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Consumer behavior at sale point and consumption according to strawberry quality: How to use those data to evaluate food waste?

Emma Pignères[a,1], Marine Masson[b,1], Steven Duret[c], David Blumenthal[b], Maëlle-Ahou Gouton[b], Nathalie Gontard[a], Hélène Angellier-Coussy[a], Valérie Guillard[a], Fanny Coffigniez[a], Sébastien Gaucel[a,*]

[a] JRU IATE, University of Montpellier, INRAE, Institut Agro, 2 Place Pierre Viala, 34060, Montpellier, France
[b] Université Paris-Saclay, INRAE, AgroParisTech, UMR SayFood, 91120, Palaiseau, France
[c] Université Paris-Saclay, INRAE, FRISE, 92761, Antony, France

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ABSTRACT

Fresh fruits and vegetables present some of the highest food loss rates, due to their high perishability. The ability to model food waste and loss is key to understanding the levers for its reduction and evaluating which parameters are the most impactful. The highest food waste occurs at consumer level. Therefore, consumer behavior must be understood to accurately model food waste. In the present study, a quantitative consumer survey was performed among 509 French consumers to understand their behavior when purchasing, storing, and eating strawberries. The results of the survey were used to create several purchasing groups, with different purchase intentions and consumption behaviors, and were combined with a state-of-the-art deterioration model to evaluate food waste. Seven scenarios were tested by varying the initial deterioration of strawberries at the supermarket. A first and most expected result of the model was the significant impact of storage management habits (temperature and duration) on the resulting food waste: all the trays that went from 0 to 1% deterioration at the supermarket to more than 95% at consumption were kept in ambient conditions. Moreover, the predicted food waste was between 9.4 and 57.5% depending on the initial deterioration at the supermarket, highlighting the impact of the upstream supply chain before retailers on food waste at the consumer level. Finally, the results showed a non-linear relationship between deterioration and consumption, and thus, food waste. By considering this diversity of consumer behaviors, this model proposes a more accurate link between deterioration and food waste compared with the existing literature.

1. Introduction

One third of the food produced each year is wasted between harvest and consumption (Food and Agriculture Organization of the United Nations, 2019a). It was estimated that the annual carbon footprint from food loss and waste (FLW) reaches 3.7 Gt annually, not including emissions related to landfills, positioning food loss and waste as the third greenhouse gas emitter after China and USA in 2010 (Jaglo et al., 2021). Moreover, food production is responsible for 70% of freshwater use and is a major driver of species extinction and eutrophication (Williams and Wikström, 2023). Packaging, with food packaging representing a large part, accounts for 44% of the worldwide plastic produced (Plastics Europe, 2022). It should be noted that FLW necessitates increased food and packaging production to compensate for the loss, thereby exacerbating the aforementioned impacts. Reducing FLW would thus have a positive environmental impact on several parameters, such as water use, biodiversity or plastic footprint, beyond carbon footprint. Some of these impacts have begun to be considered in life cycle analyses (Pauer et al., 2019). Finally, FLW has economic and social impacts. For instance, in low-income countries, reducing FLW at the local production level could

* Corresponding author.
E-mail addresses: emma.pigneres@umontpellier.fr (E. Pignères), marine.masson@agroparistech.fr (M. Masson), steven.duret@inrae.fr (S. Duret), david.blumenthal@agroparistech.fr (D. Blumenthal), maelle.gouton@agroparistech.fr (M.-A. Gouton), nathalie.gontard@inrae.fr (N. Gontard), helene.coussy@umontpellier.fr (H. Angellier-Coussy), valerie.guillard@umontpellier.fr (V. Guillard), fanny.coffigniez@umontpellier.fr (F. Coffigniez), sebastien.gaucel@inrae.fr (S. Gaucel).

[1] Emma Pignères and Marine Masson are co-first authors, they contributed equally to this work.

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increase farmers' incomes, leading to better access to food and reduced food insecurity. Additionally, decreasing FLW may result in lower food prices for consumers, depending on how the price effects are distributed along the supply chain (Food and Agriculture Organization of the United Nations, 2019b). The Food and Agricultural Organization (FAO) highlighted five steps of the supply chain during which FLW can occur: (i) agricultural production, harvest, slaughter or catch, (ii) storage and transportation, (iii) processing and packaging, (iv) wholesale and retail, and (v) consumption (households and food services) (Food and Agriculture Organization of the United Nations, 2019b). Food loss describes the decreases in both quality and quantity of food from harvest to retailer excluded. Food waste concerns decreases in quality and quantity of food at retailer, food service and consumer levels. A decrease in food quality means a loss of nutritional and/or economic value due to non-compliance with food quality standards. In contrast, a decrease in food quantity refers to the reduction in the mass of food intended for human consumption, i.e. food that is discarded. Both food loss and food waste involve decreases in food quantity and quality, but they occur at different steps of the supply chain (Food and Agriculture Organization of the United Nations, 2019b).

Considering the high environmental impact of FLW and the necessity to reduce it, accurately assessing FLW is of primary importance. To evaluate FLW for a specific food product, a solution would be to conduct a large-scale experiment, by following food products through the supply chain from production to consumption, and by reporting operating conditions and FLW. However, costs, ethic and feasibility limitations put this solution out of consideration (Duret et al., 2018). In this context, modelling is a good alternative and gives several advantages such as the possibility to test a high quantity of scenarios to understand the impact of different parameters on a resulting phenomenon. Although few studies have demonstrated a link between shelf life and food waste, a study highlighted an inverse function between shelf life and food waste and loss at retail for products within 30–50 days of shelf life. This underscores the importance of studying shelf life to accurately assess FLW (Spada et al., 2018). Thus, the first step is to build a shelf life model. The review of Coffigniez et al. (2021) indicates that to build an accurate shelf life model, three components are mandatory: a global quality parameter evolution, a transfer-reaction model coupling reaction models with gas transfer models in the food/packaging system, and consumer and stakeholder acceptability thresholds. Defining these thresholds is not always straightforward, as there can be variability within acceptability thresholds, with different tolerances among consumers and stakeholders such as retailers. Then, the challenge is to be able to quantify the decrease of FLW from the shelf life gains evaluated. For this, stakeholders and consumers' behavior must be considered (Coffigniez et al., 2021). Few authors tried to model food waste at consumer level (Coffigniez et al., 2021; Matar et al., 2020; Yokokawa et al., 2018; Manzocco et al., 2017). Manzocco et al. (2017) determined the risk of Iceberg fresh-cut salad waste based on the probability of the consumer to reject the salads at consumption, based on questionnaires led with 50 consumers. The fridge temperature variations were assessed; however, the consumer behavior in terms of storage management was not considered, neither the rejection behavior at purchase step (Manzocco et al., 2017). On the other hand, Yokokawa et al. (2018) proposed a generic framework for food waste prediction, introducing consumer behavior patterns defined at 6 stages: product selection, product storage, food consumption, food preparation, expiration date perception and packaging disposal. As many scenarios as possible combinations were tested, and the approach was validated on ham case study, in Japan. Food waste was then calculated based on the selected behaviors (Yokokawa et al., 2018). Although this approach includes a broader range of consumer behaviors, it does not consider the evolution of the food quality. Food waste was not calculated based on the food deterioration, but on consumption rate, preparation step, storage time and expiration date. Moreover, consumer behavior patterns were potential scenarios, but were not based on consumer studies: all patterns were considered as possible ones, and their frequencies among population were not quantified. As far as the authors know, the most complete food waste model, combining a deterioration reaction, a transfer-reaction model and consumer behavior is the model developed by Matar et al. (2020), done for strawberries, in France. Both deterioration reaction and gas transfers through the food packaging unit were modelled. Then, food waste at supermarket was based on consumer acceptability, considering that 50% of consumers would not buy strawberries when the deterioration was higher than 13%. At home, they considered that food waste was linear to the integral of the deterioration percentage. 132 scenarios were tested, with variations of the temperature and duration at the pre-supermarket, supermarket and consumer steps. Furthermore, they included the consumer behavior during storage by two main ways: by considering the storage conditions (fridge vs ambient) and the preservation of the packaging integrity (e.g. opening of the packaging, selecting another food container, etc.), the latter being crucial for equilibrium modified atmosphere (eMAP) efficiency. Such modelling enabled to make recommendations on consumer practices and packaging to decrease food waste, but also to quantify the impact of such changes in the resulting food waste (Matar et al., 2020). Although this study considered consumers' storage habits, it did not consider the diversity of consumer behaviors regarding the sorting of strawberries: the assumption made to calculate the food waste considers that all consumers throw only the damaged parts, independently of the overall quality of the strawberries, which might not be representative of the reality.

After roots, tubers and oil-bearing crops, fruits and vegetables (F&V) represent the second group with the highest percentage of food loss (Food and Agriculture Organization of the United Nations, 2019b). Within this category, strawberries were selected as a case study. Indeed, strawberry consumption in Europe was estimated at around 1.2 million tons or more according to the Centre for the Promotion of Imports from developing countries (CBI) and ICI Business, with a local production of roughly equivalent volume. More specifically, France is one of the largest import markets for strawberries, and French consumers have high standards regarding the taste of strawberries, mostly concerning their flavor (CBI, 2021). Moreover, strawberries contain essential nutrients and many important dietary components (Giampieri et al., 2012). Despite their benefits and popularity, strawberries have the constraint of a very short post-harvest life. They can only be stored during 1–2 days at ambient temperatures. Under optimal conditions, i.e. 0 °C and 90–95% RH, the shelf life can be increased up to 8–12 days maximum, depending on the cultivar (Shrivastava et al., 2023). Qin and Horvath (2021, 2022) focused on strawberry FLW at four steps in the US: on farm, during transportation, at retail and at consumption stage. For each of these steps, FLW for strawberries were estimated to 31%, 8.0%, 14% and 35% respectively, leading to 64% FLW in total. It means that for 1 kg of strawberries consumed, 2.8 kg need to be produced, whose 1.8 kg is wasted, mostly at consumer stage. With these high numbers, FLW contribute to 40% of the total greenhouse gas emissions of strawberries (Qin and Horvath, 2021, 2022). Several factors explain these high FLW. Beyond their physiology (respiration and transpiration) and high water activity (0.997) (Shrivastava et al., 2023) which make them highly susceptible to deterioration and microbial spoilage, strawberries are also very sensitive to vibrations during transport (Sasaki et al., 2022). All these factors make strawberries a relevant case study for modelling FLW. The study of Aschemann-Witzel et al. (2018) at the scale of waste in Uruguay, highlighted the influence of individual characteristics on waste behavior. They confirmed that in middle- and high-income countries, households are indeed the primary source of food waste (Aschemann-Witzel et al., 2018). One challenge is to understand the reasons for the waste behind the variety of food products, and if the waste is product-dependent, it is necessary to deepen the mechanisms specific to a given product. The model proposed in this study aims to fill this gap in the literature, by examining the mechanisms behind strawberry food waste at the consumer level.

To better understand the impact of consumers on strawberry waste, this study focused first on the management and perception of strawberries by French consumers from purchase to consumption. It supports the hypothesis that strawberries will be perceived differently depending on the level of degradation and that the management of the product by the consumer will be more or less favorable to this evolution. Then, all these results were combined with a deterioration equation to propose an integrated model assessing strawberry quality evolution and food waste at the consumer step, which represents the most impactful step on FLW. Regarding food waste definition, the present model focused on the decrease in quantity of food, not the decrease in quality. This new model included the purchase step, the transport from retailer to consumer, storage at consumer and consumption. The novelty of this model compared to previous ones relies mainly on the consideration of the diversity of consumer behaviors, in terms of transport, storage (time and temperature) but also purchase and eating behaviors, and the link with a food deterioration model. These behaviors were based on real consumer surveys, allowing to quantify the frequency of each of them, and thus, more realistic food waste estimations. Moreover, several simulations were performed considering different initial deterioration stages at the supermarket, as these impact consumer behaviors at purchase and the resulting food waste at consumption. This approach highlights the importance of logistics steps before retail and retail management in terms of product quality.

First, in a materials and methods section, the online consumer survey, the deterioration model and the food waste model were described. Then, the results and discussion part was divided into two sections: the results of the consumer survey were presented first, followed by the results of the food waste model. The latter included the presentation of the model parameters deduced from the survey and the food waste results considering different deterioration stages at the supermarket.

2. Materials & methods

2.1. Online consumer survey

2.1.1. Participants

Through an online questionnaire, 509 French adults were questioned, which were strawberry consumers, responsible or co-responsible for home shopping, from each region of France. All gave their informed consent. All the participants were recruited by an institute specializing in consumer studies. The data was collected anonymously, in compliance with European laws on the protection of personal data (GDPR - Regulation (EU) 2016/679).

2.1.2. Construction of the questionnaire

A preliminary qualitative study was conducted. Ten French adults, strawberry consumers, followed an in-depth interview on their purchasing habits, management and consumption of fruits & vegetables and more specifically of strawberries. From this qualitative data, the questionnaire was built in order to quantify the behaviors observed. These interviews allowed us to define the relevant aspects to be used in the online questionnaire concerning various topics, such as purchasing locations, selection criteria in stores, and the storage conditions of strawberries at home.

2.1.3. Questionnaire structure

After questions to characterize and to screen the studied population (age, gender, residential area, socio-professional category), the continuation of the questionnaire was structured in two main sections.

The first section starts with generic questions on purchasing and consumption habits of fruits & vegetables (F&V) (1A), then more specifically, of strawberries (1B).

The second section follows with questions related to the concrete presentation of a set of strawberry tray photographs, questioning the intention to purchase (2A), then to consume (2B) the presented product (in a monadic image order). These images were presented gradually according to the stage of degradation of the strawberries, described in Table 1. This scale of strawberry degradation was developed and validated by the French Interprofessional Technical Center for Fruits and Vegetables (CTIFL). Stage 1 was not considered in the questionnaire, since there was very little visual difference with stage 0. Thus, for the model, consumers' behaviors were considered similar in front of a strawberry tray with deterioration stages of 0 or 1. The pictures allowed us to have a realistic simulation of purchasing decisions, replicating a real-life situation where consumers visually assess products before making a purchase. In addition, strawberries are a product where visual appearance is crucial for perceived freshness and quality. The images help to identify the thresholds of visual acceptability for consumers. Finally, photos provide a concrete basis for participants to respond, reducing biases associated with hypothetical questions and improving the reliability of the results. For the question regarding the purchase of strawberries, consumers were asked whether they would buy the strawberries or not. For the question about strawberry consumption, four options were provided: "No, I don't eat any strawberries"; "Partly, I select the strawberries by removing, and throwing away the damaged strawberries"; "Yes, I eat the strawberries by removing, and throwing away the damaged parts"; " Yes, I eat all the strawberries".

The main topics addressed in the questionnaires are summarized in Table 2. The way they were further used in the model for assessing food waste at consumer level is also mentioned: either to determine model parameters, or for discussion of the model results. Moreover, the last columns (F&V and Strawberries) indicate whether the questions were addressed regarding fruits and vegetable in general (F&V) or more specifically regarding strawberries (Strawberries).

2.1.4. Data analysis

All data analyses were carried out using the statistical software programs XLSTAT® (Version, 2022; Addinsoft, New-York) (XLSTAT®, 2022) and JMP® (Version 16, SAS Institute Inc., Cary, NC, 1989–2023) (JMP®, 2023).

To verify the sample's representativeness of the French population, in term of age and gender, we compared sample characteristics with INSEE's 2022 census data: (1) differences in average age were assessed using Student's t-tests, (2) age and gender group distributions were compared using Chi-square tests. Furthermore, to ensure a diversity of consumer profiles, we sampled people from different regions of France and various socio-professional categories. The distribution of residential areas and socio-professional categories were evaluated with Chi-square tests.

For analyzing general purchasing data, the significance of purchasing locations and in-store selection criteria by product (fruits and vegetables in general, or strawberries specifically) were evaluated using Chi-square contingency tables. Purchase visit frequencies were categorized as follows: never, less than once a month, once a month, once every two weeks, or at least once a week. Selection criteria importance was assessed with response categories: totally agree, tend to agree, neither agree nor disagree, tend to disagree, and totally disagree. At a second level of analysis, Chi-square contingency tables were used to compare

Table 1
Stages defined by CTIFL and their description.

Stage	CTIFL definition
0	No strawberry degradation
1	*Some strawberries are pressed against the tray, in a very localized area, up to three or four light marks (*5 mm*) on all sides or two*1 cm *marks*
2	At least two large marks (2 cm) and other small ones, or three marks of 1 cm each
3	At least four or five marks larger than 1 cm and other small marks
4	Almost all strawberries are pressed against the tray, over more than half the surface of each fruit
5	There are molds and juice

Table 2
Questions addressed in the questionnaire, and the way the answers were used in the model for assessing food waste at consumer level. Green boxes mean that the questions were addressed at the F&V and/or strawberry level. Red boxes with a cross mean that the questions were not addressed for that level.

Category	Possible answers	F&V	Strawberries
PURCHASE HABITS			
Results used to determine model parameters			
Intention to purchase	Yes; no	X	
Results used for discussion			
Location	Malls; Markets; Specialty stores; Producers; Community-Supported Agriculture (CSA); Internet		
Frequency	Never; less than once a month; once a month; once every two weeks; at least once a week		
Choice criteria	Criteria for F&V and strawberries : freshness; season; France; desire; local; price; recipe; organic; packaging; assistance. Strawberries additional criteria: general condition; color; variety; juice-less; weight; odor; calyx; size For each criterion: totally agree; tend to agree; neither agree nor disagree; tend to disagree; totally disagree		
Means of transport	Car; public transport; walking; cycling		
HOME STORAGE MANAGEMENT			
Results used to determine model parameters			
Area	In the fruits and vegetables compartment of the refrigerator; on a refrigerator shelf; in the kitchen, at room temperature; other	X	
Duration	Less than a day; one day; two days; three days; four days; more than four days	X	
Results used for discussion			
Container	In their original packaging, unopened; in their original packaging, after opening it; in another packaging; other	X	
Cleaning	I wash them before storing; I wash them the first time I eat some, even if I don't plan to eat them all; I wash them as I consume; I don't wash them; other	X	
CONSUMPTION HABITS			
Results used to determine model parameters			
Intention to consume	Yes, I eat all the strawberries Yes, I eat the strawberries by removing, and throwing away the damaged part Partly, I select the strawberries by removing, and throwing away the damaged strawberries No, I don't eat any strawberries	X	
Results used for discussion			
Characterization of damaged products	Criteria: molds; texture; color; juice; smell; leaves For each criterion: totally agree; tend to agree; neither agree nor disagree; tend to disagree; totally disagree	X	

Table 3
Parameters used in the global model for food waste predictions. Values indicated after ± correspond to standard deviations and values in parentheses correspond to the confidence intervals.

FOOD & PACKAGING PARAMETERS

Parameter		Value	Unit	Reference
Strawberry variety		Charlotte		
Food density	d	705	$kg.m^{-3}$	Matar et al. (2018)
Food mass	m	280 ± 20[a]	g	This work
Food volume	V_{food}	3.972×10^{-4}	m^3	This work
Food calyxes ratio	$r_{calyxes}$	1.5	%	Markovinović et al. (2022)
Universal gas constant	R	8.314	$J.mol^{-1}.K^{-1}$	
Deterioration rate constant at T_{ref}	k_D (T_{ref})	9.93×10^{-6} (8.97×10^{-6}; 108×10^{-5})[a]	s^{-1}	Matar et al. (2018)
Reference temperature T_{ref} for deterioration rate	T_{ref_kD}	10	°C	Matar et al. (2018)
Activation energy for deterioration rate constant	E_{a_kD}	73514 ± 2205[a]	$J.mol^{-1}$	Matar et al. (2020)
Maximum percentage of deterioration	D_{max}	100	%	Matar et al. (2018)
Maximum inhibitory CO_2 concentration	$x_{CO_2\ max}$	30	%	Matar et al. (2018)
Thermal inertia of the food product and packaging material	τ	5350	s	This work
Initial temperature of the strawberries	Tp(1)	20	°C	This work
Number of strawberry trays	N	10000	dimensionless	This work

DISTRIBUTION LAWS - CONTINUOUS

Step	Distribution law	Parameters	Unit	Reference
CONTINUOUS - DURATION				
Transport (retail to consumer)	Exponential (mean)	$Exp(0.05)$	day	Derens et al. (2006)
Storage (at consumer)	Gamma (shape, scale)	$\Gamma\left(3.8; \frac{1}{2.1}\right)$	day	This work (Section 3.1.3. Storage management)
CONTINUOUS - TEMPERATURE				
Transport (retail to consumer)	Uniform (min, max)	$\mathscr{U}(15.4; 36.6)$	°C	Infoclimat (2023)
Storage (at consumer, fridge)	Normal (mean, standard deviation)	$\mathscr{N}(5.9; 2.9)$	°C	Derens et al. (2006)
Storage (at consumer, ambient)	Normal (mean, standard deviation)	$\mathscr{N}(20.9; 1.7)$	°C	BRE (2013)
CONTINUOUS - DETERIORATION				
Initial deterioration stage 0	Uniform (min, max)	$\mathscr{U}(0; 1)$	%	This work (Section 3.2.1)
Initial deterioration stage 1	Uniform (min, max)	$\mathscr{U}(1; 5)$	%	This work (Section 3.2.1)
Initial deterioration stage 2	Uniform (min, max)	$\mathscr{U}(5; 20)$	%	This work (Section 3.2.1)
Initial deterioration stage 3	Uniform (min, max)	$\mathscr{U}(20; 40)$	%	This work (Section 3.2.1)
Initial deterioration stage 4	Uniform (min, max)	$\mathscr{U}(40; 60)$	%	This work (Section 3.2.1)
Initial deterioration stage 5	Uniform (min, max)	$\mathscr{U}(60; 100)$	%	This work (Section 3.2.1)

DISTRIBUTION LAWS - DISCRETE

Step	Distribution law	Parameters	Unit	Reference
Generation of a consumer for purchase	Multinomial distribution	Table 6 (results)		This work (Section 3.1.4)
Storage (at consumer, fridge or ambient (kitchen and other)	Bernoulli (probability(ambient))	$\mathscr{B}(0.24)$	dimensionless	This work (Section 3.1.3. Storage management)
Selection of a consumption behavior	Multinomial distribution	Fig. 6 (results)		This work (Section 3.1.4)

[a] Mean values were considered in the model for these parameters.

response proportions between general fruit and vegetable data and strawberry-specific data.

To characterize typical management of strawberries at home (storage and consumption habits), response distributions were analyzed, and the prevalence of top responses was tested using Chi-square analysis. The importance of criteria defining a "damaged strawberry" was determined through Chi-square contingency tables to compare response proportions across the following categories: totally agree, tend to agree, neither agree nor disagree, tend to disagree, and totally disagree.

All theoretical possibilities for purchasing or not purchasing were considered for each decision stage, leading to $2^4 = 32$ patterns (Table S1). These 32 patterns were categorized as follows: (i) patterns not present in consumer responses, (ii) patterns present but inconsistent (illogical alternations between Yes and No across stages), and (iii) patterns present and consistent.

2.2. Deterioration model

The model described by Matar et al. (2018) (Matar et al., 2018) was used to assess the overall strawberry deterioration at the packaging level, according to a logistic equation (Equation (1)):

$$\frac{dD}{dt} = k_D(T_i)D\left(1 - \frac{D}{D_{max}}\right)\left(1 - \frac{x_{CO_2}(t)}{x_{CO_2\ max}}\right) \quad \text{(Eq. 1)}$$

where D is the percentage of deterioration surface (%) at time t (s), D_{max} is the maximum percentage of deterioration (%), $k_D(T_i)$ represents the deterioration rate constant at a temperature T_i (s^{-1}) (calculated in Equation (3)). The latter term is a dimensionless weighting parameter, representing the inhibiting effect of CO_2 on the deterioration rate, $x_{CO_2}(t)$ and $x_{CO_2\ max}$ being respectively the CO_2 molar ratio (%) in the headspace at time t and the maximum inhibitory CO_2 molar ratio (%), equal to 30% (Garcia-Gimeno et al., 2002). These parameters are given in Table 3. Although shocks and water loss can also have an impact on microorganisms' growth, only CO_2 was considered in this model. This model considers that below the threshold value $x_{CO_2\ max}$, the inhibiting effect of CO_2 linearly decreases with the decrease of CO_2 concentration, following a weighting parameter starting from 1 and stabilizing at 0. Moreover, temperature dependency of deterioration rate was taken into account via Arrhenius law and activation energy ($E_{a\_k_D}$). In the present study, a macro-perforated packaging was considered, as most present on the market. Therefore, the O_2 and CO_2 partial pressures inside and outside the packaging were constant, i.e. 0.2095 × 101,325 Pa and 0.0004 × 101,325 Pa respectively.

2.3. Food waste at consumer level model

In order to calculate food waste at consumer level, the deterioration model presented in section 2.2. was combined with results from the consumer survey presented in section 2.1. The final model was developed in MATLAB (The MathWorks Inc., Natick, Massachusetts, USA) (The MathWorks Inc, 2021) software and is represented in Fig. 1. It includes the purchase step at retailer, the transport from retailer to consumer, the storage at consumer's home and the consumption step. The model is described below according to 4 sections, referred as to a, b, c and d on Fig. 1.

All parameters used in the model are listed in Table 3.

2.3.1. Initial deterioration and relationship between deterioration stage and deterioration percentage of strawberries

The second section of the consumer survey was based on strawberry trays ranked according to 6 different stages of deterioration (0–5). To allow the use of the deterioration model, one has to convert the discrete indicator, i.e. the initial deterioration stage $Stage(t_0)$, into a continuous indicator, i.e. the initial deterioration surface $D(t_0)$. A correlation table was established between both deterioration stages and ranges of deterioration surface percentages. The initial deterioration at supermarket was defined by a deterioration stage, and the corresponding initial deterioration percentage followed a uniform distribution according to this correlation table.

To establish the correlation table, for each deterioration stage, measurements of the deterioration surface percentages were performed on several pictures showing strawberries with the considered deterioration stage, in order to associate a deterioration percentage range for each deterioration stage. The deterioration model follows an entire tray; therefore, the deterioration percentage and stage were considered for a whole tray, and not for each strawberry of a tray. All measurements were done by the same person, who was an expert from the CTIFL who has worked on the establishment of the deterioration scale presented in Table 1. More information on the building of the correlation table is available in Supplementary material.

2.3.2. Determination of the consumer group at purchasing step

No food waste was considered at the supermarket level; every tray was assumed to have been purchased by a consumer. In this study, purchasing groups were categorized based on their behavior toward strawberry tray deterioration stages: each group was characterized by a purchasing decision (buy or not buy) at each deterioration stage (Table S1) and by its representativeness within the general population. Only the patterns identified as consistent were retained to define these purchasing groups. Based on this clustering, certain groups consistently avoided purchasing trays at specific deterioration stages.

In the model, a consumer was generated for each tray and assigned to a purchasing group according to a random distribution aligned with the group representativeness observed in the survey. However, not all consumers could purchase all trays; this depended on both the tray's deterioration stage and the purchasing behavior typical of their assigned group. Only groups that indicated they would buy a tray at the given deterioration stage were represented in the purchasing distribution.

2.3.3. Evolution of temperature and time

Time and temperature evolution during transport and storage at consumer were defined according to the consumer study results for the global population.

During transport between the supermarket and the consumer. The transport duration between supermarket and consumer was assumed to follow an exponential distribution, with a parameter of 0.05 day (Derens et al., 2006). The environmental temperature followed a uniform distribution, whose parameters vary according to the location. In this study, temperatures representative of Montpellier weather in summer were considered (uniform distribution between 15.4 °C and 36.6 °C in June 2023) (Infoclimat, 2023). The duration and temperature were assumed to be the same whatever the mean of transport (i.e. by bike, by foot, by public transport or by car).

In the consumer's home. There were two possibilities for storage: either the consumer stored the strawberries in the kitchen at ambient temperature or in the fridge (no difference made between the shelves

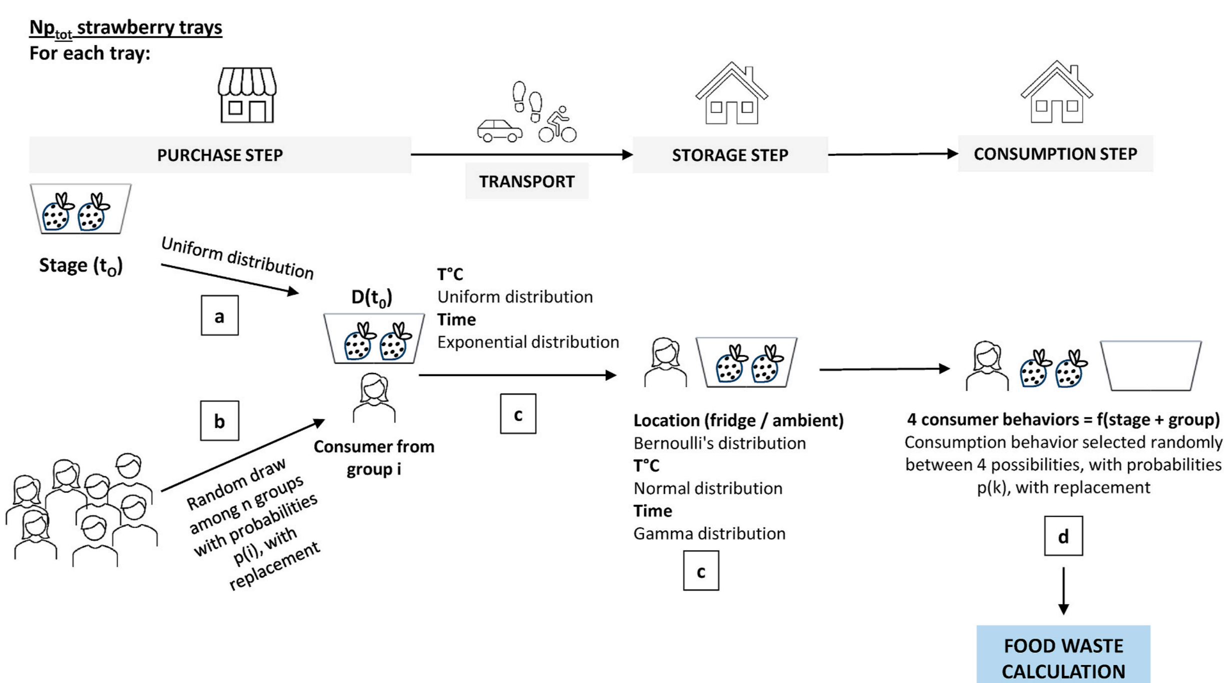

Fig. 1. Global representation of the model to estimate food waste at consumer level.

and vegetable compartment in the fridge because the relative humidity was not included in the model and the temperatures were considered to be the same). When consumers answered "Other" for storage area, it was considered that storage was done at ambient temperature and grouped with the probability to be stored in the kitchen at ambient temperature. The probability of a tray being stored in one or the other condition followed a Bernoulli distribution, with probabilities defined according to the consumer survey results. If stored in the fridge, the temperature followed a normal distribution $\mathcal{N}(5.9; 2.9)$, truncated with a minimum of 0 °C and a maximum of 12 °C (Derens et al., 2006). If stored in the kitchen, the temperature followed a normal distribution $\mathcal{N}(20.9; 1.7)$, as observed in living rooms of 823 UK households in July 2011 (BRE, 2013) (data could not be found for Montpellier in June).

Consumer study results were also used to determine the storage duration distribution. Data obtained in the questionnaire answers were given in time intervals as "less than a day" (20% occurrence), "one day" (42% occurrence), "two days" (29% occurrence), "three days" (7% occurrence), "four days" (1% occurrence) and "more than five days" (1% occurrence). To fit a statistical distribution, data were interpreted as "0–24 h", "24–48 h", "48–72 h", "72h to 96 h" and "96 to ND" (not defined data), respectively. To fit a statistical distribution on such interval data, the R package "fitdistplus" was used (Pouillot and Delignette-Muller, 2010). Several distributions were compared using the bayesian information criterion, finally, a gamma distribution was chosen (Table 3).

Strawberry temperature evolution. Regarding the strawberries' temperature, the difference between the pulp and the surface and the difference between the packaging material, the headspace and the strawberry's surface were considered negligible. Thus, in the deterioration model, the temperatures of the strawberries, headspace atmosphere and packaging were equal at time *t*, and assumed to be constant during a time step. The temperature of the strawberries, headspace and packaging unit was assumed uniform and to follow the external temperature, according to the thermal model below:

$$T_{t+1} = T_a + (T_t - T_a)e^{-\frac{t}{\tau}} \quad \text{(Eq. 2)}$$

where T_{t+1} is the temperature of the packed strawberries unit (K) at time $t+1$ (s), T_a is the temperature of the ambient air (K), T_t is the temperature of the packed strawberries unit (K) at time t (s) and τ is the characteristic time (s) of the packed food unit. The deterioration was calculated (Equation (1)) considering a mean temperature over the time step T_i (K), calculated as follows:

$$T_i = \frac{(T_t + T_{t+1})}{2} \quad \text{(Eq. 3)}$$

2.3.4. Determination of consumption behavior and calculation of food waste

It was assumed that each consumer could only buy one tray of strawberries at a time, and that one tray was consumed in one go by one consumer. For each group of consumers defined according to their behavior at purchase, a consumption behavior scheme was defined, depending on the strawberries' deterioration stage. Four consumer behaviors were tested in the consumer questionnaire: (1) eating all the strawberries, (2) removing, and throwing away the damaged parts, (3) removing, and throwing away the damaged strawberries, and (4) eating no strawberries. The occurrences of each of these behaviors were set according to the purchasing group (defined at purchase) and to the deterioration stage and were calculated from the consumer survey. In the model, for each strawberry tray, the consumer behavior was selected according to the behavior pattern (i.e. probability of each consumption behavior) of the purchasing group which was defined at the purchase step.

The deterioration model only enabled to follow a strawberry tray deterioration. It did not allow to follow each strawberry. Therefore, for behavior 3, two options were considered: food waste generated by behavior 3 was considered to be similar to that generated by behavior 2, or to be similar to that generated by behavior 4. Thus, the impact of approximating this behavior was assessed by considering minimized food waste (assimilated to behavior 2) and maximized food waste (assimilated to behavior 4). For each behavior, food waste *FW* (in kg) was calculated as follows, considering that the surface deterioration percentages were equivalent to the mass deterioration percentages:

1.
$$FW = 0 \quad \text{(Eq. 4)}$$

2.
$$FW = \frac{D}{100} \times m \times (1 - r_{calyxes}) \quad \text{(Eq. 5)}$$

3.
$$FW = FW\,(\text{case ii}) \text{ or } FW = FW\,(\text{case iv}) \quad \text{(Eq. 6)}$$

4.
$$FW = \frac{100}{100} \times m \times (1 - r_{calyxes}) \quad \text{(Eq. 7)}$$

where m is the mass of strawberries purchased (in kg) and $r_{calyxes}$ is the ratio of the mass of strawberry calyxes over the total strawberry mass (equal to 1.5%, i.e. 0.015 in the above equations).

3. Results & discussion

3.1. Consumer survey results

3.1.1. Studied population

In this study (N = 509), the average age of the participants questioned is 48.6 years old (±15.0). The average age here is higher than the French census INSEE 2022 (average age: 42.2 years), because children were excluded from this study. When analyzed by age groups (18–34, 35–44, 45–54, 55+), the sample of participants reflects the age distribution of the French adult population (Table 4). The sample is also representative in terms of gender, with 52.3% female respondents, closely aligning with the 51.7% female representation in the French population. Regarding the distribution of social and demographic factors, within this population sample surveyed, all socio-professional categories were represented, with an over-representation of executives and assimilated (47.3 %). The residential areas were balanced, between the representation of areas with a density lower or higher than 100,000 inhabitants (Table 4).

3.1.2. Purchasing consumer practices

Consumer habits for purchasing fruits and vegetables, including strawberries specifically, were examined from store to home.

3.1.2.1. Purchase location. The chi-squared test conducted to compare the two modalities (yes and no) for each mean of transportation shows that the majority of French respondents (75%) use a car to shop for fruits and vegetables, a significantly higher proportion compared to those who use public transport, cycling, or walking ($\chi^2 = 966.86$, $p < 0.001$).

The chi-squared test conducted to compare purchase frequencies across the different purchase locations shows that shopping frequency for fruits and vegetables is predominantly "at least once a week" at malls

Table 4
Summary information about participants taking part in the research.

	Participants taking part in the research (n = 509)	French Census (INSEE, 2022)	χ^2 Sig.
Age range			0.40 ns
18–34 yr.	24.7 %	22.6 %	
35–44 yr.	18.1 %	16.3 %	
45–54 yr.	17.3 %	17.0 %	
55+ yr.	39.9 %	44.1 %	
Gender			0.01 ns
Females	52.3 %	51.7 %	
Males	47.7 %	48.3 %	
Socio-professional group			106.53 ***
Executives and assimilated	47.3 % A		
Employees and assimilated	35.6 % B		
Inactive	17.1 % C		
Residential area			2.86 ns
Low density (<100K inhab.)	47.3 %		
High density (>100K inhab.)	52.7 %		

χ^2 test, ***p < 0.001, ns = not significant difference.

and markets, while Community-Supported Agriculture (CSA) and online purchases are overrepresented in the “never” category ($\chi^2 = 1206.37$, $p < 0.001$). For strawberries specifically, a similar trend is observed, although with a lower purchase frequency across malls, specialty stores, producers, CSA, and online platforms ($\chi^2 = 823.29$, $p < 0.001$).

Although the trend is similar, we observe that among the 61% of consumers who purchase fruits and vegetables weekly at supermarkets, only 27% include strawberries in their purchases (Fig. 2). Indeed, the chi-squared test conducted to compare purchase frequencies across fruits and vegetable and strawberries in mall indicates that strawberries are not typically a standard component of weekly fruit and vegetable shopping routines ($\chi^2 = 146.57$, $p < 0.0001$).

3.1.2.2. Selection criteria. For fruits and vegetables, an over-representation of respondents "totally agree" on the importance of freshness, seasonality, French origin, and personal preference as selection criteria ($\chi^2 = 1213.75$, $p < 0.001$). For strawberries, over 50% "totally agree" on the importance of seasonality, general condition, freshness, and French origin ($\chi^2 = 398.47$, $p < 0.001$), indicating higher importance compared to general fruits and vegetables. For both categories, more respondents "totally disagree" on the relevance of organic, packaging, and social reintegration assistance criteria (Fig. 3).

3.1.3. Home strawberry management habits

3.1.3.1. Storage management. Once home, different strawberry management strategies were evidenced (Table 5).

Comparably, consumers either keep the original packaging intact (31%), keep it open (32%), or use another container (35%). Mostly, 63 % of consumers keep (in full or partially) the original packaging of the product.

The strawberries are then mostly stored at cool temperature in the refrigerator (76%), more frequently in the vegetable drawer (51%). Only a fifth (21%) of consumers keep them in the kitchen, at room temperature. 3% of consumers answered “Others”. In the consumer model, it was thus considered that 24% of consumers would store strawberries under ambient conditions.

In equivalent proportions, they are kept either dry or after moistening ($\chi^2 = 2.88$, p-value = 0.09). For 56% of consumers, they are stored dry, then cleaned (51%) or not (5%) before consumption. For 44% of consumers, they are cleaned before their total (21%) or partial storage life (23% all washed after the first use).

Once at consumer’s home, their conservation is of short duration: 20% of consumers store them less than a day (i.e. 0-24h), 42 % store them one day (i.e. 24h–48h), 29% store them for two days, 7% store them three days, and 2% store them four days or more.

3.1.3.2. Perception of strawberries’ deterioration by consumers. There

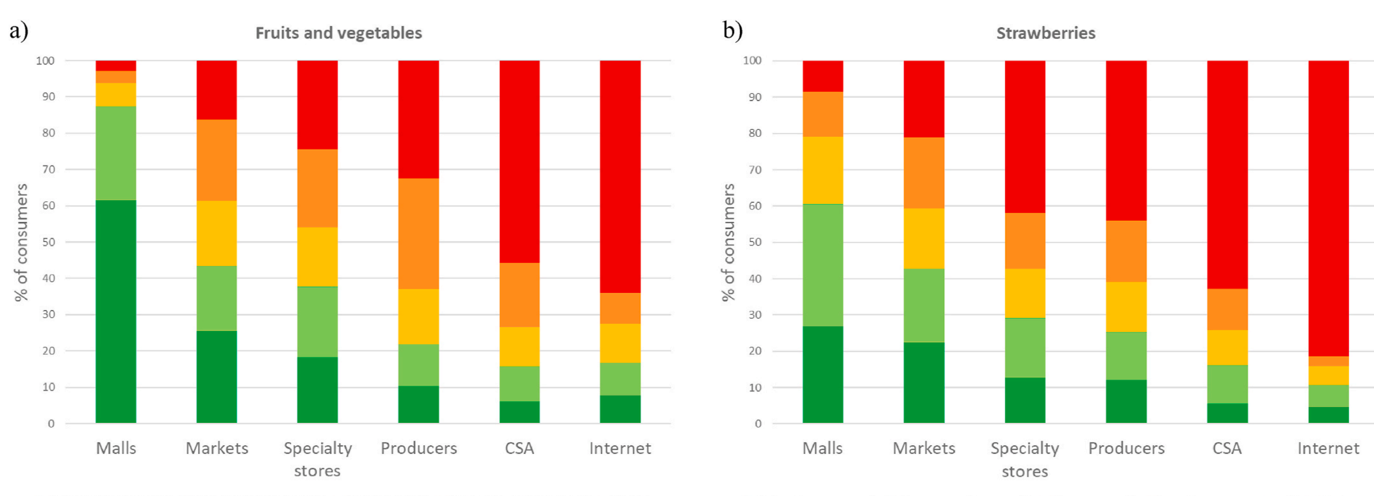

Fig. 2. Frequentation of locations for the purchase of a) fruits and vegetables and b) more specifically for strawberries (raw data: https://doi.org/10.57745/H7AWBV). *CSA: Community-Supported Agriculture.

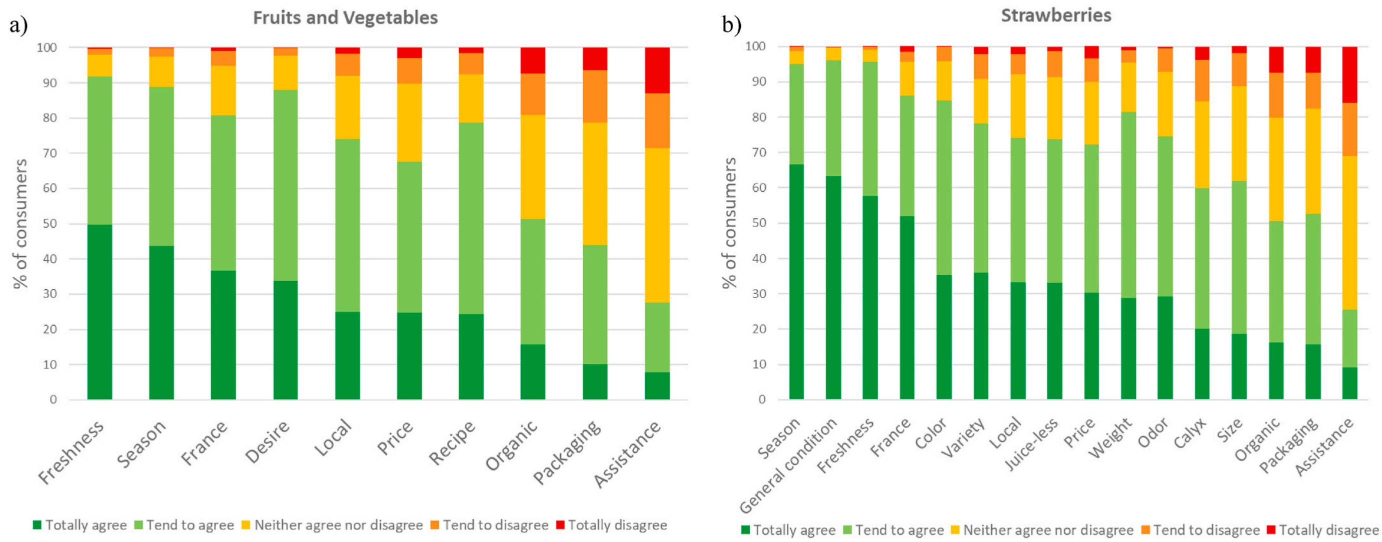

Fig. 3. Selection criteria in a) fruits and vegetables purchase and b) strawberries purchase (raw data: https://doi.org/10.57745/H7AWBV).

Table 5
At home strawberries management typicality, Summary of the Chi-square analysis.

		χ^2 Sig.
Storage container		197.08 ***
In their original packaging, unopened	31.4 % A	
In their original packaging, after opening it	32.0 % A	
In another container	34.8 % A	
Other	1.8 % B	
Storage area		317.68 ***
In the fruits and vegetables compartment of the refrigerator	51.1 % A	
On a refrigerator shelf	25.1 % B	
In the kitchen, at room temperature	20.5 % B	
Other	3.3 % C	
Storage washing condition		501.51 ***
I wash them before storing	20.6 % B	
I wash them the first time I eat some, even if I don't plan to eat them all	23.2 % B	
I wash them as I consume them	50.9 % A	
I don't wash them	4.9 % C	
Other	0.4 % D	
Storage time before consumption		511.57 ***
Less than a day	19.6 % C	
One day	42.0 % A	
2 days	29.3 % B	
3 days	7.1 % D	
4 days	1.2 % E	
More than 4 days	0.8 % E	

χ^2 test, ***p < 0.001.

were differences on the importance given to the criteria for the identification of a damaged strawberry (χ^2 = 325.08, p-value <0.001). The participants who "totally agree" with the importance given to the criteria "mold" (63 %) and "texture" (44 %) were overrepresented in the identification of a damaged strawberry (Fig. 4).

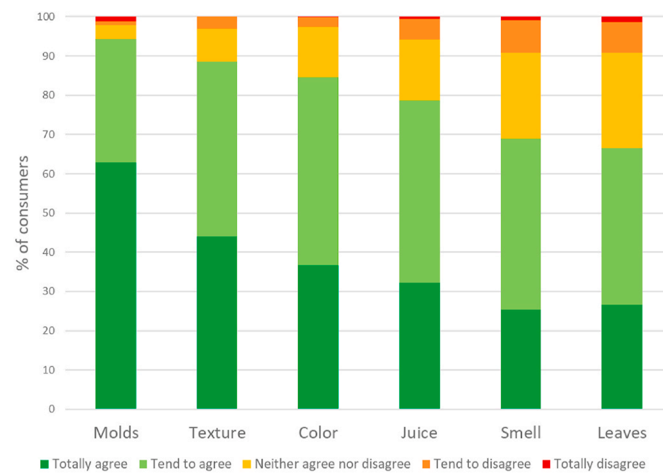

Fig. 4. Criteria defining a damaged strawberry (raw data: https://doi.org/10.57745/H7AWBV).

3.1.4. *Acceptance for purchase, consumption and consumer profiles*

Finally, a focus was made on the acceptance of strawberries from selection to consumption, according to their perceptual evolution. The second section followed with questions related to the concrete presentation of a set of strawberry trays photos, questioning the intention to purchase (2A), then to consume (2B). The answers from the global population are presented in Fig. 5. Consumers mainly purchase strawberries when their deterioration stage is 0 or 2. Half of the consumers said they would buy it when the deterioration stage was 3, and more than half of the consumers would not buy it when the deterioration stage was 4 or 5.

However, consumers were more likely to consume strawberries until later stage, since 64% of consumers would eat all the strawberries or cutting off the damaged parts when strawberries are at stage 4.

Among 32 theoretical purchasing patterns, 19 patterns were present in the studied population, among which 11 were identified as consistent (Table 6). For example, Group 11 buys strawberries at all stages, while Group 7 buys only at stage 0. Group 6, conversely, avoids strawberries at stage 0 but buys at other stages.

Then, for each purchasing group defined based on their purchase behavior, consumption behavior could be defined and showed a high variability of consumer profiles (Fig. 6). Groups 6 and 11 for instance do

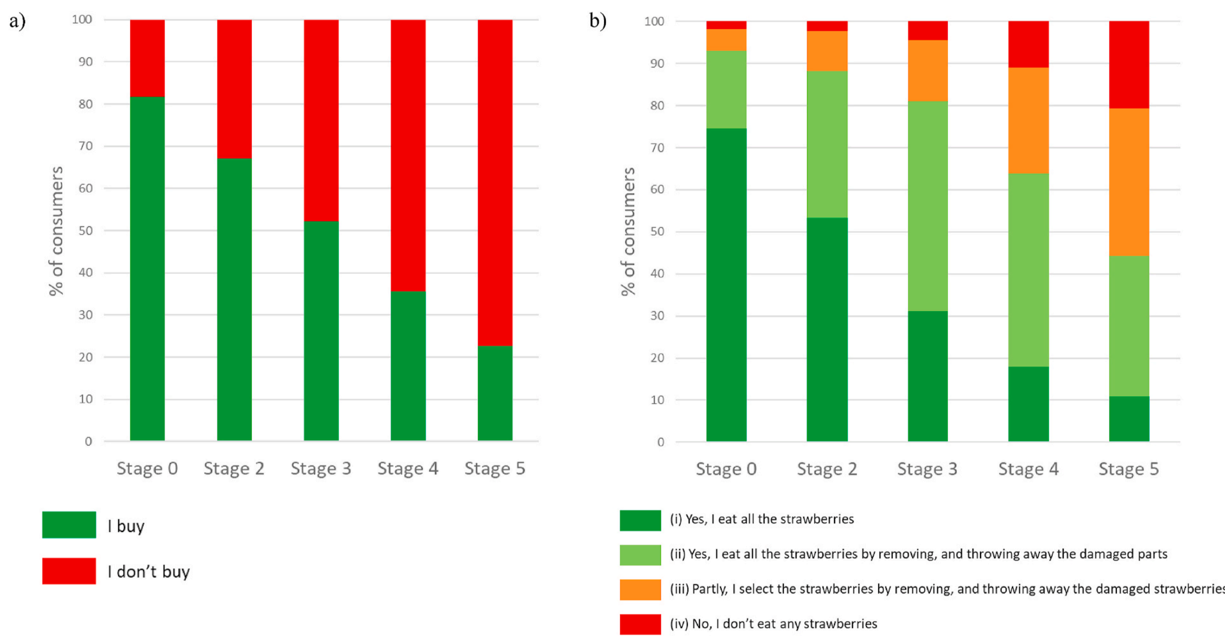

Fig. 5. a) Purchase intent and b) consumption intent of the tray presented, with different deterioration stages (raw data: https://doi.org/10.57745/H7AWBV).

Table 6
Purchasing behavior for each purchasing group.

Purchasing group	Deterioration stage					Frequency of each group (%)
	S0	S2	S3	S4	S5	
11	Yes	Yes	Yes	Yes	Yes	26.82
10	Yes	Yes	Yes	Yes	No	11.53
9	Yes	Yes	Yes	No	No	18.35
8	Yes	Yes	No	No	No	18.82
7	Yes	No	No	No	No	18.82
6	No	Yes	Yes	Yes	Yes	0.24
5	No	Yes	Yes	Yes	No	0.47
4	No	Yes	Yes	No	No	2.12
3	No	Yes	No	No	No	1.41
2	No	No	Yes	Yes	No	0.47
1	No	No	Yes	No	No	0.94

not waste a lot and eat full or part of strawberries even when the deterioration is high. Thus, Group 11 does not waste a lot at the retailer and household steps. On the contrary, group 7 and 8, who only bought strawberries with low deterioration stages, accordingly, waste a lot at consumption when the deterioration stage is high (4 or 5).

Deterioration stage 1 was not considered in the consumer survey, since no visual difference was seen on the pictures with deterioration stage 0. Thus, for the following food waste model, consumer behavior in terms of purchase and eating for deterioration stage 1 was considered to be the same as consumer behavior for deterioration stage 0.

Chi-square analysis showed no significant association between purchasing groups and storage location or duration, justifying a consistent storage behavior across all groups.

3.2. Food waste model

3.2.1. Relationship between deterioration stage and deterioration percentage

The correspondence between all the deterioration stages and deterioration percentages is given in Table 3. Stage 0 corresponds to]0–1%], Stage 1 to [1–5%], Stage 2 to [5–20%], Stage 3 to [20–40%], Stage 4 to [40–60%] and Stage 5 to [60–100%]. The deterioration model follows a logistic equation (Equation (1)): if the initial deterioration is equal to 0%, the deterioration will remain equal to 0% over time. Thus, for stage 0, the initial deterioration was strictly superior to 0%.

It is worth noting that the percentage of deterioration is representative of all kinds of defects on the strawberry surface, including molds, changes in texture and changes in color, without considering the prioritization among criteria defining a damaged strawberry given by the consumers in Fig. 4. Moreover, since the measurement of the deterioration was done visually and on the strawberry surface without considering the calyxes, juice, smell and leaves criteria were not considered. However, these last parameters can often be combined with changes in texture or color, which are themselves considered. Moreover, one should keep in mind that the percentage ranges were defined by experts. Thus, it was assumed that the selected percentage ranges were representative of every single deterioration mark on the strawberries. However, this deterioration may not be perceived as such by consumers. Therefore, when a consumer said to eat only the non-damaged part, the model would consider the “real” non-damaged part, which might be different from the perceived non-damaged part. This means that the present model may overestimate the food waste at consumer level. The correlation table between deterioration stages and percentages has a paramount impact on the absolute results. Thus, validating it by checking the difference of perceptions of damages between consumers might be interesting to get more accurate results.

3.2.2. Model parameters

The results of the consumer study enabled to fulfill the missing parameters for the global model (Table 3).

The consumer questionnaire results showed that 44% of consumers clean the strawberries before total or partial storage. Although this consumer behavior most probably impacts the further strawberry deterioration evolution, it was not possible to take this information into consideration in the model, which might underestimate the food waste for these consumers.

3.2.3. Model results and impact on food waste

Simulations were performed considering seven scenarios: all trays had the same initial deterioration stage, each scenario considering one of the six deterioration stages (0, 1, 2, 3, 4 and 5). Since stage 1 was not included in the questionnaire, because no visual difference could be seen

Fig. 6. Eating behavior for each purchasing group (raw data: https://doi.org/10.57745/H7AWBV).

between stage 0 and stage 1 on the pictures, consumer behavior observed for stage 0 was considered to be the same as for stage 1. An additional run was performed with a mix of trays with different initial deterioration stages (from 0 to 5), with an equiprobable distribution between each stage. No scenario may be fully representative of reality, even the last one, since the distribution of deterioration stages would most likely not be uniform. Indeed, the biological variability that exists among strawberries at supermarket should also be considered, as it would lead to different deterioration stages even for strawberries belonging to the same cultivar, harvested at the same time and following

Table 7
Food purchased (kg) and food waste (in kg and %) for each scenario (10,000 trays), globally and per purchasing group. Food waste percentage was defined as the total food waste (kg) over the total purchased food (kg). The mass of the calyxes was removed from both masses of food waste and purchased food. Stages represent the stage at purchase, which may differ from stage at consumption.

	INITIAL STAGE AT PURCHASE						
	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Mix (0–5)
GLOBAL							
Purchase (kg)	2758[b]	2758	2758	2758	2758	2758	2758
Food waste (kg)	260	557	1026	1517	1647	1586	1108
Food waste (%)	**9.4**	**20.2**	**37.2**	**55.0**	**59.7**	**57.5**	**40.2**
PURCHASING GROUP 1 (0.9% of global population)							
Purchase (kg)	0	0	0	42.7	0	0	5.0
Food waste (kg)	0	0	0	24.9	0	0	3.4
Food waste (%)[a]	NA	NA	NA	**58.2**	NA	NA	**69.1**
PURCHASING GROUP 2 (0.5% of global population)							
Purchase (kg)	0	0	0	18.5	34.5	0	8.0
Food waste (kg)	0	0	0	12.7	28.8	0	5.7
Food waste (%)[a]	NA	NA	NA	**68.6**	**83.7**	NA	**71.7**
PURCHASING GROUP 3 (1.4% of global population)							
Purchase (kg)	0	0	49.4	0	0	0	10.8
Food waste (kg)	0	0	20.1	0	0	0	4.7
Food waste (%)[a]	NA	NA	**40.7**	NA	NA	NA	**43.7**
PURCHASING GROUP 4 (2.1% of global population)							
Purchase (kg)	0	0	70.3	98.2	0	0	29.5
Food waste (kg)	0	0	28.6	65.4	0	0	15.4
Food waste (%)[a]	NA	NA	**40.7**	**66.6**	NA	NA	**52.3**
PURCHASING GROUP 5 (0.5% of global population)							
Purchase (kg)	0	0	16.3	20.7	31.4	0	11.6
Food waste (kg)	0	0	8.1	14.1	25.7	0	7.6
Food waste (%)[a]	NA	NA	**49.9**	**68.1**	**81.9**	NA	**65.3**
PURCHASING GROUP 6 (0.2% of global population)							
Purchase (kg)	0	0	8.5	7.2	13.5	24.5	10.5
Food waste (kg)	0	0	3.6	5.1	11.0	22.9	8.5
Food waste (%)[a]	NA	NA	**41.6**	**70.9**	**81.7**	**93.1**	**81.4**
PURCHASING GROUP 7 (18.8% of global population)							
Purchase (kg)	551.0	551.0	0	0	0	0	184.8
Food waste (kg)	67.6	163.5	0	0	0	0	38.4
Food waste (%)[a]	**12.3**	**29.7**	NA	NA	NA	NA	**20.8**
PURCHASING GROUP 8 (18.8% of global population)							
Purchase (kg)	553.3	553.3	658.9	0	0	0	295.4
Food waste (kg)	52.5	115.2	296.7	0	0	0	80.2
Food waste (%)[a]	**9.5**	**20.8**	**45.0**	NA	NA	NA	**27.2**
PURCHASING GROUP 9 (18.4% of global population)							
Purchase (kg)	542.2	542.2	625.2	841.7	0	0	406.8
Food waste (kg)	57.3	114.8	278.6	590.9	0	0	163.2
Food waste (%)[a]	**10.6**	**21.2**	**44.6**	**70.2**	NA	NA	**40.1**
PURCHASING GROUP 10 (11.5% of global population)							
Purchase (kg)	338.4	338.4	408.2	509.4	792.1	0	412.3
Food waste (kg)	32.2	68.6	168.5	339.1	651.2	0	218.0
Food waste (%)[a]	**9.5**	**20.3**	**41.3**	**66.6**	**82.2**	NA	**52.9**
PURCHASING GROUP 11 (26.8% of global population)							
Purchase (kg)	773.1	773.1	921.2	1219.6	1886.5	2733.5	1383.4
Food waste (kg)	50.3	95.1	222.1	464.9	930.5	1563.3	563.2
Food waste (%)[a]	**6.5**	**12.3**	**24.1**	**38.1**	**49.3**	**57.2**	**40.7**

[a] Food waste (%) is not exactly equal to the ratio of food waste (kg) over purchase (kg) presented in the table because round numbers were presented in the table, and food waste was calculated based on full numbers.
[b] 2758 kg of purchased strawberries correspond to 10,000 trays of 280 g of strawberries, from which the calyx mass (1.5%) was removed.

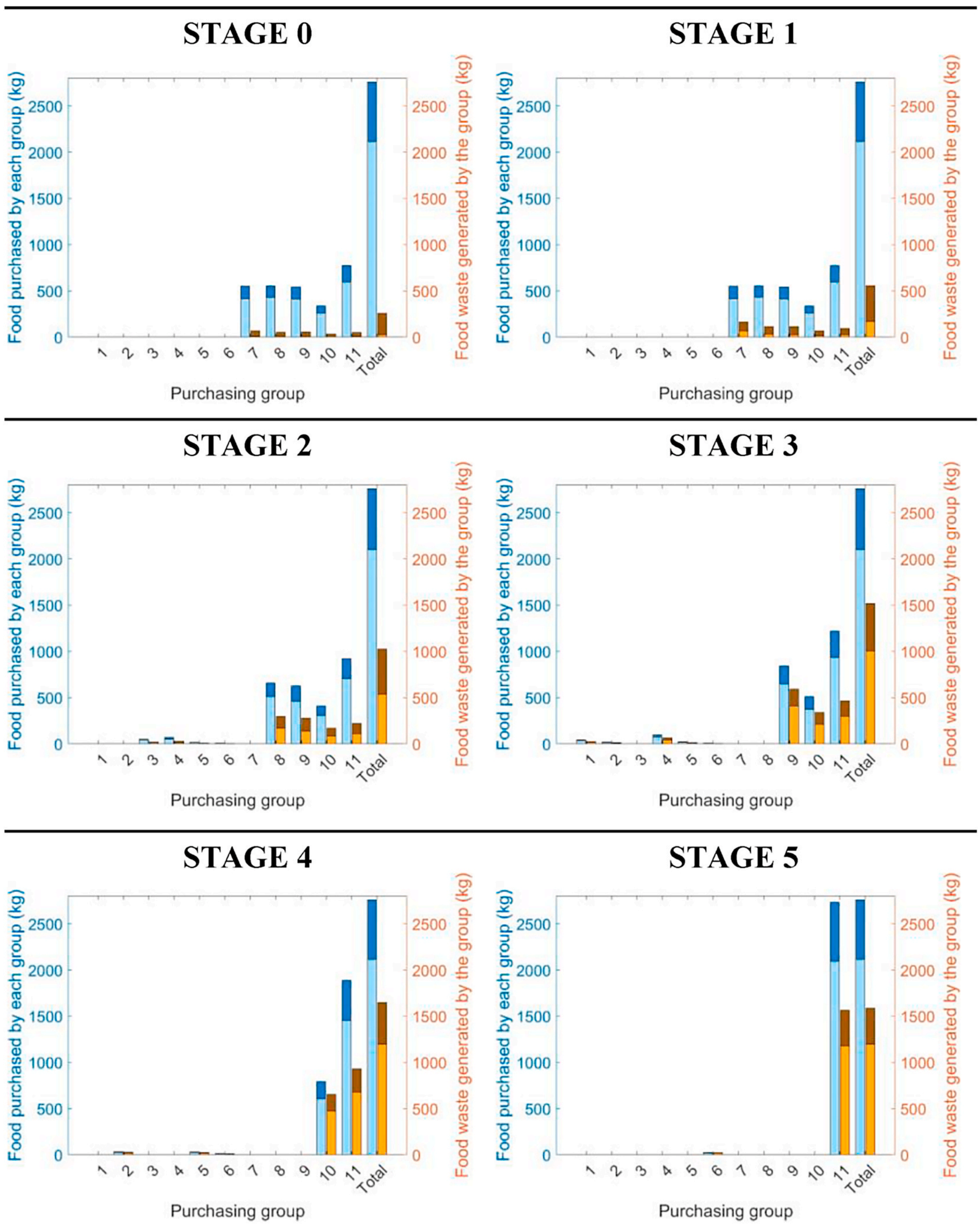

Fig. 7. - Strawberries purchased (blue) vs wasted (orange) (in kg) by each purchasing group and in total, according to storage condition at consumer, in the fridge (light color) and in ambient (dark color). Results for each scenario (initial stage at supermarket).

the same logistic steps until the retailer. Moreover, strawberry trays from different logistic chains could be mixed at the retailer. However, the purpose of the current study was to assess the impact of product deterioration at supermarket on the FLW at consumers, rather than to be realistic in terms of product deterioration at the supermarket. For each scenario, $Np_{tot} = 10{,}000$ trays were considered. Estimated food waste for the seven scenarios are in Table 7. However, in Figs. 7–9, the results with the mix of trays are not presented. They are available in Supplementary materials (Table S2). The initial deterioration stages at supermarket differ according to product variability, arising from biological and/or harvesting variations, and also partly according to the distribution channels observed in Fig. 2: stage 0 or 1 at supermarket could be partly associated to a short upstream supply chain with refrigerated conditions and little handling, leading to small deterioration, whereas stage 3 at supermarket could be associated to longer upstream supply chain and/or with a cold chain that is not always respected. Stage 5 at supermarket could be representative of defects or issues encountered in the upstream cold chain. Therefore, considering six initial deterioration stages allows to assess the importance of the distribution channel as well as the upstream supply chain conditions on the resulting food waste. The figures show the results when consumer behavior 3 ("Partly, I select the strawberries by removing, and throwing away the damaged strawberries") is assimilated to consumer behavior 2 ("Yes, I eat all the strawberries by removing, and throwing away the damaged parts"). The results when consumer behavior 3 is assimilated to consumer behavior 4 ("No, I don't eat any strawberries") were only discussed in this section.

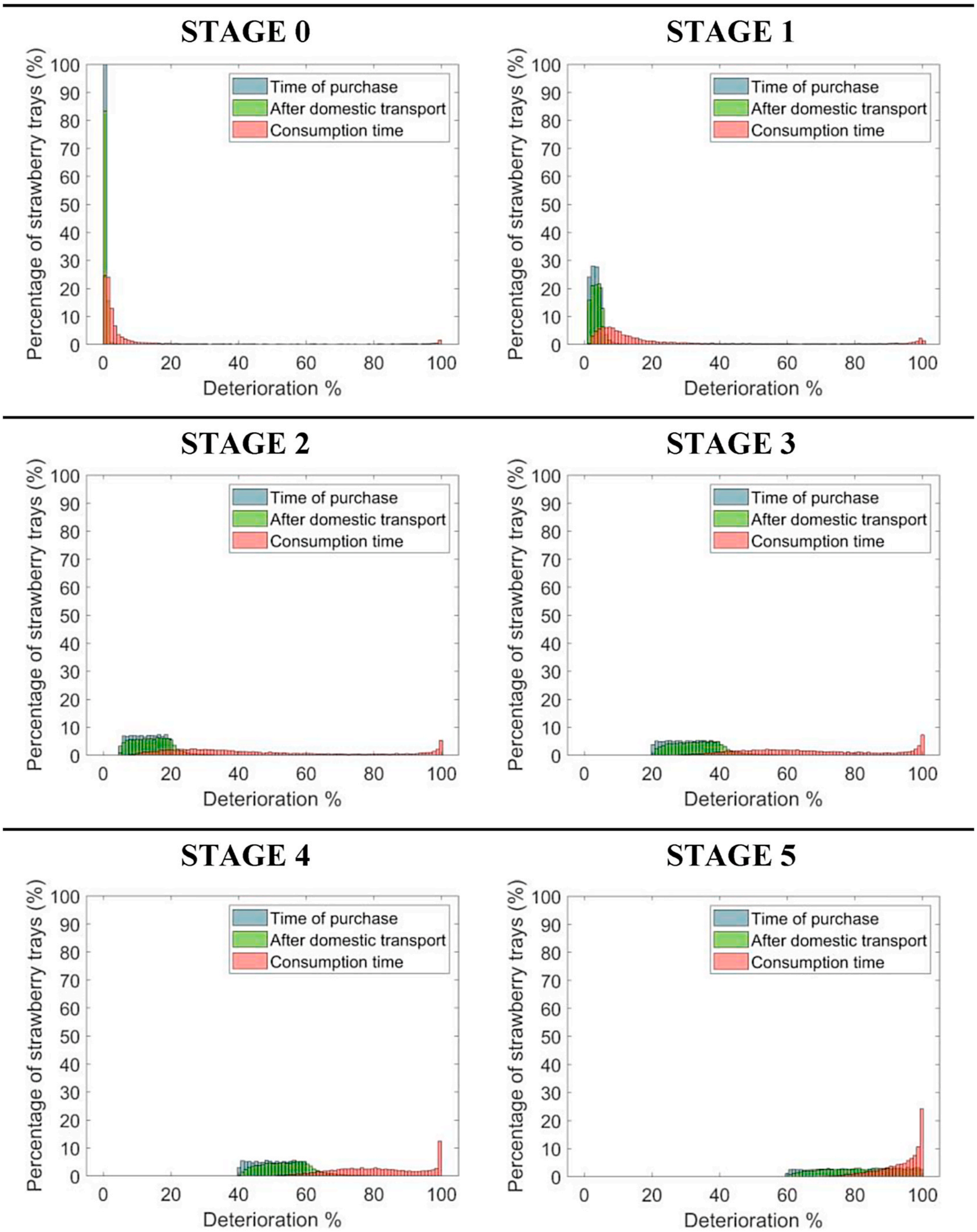

Fig. 8. - Deterioration (%) at time of purchase, after transport and at consumption time. Results for each scenario (initial stage at supermarket).

As shown in Table 7, total food waste increases with the initial deterioration stage, going from 9.4% with initial stage of 0 to 59.7% with initial stage of 4. The first value is coherent with what was found by Matar et al. (2020), who suggested a food waste of 9.21% when considering a non-modified atmosphere packaging and an initial deterioration of 0.2% (i.e. stage 0) (Matar et al., 2020). A slight decrease is observed between initial stage 4 and initial stage 5. This can be explained by the fact that when they reach a stage 5, strawberry trays are only bought by group 11 and group 6, the latter representing 0.24% of the global population. Therefore, almost only consumers from group 11 buy these trays. Yet, when looking at the consumer survey results, one can see that group 11 does not waste a lot and eat all strawberries or part of them even when the deterioration stage is high. In Table 7, one can also see that percentage of food waste generated by group 11 is always lower than for other groups and lower than the average food waste. This can explain the slightly lower result observed for stage 5 compared to stage 4, whose trays are bought by a higher diversity of consumers, including group 10 whose 18% of consumers throw the whole tray when deterioration stage is 5 at consumption.

Stage 0 at supermarket represents the lowest degradation possible at supermarket. This suggests an unavoidable minimum food waste percentage at consumer level, which is 9.4% in the present case. However, this unavoidable minimum food waste may change, according to the location for instance, which will impact the temperature and duration of transport. Consumers could also be advised to keep strawberries for a maximum of two days for instance. Table 7 also highlights the

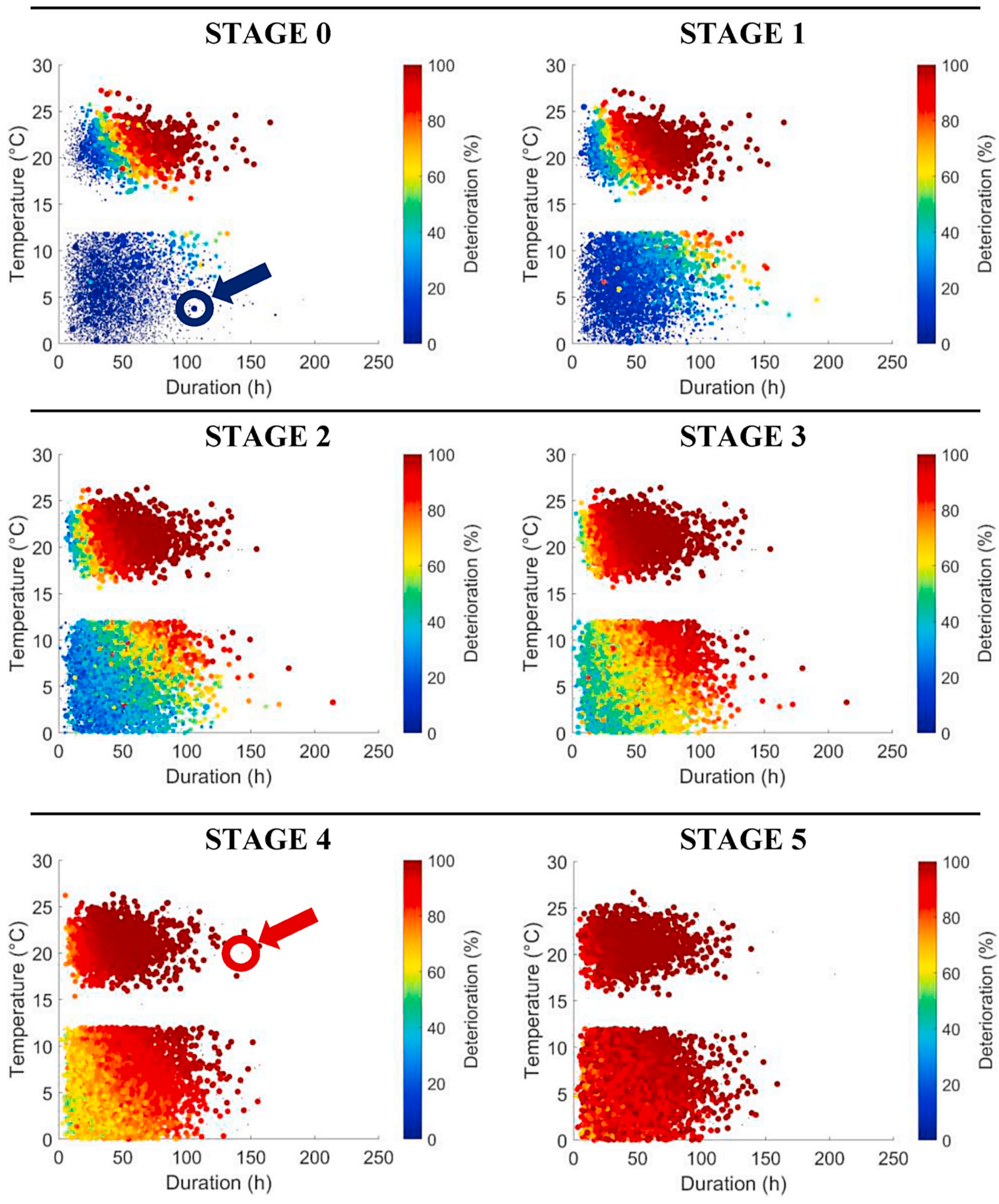

Fig. 9. - Percentages of deterioration according to temperature and time of storage. The size of the markers is linked to the food waste through a linear function. Results for each scenario (initial stage at supermarket).

paramount impact of the upstream supply chain conditions: indeed, if all strawberries are already at stage 1 at the retailer, the food waste is doubled, and it reaches 55% when initial deterioration stage is 3, which is significantly higher. In reality, there is a mix of trays with different deterioration stages on the supermarket shelves. Then, starting with a mix of strawberry trays (from stage 0–5), the total estimated food waste was 40.2%, which is close to the 35% found in the literature for the US market (Qin and Horvath, 2021), underlying the realistic aspect of the model. Moreover, the mix simulated in this study included strawberry trays with a deterioration stage of 5, which is very high (>60%) and might not be representative of the reality in supermarkets. Moreover, although more realistic than considering only trays with the same deterioration stage at supermarket, this scenario does not represent the real upstream logistics, which are not simulated in this model. This could explain the higher food waste results in the present study compared to the one of Qin et al. (2021) (Qin and Horvath, 2021). Differences might also be due to the different geographical areas: logistics conditions as well as consumers' behaviors and product variety and thus, physiological behavior, might be different in France and in the US. To calculate the food waste in the present study, it was considered that eating behavior 3 resulted in the same waste as eating behavior 2, i. e. when the consumer said that they only eat the non-damaged strawberries, it was considered that the consumer eats only the non-damaged parts of the strawberries and throw the rest away. This assumption may underestimate the real food waste. By considering that eating behavior 3 resulted in the same waste as eating behavior 4, i.e. if there is at least one damaged strawberry in the tray, the consumer throws the whole tray away, the food waste increases from 9.4% and 55% to 13.8 and 61% for initial deterioration stages of 0 and 3 respectively. Making this second assumption may overestimate real food waste, while the first assumption may underestimate real food waste. The reality must be in between. According to the consumer study results, eating behavior 3 represents respectively 5%, 5%, 7%, 8%, 25% and 36% of the eating behavior when considering stages 0, 1, 2, 3, 4 and 5 at consumption. Thus, the approximation of assimilating eating behavior 3 to another one will be mainly impactful for stages 4 and 5 at consumption. Considering the seven scenarios performed in this study, with eating behavior 3 assimilated to eating behavior 2, eating behavior 3 represented from 7 to 22% of the eating behaviors and was responsible for 23 to 31.5% of the generated food waste, which is quite impactful. However, this assimilation was compulsory since the model does not allow to follow the deterioration of each strawberry, but only the global tray deterioration. Further improvements could include the modification of the deterioration model to follow each strawberry deterioration over time, or a deeper consumer study to better understand behavior 3 and assess if it would be closer to behavior 2 or 4.

Food waste is not only dependent on the initial deterioration, but also on the consumer behavior, i.e. the eating behavior and the storage conditions (Fig. 7). Indeed, when initial deterioration stage was 3, consumers from group 9 wasted 70.2% of the strawberries they bought, while group 11 wasted less than half of their purchase (38.1%) (Fig. 7 – Stage 3). It shows the impact of the consumer behavior and most of all, the necessity to consider their diversity. Moreover, in total, 24% of the strawberries bought were stored at ambient temperature and represent a higher percentage of the strawberries wasted for initial deterioration stages of 0, 1 and 2, evidencing the positive effect of cold storage, and the importance of considering storage location at the consumer in the food waste model. However, from initial stage 3, strawberries stored in the fridge were wasted just as much as those stored at ambient temperature. This could be due to the already advanced deterioration percentage of the strawberries from the supermarket, so that cold storage is not sufficient to prevent further deterioration. However, this underlines a limit of the model: the same storage time and temperature probabilities were applied whatever the initial deterioration stage. One can imagine that consumers who buy strawberries at already advanced deterioration stage might eat them quicker than when they buy them at stage 0 or 1, or that the probability of storing them in the fridge would be higher than 76%. Conversely, the same consumer might exhibit different purchasing behaviors depending on the intended time of consumption: the same consumer might be less strict regarding strawberry deterioration if the strawberries are to be consumed within the next hours than if they are bought to be consumed over the week. All these correlations between the model parameters distributions are not taken into account in the model. A more accurate description of the consumer storage habits according to the initial deterioration stage and according to each model parameter may increase the accuracy of the model.

As seen in Fig. 7 and Table 7, strawberries at different stages were not bought by the same groups of consumers. Each group has a different purchasing behavior, but also a different eating behavior, some groups wasting more than others. Therefore, different consumption behavior would be excepted depending on the deterioration stage at purchase, influencing the subsequent food waste. Looking at the results for a mix of trays, all purchasing groups were represented, highlighting the relevance of considering the diversity of consumers. However, the same storage behavior in terms of location (i.e. temperature) and duration, was considered for all consumers, since no specific tendency was observed according to the purchasing groups.

In Fig. 7, the purchase and waste quantities were described, according to the strawberry deterioration stage at purchase. However, food waste was calculated from the strawberry deterioration stage and percentage at the consumption time, and this stage can greatly differ from the purchase one. Fig. 8 shows the deterioration percentages at three steps: at time of purchase, after transport and at consumption time. On one hand, the transport step has a lower impact on the deterioration than the storage step, mainly due to its short duration: half of the trays bought at stage 0 had a transport time below 51 min and half of the trays bought at stage 3 had a transport time below 49 min. However, even though the duration is short, between 14 and 21% of the trays changed deterioration stage during transport: 14.9%, 18.2%, 15.9%, 19.0%, 20.3% and 14.3 % of the trays changed deterioration stage when considering respectively stage 0, stage 1, stage 2, stage 3, stage 4 and a mix of trays at supermarket. It confirms the relevance of considering the transport step in the model. This impact can be explained by the temperature during transport that was equally distributed between 15.4 and 36.6 °C, which is relatively high considering that the recommended storage temperature for strawberries is 0 °C (Shrivastava et al., 2023). However, the storage step at consumer's is much more impactful: indeed, storage time is much higher, with a median of 40 h for simulations done starting from stage 0 and stage 3. During storage, for all scenarios except the one starting with a deterioration stage of 5, more than 64% of trays changed deterioration stage compared to the deterioration stage after transport, with a maximum of 89% for the run considering an initial stage of 3 at supermarket. However, it is worth noting that a hypothesis was done regarding storage duration at consumer: it was considered that "Less than a day" corresponded to 0–24h, without knowing if most of these consumers will consume the strawberries within 3 h, 6 h or 12 h which could be related to the time of purchase. This difference in storage duration has an impact on the resulting food waste, mostly if stored in ambient. It could be relevant in a further consumer survey to ask more precisions about the time between purchase and consumption to increase the accuracy of the model. Nevertheless, considering the present results, whatever the initial deterioration percentage, most trays changed deterioration stage between supermarket and consumption, highlighting the importance of considering both consumer purchase and eating behaviors, since the deterioration stage will most often differ between both steps. Moreover, whatever the initial deterioration stage, some trays will reach more than 95% of deterioration at consumption time. Of course, the higher the initial deterioration percentage, the higher the number of trays that reached such high deterioration (3% of trays purchased at a deterioration stage of 0 vs 16% of the trays purchased at a deterioration stage of 3). When looking further at the data, 100% of the first ones and 96% of the second ones were stored by consumers in ambient conditions. As expected, refrigerated storage seems to be the most efficient method to decrease deterioration, and thus, food waste. For strawberries which remain stored in ambient conditions, which represent 24% according to the consumer survey and conducted to the majority of strawberries wasted when initial deterioration at supermarket was low, an equilibrium modified atmosphere packaging (eMAP) may be another solution to decrease food waste. Moreover, eMAP could also bring benefits all along the upstream supply chain, leading to strawberry trays with lower deterioration stages at the supermarket, decreasing the frequency of high deterioration stages at consumers' households. In case of fresh respiring products such as strawberries, an eMAP (optimal O_2 and CO_2 % in the packaging headspace) is obtained by the equilibrium between respiration of the food product, i.e. O_2 consumption and CO_2 production, and gases fluxes through the packaging, controlled by its permeability properties. For strawberries, optimal headspace gas composition is 5–10% O_2 and 15–20% CO_2 (Sousa-Gallagher et al., 2013). Matar et al. (2020) showed that considering the current consumer habits (considering the consumers that open the packaging during storage, and therefore loose the eMAP benefits), the use of eMAP technology could decrease waste by 18% for strawberries. According to the latter study, assuming that 100% consumers stored their strawberries at ambient temperature and kept the packaging closed until consumption, i.e. eMAP maintained throughout the entire shelf life, food waste would be reduced by 41% compared to a similar scenario without eMAP (Matar et al., 2020). However, it is challenging to design an eMAP that works at both ambient and refrigerated temperatures, thus, eMAP designed for ambient conditions would not impact strawberries stored in the refrigerator (Matar et al., 2020). In the present consumer study, 31.4% of consumers said they kept the original packaging, without opening. eMAP designed for ambient conditions would therefore be beneficial if these consumers were also the ones that store strawberries under ambient conditions.

The effect of storage temperature and duration is presented in Fig. 9. First, the higher the storage duration, the higher the deterioration. Moreover, as already observed on the previous figures, higher deterioration and food waste occur when strawberries are stored in ambient conditions. However, another, and more unexpected result, is the presence of high waste for low deterioration values (large blue points) and low waste for high deterioration values (small red points), which is depicted by the size of the markers, linear to the food waste (the higher the size, the higher the food loss). It means that despite their low deterioration percentages, some strawberries were thrown away, and in the second case, that some consumers ate strawberries even when they were highly damaged. This is coherent with the consumer study results, which showed that some groups, like group 11, were eating strawberries even when the deterioration was high, whereas others wasted a lot, even when the deterioration was low. However, it is worth noting that the results from the consumer survey, although representative of a large number of consumers ($N = 509$) remain declarative results. Further qualitative study should be done to confirm that what consumers said is what consumers really do. Nevertheless, one key conclusion is that the correlation between food waste and food deterioration is not straightforward and not always linear, as assumed in (Matar et al., 2020). This is related to the diversity of consumers' behaviors that were drawn from the consumer survey and shows their impact on the calculated food waste, and thus, the importance of considering them in models intended to quantify food waste. In models previously described in the literature, the consumer behavior was considered as a global behavior, representative of the average behavior of the global population for strawberries (Matar et al., 2020) and for other food products (Coffigniez et al., 2021). Thus, the consideration of the diversity of consumer behaviors proposed in the present model is a step forward towards more accurate food waste estimations.

The diversity of consumer behaviors could be even more developed. In this model, strawberries are considered as a case study, and consumer behavior in terms of preferences at purchase and consumption and in terms of storage habits are considered. Strawberries can also be transformed into meals such as fruit salads or cakes. This is also the case of most of raw ingredients, which must be converted before consumption. In that case, more parameters can play a role in food waste, as underlined by the model of Lusk and Ellison (2017), such as time spent in leisure, at work and in conversion of food into meals as well as relative prices of food and wage rates (Lusk and Ellison, 2017). Food preparation was also considered in the model proposed by Yokokawa et al. (2018). Economic and time constraints could be interesting to refine the purchasing groups and add accuracy to the model.

4. Conclusion and perspectives

4.1. Conclusions and work contributions

The consumer study revealed that consumers would more easily accept deterioration at time of consumption than at purchase, with a high variability of tolerance threshold for strawberry degradation among consumers. The diversity of behaviors was represented through the constitution of eleven purchasing groups. The results of the food waste model at consumer level evidenced how the combination of a deterioration model with consumer behaviors, such as storage management (time and temperature), as well as purchase and eating behaviors, successfully allowed to calculate food waste, taking into consideration the diversity of consumers. Indeed, the link between deterioration and food waste is not always straightforward, and even though there is an obvious link between both values, the diversity of consumer behaviors must be added to the equation. Another take-away from this study is the impact of the initial deterioration stage at supermarket. Food waste was more than 5 times higher when strawberries had an initial deterioration stage of 3 (20–40% deterioration) compared to an initial deterioration stage of 0 (0–1% deterioration). This highlights the uppermost importance of limiting as much as possible the strawberries deterioration during all the logistic steps preceding the purchase step. Furthermore, it is worth noting that the deterioration stage at purchase was most of the time different than the deterioration stage at consumption, showing the importance of considering consumer behavior at both steps, but also the necessity to limit deterioration between these two steps. This model could be applied in various ways to benefit society. Firstly, it can be used to identify the key factors responsible for FLW, thereby guiding policy and marketing strategies. For instance, recommendations could be made regarding storage location, encouraging the 24% consumers who store their strawberries at ambient temperature to store them in the fridge. This could also guide technological choices, such as using other preservation techniques like eMAP. Finally, given the significant impact of deterioration at retail, strategies could be implemented to enhance product protection in upstream logistics. This methodology could also be transposed to other fruits and vegetables.

4.2. Limitations

This work also highlighted some limitations of the model. In the present model, strawberry degradation and FLW are considered to be dependent only on time, temperature and consumer behavior. One missing element is the biological variability of strawberries, which appears from harvest and can lead to more variability in the results. Considering this variability could be beneficial for more accurate results. Moreover, although no significant correlation was found between purchasing groups and storage location or duration, correlations might be found between storage duration and storage location, or storage duration and consumer behavior. For example, if consumers buy strawberries that they will eat within a day, they might accept higher deterioration and might keep them at ambient temperature. A deeper study on correlations between these parameters could once again increase the accuracy of the model. Finally, in the present model, all strawberry trays were bought, without considering food waste at the supermarket. However, the fact that some purchasing groups do not buy strawberries at certain deterioration stages could lead to waste at the retailer step which could be interesting to add in the global food loss and waste calculation.

4.3. Further work

To predict accurate absolute values, a larger model including all steps from harvest to consumption is essential and will be conducted in further work. The deterioration model used in this study includes the inhibitory effect of CO_2 on *Botrytis cinerea* development considering O_2 and CO_2 concentrations evolving in the headspace. This modelling tool could therefore be used to assess the impact of using an eMAP packaging, with 15–20% CO_2, as recommended for strawberries, versus current packaging, with 0.04% CO_2. Thus, this deterioration model is powerful to assess different packaging alternatives in terms of deterioration. Most of all, combined with the consumer model developed in this study, it is a powerful tool to assess the impact of a new packaging on the resulting food waste. From an environmental perspective, this would help to evaluate the global impact of a packaging, considering direct (e.g. packaging material product, packaging end-of-life) and indirect (e.g. food waste) impacts, and could therefore be used as a tool to recommend one or other packaging solution, from policy or industry points of views.

CRediT authorship contribution statement

Emma Pignères: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Marine Masson:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Steven Duret:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – review & editing. **David Blumenthal:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing. **Maëlle-Ahou Gouton:** Conceptualization, Data curation, Investigation, Writing – original draft. **Nathalie Gontard:** Conceptualization, Funding acquisition. **Hélène Angellier-Coussy:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. **Valérie Guillard:** Conceptualization, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing. **Fanny Coffigniez:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. **Sébastien Gaucel:** Conceptualization, Data curation, Methodology, Software, Supervision, Validation, Writing – review & editing.

Data availability

All data and model codes are available in the following dataset: https://doi.org/10.57745/6TPZZZ.

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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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crfs.2025.101001.

Data availability

I have shared the link to my data/code at the Attach file step
Consumer behavior at sale point and consumption according to strawberry quality: how to use those data to evaluate food waste? (Original data) (entrepot.recherche.data.gouv.fr)

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