disclose such sensitive and /or confidential information. Therefore, hypothesis was made to investigate loss reduction impact at supermarket level obtained thanks to EMAP from 10.5 (slight increase of loss) to 5% (best hypothetical reduction achieved), everything else being equal (duration and temperature steps at the supermarket). These impacts of loss variation at supermarket step was compared with MPP strategies, for which this parameter remains unchanged (10 % losses). In this uncertainty analysis, codification and name of scenario remained unchanged, subscript always refer to storage duration and temperature at the consumers' level.

Table 1
Min and max values of temperature, duration and losses for each of the postharvest chain parameters investigated in the present study. All data come from Matar et al. (2020) except uncertainty on the losses estimation at household (about 10 %) according to the results of FUSION EU project (Stenmarck et al., 2016).

Steps		Duration	Temperature	Losses	Min losses	Max losses
Supply chain	Packaging	1–5 (h)	20−30	2 %	1 %	2 %
	Precooling	1 – 3 (h)	0−2	–	–	–
	Transport 1	14 -16 (h)	2−4	–	–	–
	Wholesaler	1−12 (h)	2−4	2 %	1 %	2 %
	Transport 2	5 – 12(h)	7−8	–	–	–
	Central purchase	1 – 12 (h)	7−8	0 %	0 %	1 %
	Transport 3	0.5 – 3 (h)	7−8	–	–	–
	Supermarket	5 min – 3 h. (reception) 6 – 24 h (storage) 1 – 12 h (shelves)	2−20 (reception) 2−10 (storage) 10−25 (shelves)	10 %	n.d.	n.d.
Consumer step	Transport 4	0.5 – 2 h	20			
	MPP $_{25\ ^\circ C,\ 1\ d}$	1 d	25	3.35 %	3 %	3.7 %
	MPP $_{5\ ^\circ C,\ 1\ d}$	1 d	5	2 %	1.8 %	2.2 %
	EMAP $_{STD,\ 25\ ^\circ C, 1\ d}$	1 d	25	2.3 %	2 %	2.5 %
	EMAP $_{OPT,\ 25\ ^\circ C,\ 1\ d}$	1 d	25	1 %	0.9 %	1.1 %
	MPP $_{25\ ^\circ C,\ 3\ d}$	3 d	35	30 %	27 %	33 %
	MPP $_{5\ ^\circ C,\ 3\ d}$	3 d	5	3.5 %	3 %	4 %
	EMAP $_{STD,\ 25\ ^\circ C,\ 3\ d}$	3 d	25	17 %	15 %	19 %
	EMAP $_{OPT,\ 25\ ^\circ C,\ 3\ d}$	3 d	25	7.2 %	6.5 %	8 %

3. Results and discussions

3.1. Contribution of the different supply chain stages on environmental impacts

First, we analyse the share of environmental impacts between the consumer step and the supply chain. Our finding indicates that environmental impacts are dominated by the supply chain (Table A2 – Supplementary material). Impacts at consumer step are dominated by transportation between supermarket and household, more than 90 % of the environmental impact of this step for most impact categories for all scenarios (results not shown). Relative contribution analysis of processing steps on the overall environmental impacts of the strawberry farm to fork system is presented in Fig. 3. As expected strawberry production was the main contributor (range from 11 to 97 % of impact share for ionizing radiation and water scarcity respectively) as it was commonly observed for many farm to fork systems (Frankowska et al., 2019; Girgenti et al., 2014; Svanes and Johnsen, 2019). Transports was the second main contributor (range from 1 to 71 % of the impact for water scarcity and photochemical ozone formation respectively). Direct impacts of packaging was limited and range from almost 0 % for ozone depletion to 19 % eutrophication freshwater and resource depletion and confirm previous finding (Frankowska et al., 2019; Svanes and Johnsen, 2019) This finding fully justified the simplification made that considers that conventional packaging and new EMAP materials have same direct impacts. Contribution of electricity in post-harvest stages, mainly used for cooling operations, was very low: less than 2 % except for ionizing radiations (51 %) and resource use, energy carriers (9 %). Relative contribution of main pre-consumer's steps (production site, wholesaler, central purchase and supermarket) on the overall environmental impacts of the strawberry farm to fork system confirm this finding, i.e. strawberry production was the most impacting step (Supplementary material Figure A1). Wholesaler stage was the second main contributor (range from 2 to 65 % of the impact for water scarcity and ionizing radiation respectively). This was mainly due to the refrigerated transportation from production to wholesaler. Our results show that for strawberry farm to fork system, which environmental impacts are driven by food production itself, indirect impact of packaging strategy, i.e.

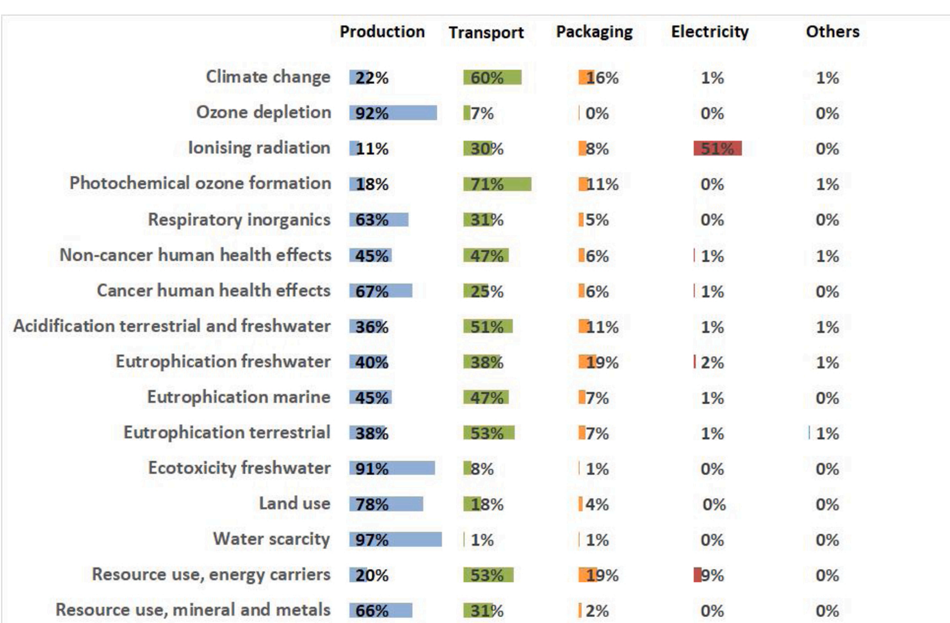

Fig. 3. Contribution analysis of 1 kg of strawberry at the gate of the supermarket. Consumer step is excluded of this analysis. Contributions of strawberry production, transport all along the postharvest chain, packaging used to pack strawberries, electricity used in the postharvest chain are highlighted (electricity used for strawberry production is included in "Production"). Other contributors (mainly other inputs needed for waste treatment processes) are gathered in the last "Others" contributor. Raw data could be downloaded at: https://doi.org/10.5281/zenodo.3938995.

efficiency to prevent food loss, could overpass its direct impacts which are limited. It is thus of primary importance to include this indirect effect in the environmental impact assessment and promote packaging strategies that enhance product shelf lives. Several authors in the literature have drawn similar conclusions (Silvenius et al., 2014; Wikström et al., 2014).

3.2. Comparison between conventional and EMAP solutions

3.2.1. Short-storage duration at consumer stage

Environmental impact assessment of short-storage scenario of 1 day is provided in Fig. 4. Results show that conventional storage conditions, MPP at 5 °C or 25 °C, and modified atmosphere conditions, $EMAP_{STD,25\ °C,1\ d}$ and $EMAP_{OPT,25\ °C,1\ d}$, have similar environmental impacts. $MPP_{5\ °C,1\ d}$ differs from the three other scenarios by the use of refrigeration. For the three remaining scenarios, household storage at ambient temperature is assumed and the quantity of strawberry losses generated ranged between 1 % for $EMAP_{OPT,25\ °C,1\ d}$ to 3.35 % for $MPP_{25\ °C,1\ d}$ respectively. The losses generated during this day at household were very low whatever the packaging and storage conditions and, as expected, barely affect results of the environmental assessment for the 16 mid-points indicators considered ($MPP_{25\ °C,1\ d}$ being the reference for all comparisons). The additional day of cold chain for $MPP_{5\ °C,1\ d}$ did not hamper the overall environmental impact of the food chain except for ionizing radiation due to the French electricity mix, dominated by nuclear power (70.2 % of production share in 2016), considered in this assessment. However, although the differences are small, pairwise comparisons from the uncertainty analysis, indicates a significant benefit of EMAP packaging strategies compared to the conventional $MPP_{25\ °C,1\ d}$ packaging (Supplementary material Figure A2, a) and b)). When comparing impacts of $EMAP_{OPT,25\ °C,1\ d}$ to $MPP_{5\ °C,1\ d}$, we obtain similar results (Figure A2, c)). For these three comparisons, our results show an interest of using EMAP instead of conventional packaging strategies to reduce losses and thus associated environmental impacts. Moreover, EMAP's performance shows that this strategy is relevant for freeing the consumer from the cold chain, thus making it possible to reduce environmental impacts associated with cold production. However, this conclusion is only valid if the packaging is used by the consumer in an optimal way that guarantees the integrity of its protective functions. Matar et al. (2020) demonstrated that a majority (79 %) of French consumers removed the packaging just after purchase, systematically or at least every other time, annihilating its protecting function. This underlines the lack of awareness of consumer regarding packaging function (Williams et al., 2012). Therefore, it becomes important that packaging design enables the consumer to be provided with comprehensive information about the conditions of conservation before use and packaging functions to ensure its real benefits (Wikström et al., 2019; Williams et al., 2020).

For the $EMAP_{STD,25\ °C,1\ d}$, results are more contrasted (Supplementary material Figure A2, d)). Therefore, it is not easy to determine which strategy best perform ($EMAP_{STD}$ or cold chain). This result was explained by similar effectiveness of both strategies and their effect on food losses at consumer stage which partially overlaps (2–2.5 % for $EMAP_{STD,25\ °C,1\ d}$ and 1.8–2.2 % for $MPP_{5\ °C,1\ d}$).

3.2.2. Long-storage duration at consumer stage

Environmental impact assessment of long-storage scenario of 3 d at consumer step is provided in Fig. 5. Angellier-coussy et al. (2013b), Guillard et al. (2018) and Verghese et al. (2015) identified EMAP packaging as a promising option to reduce food losses of fruit and vegetables. Our results show significant lower environmental impacts for modified atmosphere conditions ($EMAP_{STD,25\ °C,3\ d}$ and $EMAP_{OPT,25\ °C,3\ d}$) compared to $MPP_{25\ °C,3\ d}$, whatever the impact category considered (Supplementary material Figure A3, a) and b)). This was mainly due to the lower losses recorded in EMAP (7–17 % for $EMAP_{OPT,25\ °C,3\ d}$ and $EMAP_{STD,25\ °C,3\ d}$ respectively) compared to conventional storage at ambient temperature, $MPP_{25\ °C,3\ d}$ (30 %). As expected, $EMAP_{OPT,25\ °C,3\ d}$ better perform than $EMAP_{STD,25\ °C,3\ d}$ due to the better internal gas conditions achieved with optimized EMAP (result not shown). EMAP solution should thus be preferred compare to conventional perforated packaging for ambient storage.

Comparing now EMAP solution at ambient temperature and conventional packaging at chilled temperature (EMAP versus fridge), $EMAP_{STD,25\ °C,3\ d}$ impacts were about 30 % higher in all categories (except ionizing radiation) than that of $MPP_{5\ °C,3\ d}$ (Fig. 5). The amount of losses generated in $MPP_{5\ °C,3\ d}$ (3.5 %) was much lower than that in $EMAP_{STD,25\ °C,3\ d}$ (17 %). In spite of the additional environmental cost of the cold chain in $MPP_{5\ °C,3\ d}$, this later was not high enough to

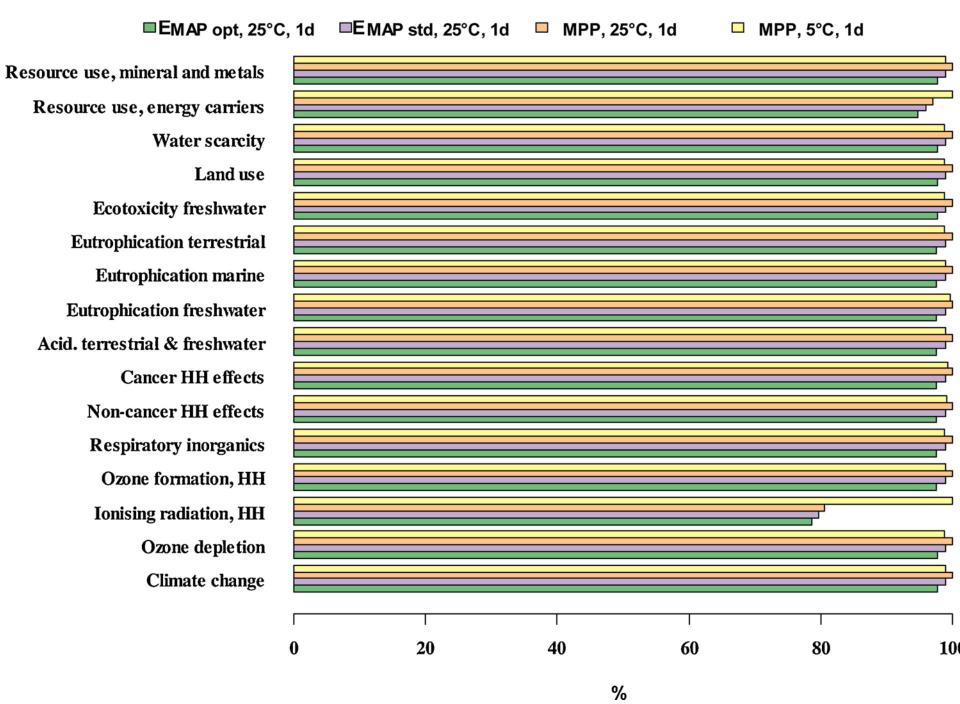

Fig. 4. Relative comparison between four storage conditions at consumer level for short storage duration of 1 d: $MPP_{25\ °C,1\ d}$ (macro perforated packaging at ambient temperature), $MPP_{5\ °C,1\ d}$ (macro perforated packaging and cold storage), $EMAP_{STD,25\ °C,1\ d}$ (modified atmosphere packaging at ambient temperature) and $EMAP_{OPT,25\ °C,1\ d}$ (optimized modified atmosphere packaging at ambient temperature). For each impact category, the most impacting scenario is normalized at 100 %. The other scenarios are expressed relatively to the most impacting one. Raw data could be downloaded at https://doi.org/10.5281/zenodo.3938995.

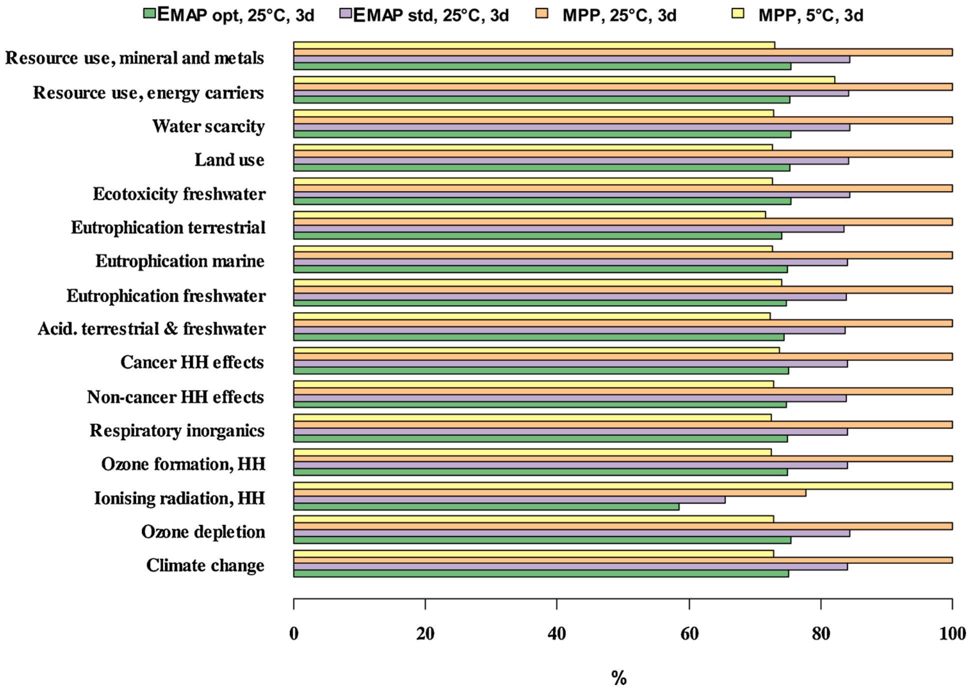

Fig. 5. Relative comparison between four storage duration at consumer level for long storage duration of 3 d: MPP$_{25\ ^{\circ}C,3\ d}$ (macro perforated packaging at ambient temperature), MPP$_{5\ ^{\circ}C,3\ d}$ (macro perforated packaging and cold storage), EMAP$_{STD,25\ ^{\circ}C,3\ d}$ (modified atmosphere packaging at ambient temperature) and EMAP$_{OPT,25\ ^{\circ}C,3\ d}$ (optimized modified atmosphere packaging at ambient temperature). For each impact category, the most impacting scenario is normalized at 100 %. The other scenarios are expressed relatively to the most impacting one. Raw data could be downloaded at https://doi.org/10.5281/zenodo.3938995.

counterbalance the indirect environmental benefit made by reducing food losses (Figure A3, d)). Standard, commercial EMAP (EMAP$_{STD}$) used alone (without combination with cold chain) could not reduce significantly the environmental impacts of the supply chain compared to the exclusive use of the cold chain in the conditions investigated here.

Considering now the optimal EMAP solution (EMAP$_{OPT,25\ ^{\circ}C,3\ d}$), environmental impacts of EMAP$_{OPT,25\ ^{\circ}C,3\ d}$ and MPP$_{5\ ^{\circ}C,3\ d}$ were in the same range, for all impact categories (Fig. 5), except for ionizing radiation which was high for MPP$_{5\ ^{\circ}C,3\ d}$ concomitantly to the use of nuclear power for cold chain. Results of uncertainty analysis show that impacts of MPP$_{5\ ^{\circ}C,3\ d}$ remains significantly lower than that of EMAP$_{OPT,25\ ^{\circ}C,3\ d}$ for most of the impacts categories (Supplementary material Figure A3, c)). This finding confirms that the modified atmosphere used alone does not make it possible to obtain the same performance as the use of cold chain for preserving food product over a long period of storage at consumers' home. These conditions were strongly restrictive: EMAP was used as an alternative to the use of cold chain and not in synergy with cold chain in this approach. For comparison, when combining EMAP and refrigeration, a slight improvement of the loss reduction was obtained compare to MPP $_{5\ ^{\circ}C,3\ d}$ (2% for EMAP$_{OPT,5\ ^{\circ}C,3\ d}$ and 2.3 % EMAP$_{STD,5\ ^{\circ}C,3\ d}$) that still permitted to improve environmental impact of the whole system compare to use of cold chain only (MPP $_{5\ ^{\circ}C,3\ d}$) (Supplementary material, Table A3).

3.3. Impact of EMAP at consumer's and supermarket level

Use of EMAP is expected to achieve large strawberry loss reduction at the supermarket too and not only at the consumer level. This is all the more important to consider this impact at supermarket since losses are the main driver for environmental impacts. In addition, in the previous part focusing on food loss reduction at consumer's level only (see 3.2), several comparisons were made for which it was not possible to conclude in terms of environmental benefit (EMAP$_{STD,25\ ^{\circ}C,1\ d}$ versus MPP$_{5\ ^{\circ}C,1.\ d}$) or which lead to conclude to higher environmental impacts of EMAP strategies compare to conventional solutions based on cold chain (EMAP$_{OPT,25\ ^{\circ}C,3\ d}$ versus MPP$_{5\ ^{\circ}C,3\ d}$, EMAP$_{STD,25\ ^{\circ}C,3\ d}$ versus MPP$_{5\ ^{\circ}C,3\ d}$). Cumulating the benefit of EMAP at consumer plus distribution steps may help to decipher the real benefit of EMAP as alternative to cold chain at household.

Because, precise loss rates at the supermarket was not known due to the reluctance of wholesalers and distributor to disclose this sensitive information when it is explicitly demanded (Matar et al., 2020), we decided to vary arbitrary food loss reduction at supermarket level to represent the potential benefit that EMAP may have, everything else being equal (duration and temperature at supermarket level). Food loss reduction at supermarket level was varied from 10.5, which is no benefit at all, to 5 % losses and this reduction was to be superimposed to the benefit of EMAP already observed in the different consumers' scenario.

For short-storage duration at consumer level, results of sensitivity analysis for EMAP$_{STD,25\ ^{\circ}C,1\ d}$ versus MPP$_{5\ ^{\circ}C,1\ d}$ show that for food losses at supermarket greater than 10.3 %, the conventional fridge storage at household best performs from an environmental point of view (Supplementary material Figure A4). For food loss at supermarket range from 10.3 to 9.5 %, both strategies present similar environmental impacts. It is thus impossible to determine which strategy should be encouraged in that case. For 9.5 % and below of loss at supermarket, losses of raw product on the overall supply chain became lower for EMAP$_{STD,25\ ^{\circ}C,1\ d}$. Then, this strategy became interesting compared to the fridge one from an environmental point of view. Our results show a very narrow range of food loss to switch from one strategy to another. Food loss at supermarket is thus a highly sensitive parameter which greatly influence our results. Further investigations should be done to precisely estimate this parameter and produce more robust recommendations.

For long-storage duration at consumer's home, sensitivity analysis for EMAP$_{OPT,25\ ^{\circ}C,3\ d}$ versus MPP$_{5\ ^{\circ}C,3\ d}$ show that for food losses at supermarket greater than 8 %, conventional storage present lower environmental impacts (Supplementary material Figure A4). When they range from 8 to 6.5 %, environmental performance of both strategies was similar. In contrast, when food losses were lower than 6.5 % the benefit of using modified atmosphere was significant, due to lower strawberry losses on the overall supply chain. For long storage duration at consumers' home, where household losses are thus automatically higher than for short storage duration, the losses decrease at supermarket level must be higher in comparison to compensate the highest losses at households. Our analyses demonstrate that for this packaging strategy, results are less sensitive to this parameter.

Finally, for EMAP$_{STD,25\ ^{\circ}C,3\ d}$ versus MPP$_{5\ ^{\circ}C,3\ d}$, whatever the value of food loss parameter at supermarket (range from 10.5 to 5 %), MPP$_{5}$

$_{°C,3\ d}$ was the best option from environmental perspective (result not shown). Indeed, it was impossible to compensate losses at households in $EMAP_{STD,25\ °C,3\ d}$ by losses decrease at supermarket.

If EMAP is not fully optimized and fit to the strawberry needs in order to decrease product's losses at a maximum at both, supermarket and consumer levels, there is no environmental benefit in comparison with the use of cold chain at households. This is of course for strawberry supply chain, in the conditions studied here.

3.4. EMAP as an alternative to refrigeration to prevent food losses

For high perishable food products, losses and waste management has been identified as a major contributor to environmental burdens in these food chains (Scherhaufer et al., 2018), especially for fresh fruits and vegetables. Most of fresh fruits display indeed a very short post-harvest shelf-life due to their intensive post-harvest metabolism. Refrigeration is identified as the most effective option for minimising respiration and deterioration and thus to reduce food loss and waste all long the post-harvest chain (Singh, 2011). In the peculiar case of fresh strawberries, this option is essential: this high perishable fruit displays a very high respiration rate 50–100 ml CO_2 h^{-1} kg^{-1} produced at 20 °C (Matar et al., 2018) and is also highly sensitive to moulds development, especially *Botrytis cinerea* (Hertog et al., 1999). Challenging post-harvest storage of strawberries was up to now mostly managed through cooling (Vaysse et al., 2015). However, this option puts pressure on fossil resources and generates environmental impacts related to the production and use of refrigeration systems (Maykot et al., 2004).

Among alternatives to refrigeration, Equilibrium Modified Atmosphere Packaging (EMAP) appears as a good alternative to partially replace cold chain use in the post-harvest chain of strawberries, especially at the distribution and consumer steps. In case of respiring food product, modified atmosphere is created by the product itself through its respiration until equilibrium with gas permeation flux though the packaging is reached. This technique is based on existing packing machine (strawberries are indeed mostly packed in tray wrapped with macro-perforated plastic pouch). The microperforated film of the standard packaging just needs to be replace by another film with adequate gas permeabilities. EMAP slows down respiration at ambient temperature and is a good solution for fruits such as strawberries for which refrigeration is not the preferred solution at the distribution and consumers steps. Indeed, only 43 % of French consumers store fresh strawberries in the fridge at home (Matar et al., 2020). Previous study has highlighted the benefit of EMAP at ambient temperature to decrease strawberries loss at household (Matar et al., 2020).

To deepen the benefit of EMAP in the post-harvest chain of fresh strawberries, we investigate in the present study the option of using EMAP packaging at ambient temperature as an alternative to conventional storage conditions (MPP plus refrigeration) to reduce environmental impacts of strawberries' farm to fork system. Reduction of postharvest loss is expected to have a great impact on the reduction of environmental impacts but technologies used to limit this loss (such as cold chain) display also direct impacts that may counterbalance their positive effect on food loss reduction. Our findings show that the alternative strategy is valuable to reach more sustainable post-harvest chains, even if the use of refrigeration remains the best option to prevent food losses. EMAP for short storage duration (1 d) is interesting in all cases as alternative to refrigeration at households. EMAP for long storage duration (3 d) is also a good alternative to standard packaging at ambient temperature but not at cold temperature. Indeed, the benefit of refrigeration for long term storage of strawberries at home remains the highest due to its great effect on loss reduction, in spite of all direct impacts of the cold production. However, refrigeration is not the most preferred option by consumer (Matar et al., 2020) and in the case of ambient storage, EMAP packaging presents in all configurations, best performance in food preservation, compared to MPP and for a similar environmental cost. Indeed, this technology does not need any injection of additional gases to modify the atmosphere within the packaging, and thus prevent from impacts transfer. There are no additional costs to consider due to modified atmosphere technology. In addition, EMAP is expected to reduce food loss at the supermarket level too, in an extend that still needs to be clearly quantified. Our sensitivity analysis revealed that, by decreasing losses from 10 % to 8%, EMAP at ambient temperature becomes a valuable option in all configurations including long storage duration at household.

These findings were obtained using an optimized EMAP, i.e. by using a packaging film that owns gas permeabilities that perfectly fit strawberry respiration, which is not yet available. Indeed, same environmental performance could not be achieved by using a standard EMAP with commercially available film. In addition, impact of cold chain was estimated using French characteristics as regard electricity production so conclusions of the present article may be not directly transposable to other countries. Finally, use of EMAP may be not well understood by consumers and manage at household. Indeed, about 79 % of French consumers remove the packaging before storing strawberries, disrupting the modified atmosphere and losing its benefit on strawberry preservation (Matar et al., 2020). Improvement of the indirect functions of packaging, i.e. provide comprehensive information to the consumer for a proper use of the packaging, is required to take advantage of all the environmental benefit of the packaging.

4. Conclusion

Life cycle assessment (LCA) was applied to a strawberries farm to fork system from production till the consumer household considering food losses, packaging production, disposal and benefit on food losses reduction, to assess the potential environmental benefits of modified atmosphere packaging compared to conventional macro perforated packaging at two storage temperatures and two storage durations. This study confirms that for high perishable food product, direct impact of packaging is limited. Indeed, the main driver of the overall environmental impacts is the strawberry production stage. Thus, considering the indirect effect of technologies of preservation (packaging, cold chain, etc) used to protect and increase shelf life of the product is of primary importance to assess environmental impacts of the whole packed product. This is particularly important for assessing packaging strategies for which indirect, positive impacts are usually neglected. At the consumer level, it was found that for short storage duration (1 d) $EMAP_{OPT}$ packaging presents significantly lower environmental impacts at ambient temperature compared to low temperature storage. For $EMAP_{STD}$, it was not possible to conclude as both strategies present similar environmental impacts. However, even if the differences are significant, they remain very small and question the real benefits of EMAP for such storage duration. For long storage duration (3 d), EMAP packaging presents real benefits compared to MPP at ambient temperature. However, compared to the low temperature storage, EMAP strategy is not an efficient alternative to prevent from food losses and reduce environmental impacts.

Finally, we investigated the sensitivity of our results to the parameter food losses at supermarket stage, as this parameter is one of the most critical and uncertain one in our LCA model. It was found that for several comparisons between packaging strategies, results were highly sensitive to this parameter. Depending on its value, conclusions regarding the best packaging strategy can drastically change. This demonstrated the need for further research to precisely determine food losses parameters in such product supply chain environmental assessments. At least, we recommend to systematically perform uncertainty analyses to determine the robustness of LCA results. This work was based on data from a detailed survey on consumer behaviour and strawberry supply chain. It is therefore a step forward in achieving LCA of food products and understanding their environmental impacts among the whole supply chain.

Author agreement statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process. He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.postharvbio.2021.111521.

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