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Economic and environmental assessment of food waste reduction measures – Trialing a time-temperature indicator on salmon in HelloFresh meal boxes

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A R T I C L E I N F O

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A B S T R A C T

Food waste is a major challenge for society, causing economic, environmental and social problems. Time-temperature indicators showing a dynamic expiry date are discussed as one promising technology to help reducing food waste along the food supply chain of perishable foods like fish. In the present article, the implementation of the time-temperature indicator Keep-it® as an alternative date coding method on prepacked salmon in HelloFresh meal boxes is assessed regarding its effectiveness on reducing food waste and its sustainability across the economic and environmental dimension. In a first step, an online survey among 1589 HelloFresh customers was used to determine consumers' understanding and perception of the Keep-it® indicator and to estimate its potential impact on food waste-related behavior. Results show that the Keep-it® indicator was perceived to be reliable, helpful and intuitive to use (mean values of these attributes range between 3.7 and 4.3 on a five-point Likert scale). In contrast, more than half of the participants could not correctly interpret the meaning of currently used expiry dates (use-by and best before). Furthermore, results indicate that the Keep-it® indicator has the potential to reduce food waste at consumer level. In a second step, results of the survey were used to quantify the potential amount of food waste reduction and to evaluate the economic and environmental impacts of the Keep-it® indicator implementation along the food chain using the calculated Cost-Benefit Ratio. Per one EUR invested, using the Keep-it® indicator instead of the currently used use-by date results in 0.1 kg food saved from becoming waste, 0.44 kg CO_2eq less emitted and 2.05 € less spent.

1. Introduction

Global food waste is estimated to be approximately one-third of the edible parts of food produced for human consumption annually (FAO, 2011), which equals 1.3 billion tons of edible food wasted and an associated environmental impact of 3.3 billion tons of CO_2 equivalents and direct economic costs of USD 750 billion based on producer prices (FAO, 2013). Further considering environmental and social costs, the full costs of food waste amount to approximately USD 2.6 trillion annually (FAO, 2014). Accordingly, food waste is a major challenge for the society, causing economic, environmental and social problems (Amicarelli et al., 2021) and wasting food means missed opportunities to feed the growing world population (Martin-Rios et al., 2021).

Against this background, the United Nations (2015) adopted the target 12.3 in the Sustainable Development Goals (SDGs) aiming at halving per capita global food waste at retail and consumer levels and reducing food losses along production and supply chains (including post-harvest losses) by 2030. At European level, the aim of reducing food waste is implemented as one of the priority areas in the EU Action plan for the Circular Economy (European Commission, 2015) and Germany deals with the topic within the framework of the National Strategy for Food Waste Reduction (Federal Ministry of Food and Agriculture, 2019).

According to Reynolds et al. (2019) the consumption stage is the largest single contributor to the amount of food waste generated for developed countries. For example, the share of food waste generated in private households is estimated to be approximately 53% for Europe (Stenmarck et al., 2016) and 52% for Germany (Schmidt et al., 2019). Food waste practices as well as factors that foster and impede the generation of food waste on household level are therefore increasingly analyzed, but the evidence on why food waste occurs remains scattered (Schanes et al., 2018). Along all stages of food-related practices and routines in households (e.g. shopping, cooking, eating), assessing edibility and safety of food items has a major impact on the amount of generated food waste and people sometimes experience a conflict between trying to avoid food waste and protecting themselves from

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food-related health risks. Concerns about food safety may cause people to interpret any date label as a use-by date and therefore throw away food items that have expired although they are actually still safe to eat (Schanes et al., 2018). A recent study by WRAP (2022) found that the date label has a clear influence on disposal decisions, whereby for milk and yogurt, the use by date appears to provide a protective measure when products are within date, but when products are on, or after the date, they prompt higher disposal. Accordingly, authors suggest that there is scope to reduce waste of (dairy) products by extending the expiry dates (where it is safe to do so) to give citizens more time to consume products before they pass or reach the date and to prevent them from throwing away food items which are still in good condition (WRAP, 2022). However, a reduction of food waste can only be achieved by extending the expiry dates, when consumers are able to interpret them correctly. According to Zeinstra and van der Haar (2020) various studies point to the fact that consumers are insecure in handling different expiry dates on food products, and this lack of knowledge leads to more food waste. ReFED (n.d.) estimated that confusion over the meaning of date labels account for about 7% of all consumer food waste in the US. This share is estimated to be slightly higher for the EU, where 10% of annual food waste can be attributed to date marking issues (European Commission, 2018). Accordingly, a big potential for reducing food waste on household level lies in optimizing date-labelling of pre-packed food (Schanes et al., 2018; WRAP, 2022). One possibility of optimizing date-labelling is the usage of technological innovations in the field of intelligent packaging.

Many studies highlight the potential of intelligent packaging in general, and of monitoring the temperature through the entire food supply chain in particular, would contribute to a reduction of food waste (Brennan et al., 2021; Dohlen et al., 2019; Mercier et al., 2017; Mohebi and Marquez, 2015; Müller and Schmid, 2019; Rossaint and Kreyenschmidt, 2015; Shimoni et al., 2001). Time-temperature indicators (TTIs) are one of the smart devices belonging to the broad field of intelligent packaging systems (Fang et al., 2017; Mohebi and Marquez, 2015). In contrast to commonly used static shelf-life determinations (e.g. use-by date or best before date), TTIs are able to dynamically estimate the remaining shelf-life based on the temperature history of each product and expressing it as a visible, easy to understand response (Taoukis and Labuza, 1989, 2003). With regard to the aim of reducing food waste, the advantage of this dynamical adjustment of shelf life is twofold. On the one hand, it can improve food safety because TTIs would detect temperature abuses allowing products to spoil before they reach the fixed date label (Buisman et al., 2019). On the other hand, TTIs can show a longer shelf life of the product compared to commonly used static shelf life determinations, when the product is not exposed to adverse temperature conditions or are better stored than assumed (Shimoni et al., 2001; Taoukis and Labuza, 1989).

However, there are also some challenges related to legislation (Fang et al., 2017) and high cost in the area of commercial application (Wang et al., 2015) leading to the fact that TTIs are not used widely so far (Müller and Schmid, 2019). Furthermore, a systematized literature review of Brennan et al. (2021) shows, that there is very little research examining consumers' perceptions of food packaging and technologies directly addressing the reasons for household food waste are under researched. Furthermore, more research is needed to explicitly explore consumer perceptions, understandings, and acceptance of these packaging technologies.

The present article addresses the derived research gap on TTIs through a case study on the use of TTIs on fresh and prepacked salmon in meal-kit boxes. Fish next to seafood is the main category of food that is handled frozen by HelloFresh, which offers the opportunity to switch from the application of a use-by date to the use of a TTI along the whole food chain. In a first step, an online survey among meal-kit customers was used to determine consumers' perception of the TTI in comparison to commonly used expiry dates and to estimate its potential impact on food waste-related behavior. If consumers perceive the TTI as reliable, helpful and intuitive to use, TTI should be able to reduce food waste in households. In a second step, the food waste reduction potential derived from the survey is used for the economic and environmental assessment of the TTI implementation. We hereby evaluate the effectiveness of the TTI on food waste reduction and the extent to which the implementation of the indicator on prepacked salmon in meal-kit boxes could affect the related supply chain sustainability across the economic and environmental dimension. Linking consumers' perception on TTIs with an assessment of related economic and environmental impacts could help to develop focused strategies for date-labelling to reduce food waste in households.

2. Materials and methods

The present case study was set up following a collaboration with HelloFresh, one of the world's leading companies of meal-kit delivery service, and Keep-it® Technologies, a Norwegian company that developed the intelligent and responsive shelf life indicator Keep-it®. HelloFresh achieved a revenue of approximately 6000 million € in 2021 with its activities in 17 countries comprising 176 million households of which 7.22 million are active customers (HelloFresh SE, 2022). A description of the working principles of TTIs in general and the Keep-it® indicator in particular, can be found in the supplementary material A, Table S1. The case study was carried out in the context of the German National Strategy for Food Waste Reduction and the related research project "Dialogue Forum on Wholesale and Retail Trade"[1].

2.1. Survey and data collection

The trial of the Keep-it® indicator on prepacked salmon in HelloFresh meal-kit boxes is analyzed using a survey among HelloFresh customers. The survey builds on a previous study carried out by the Wageningen Food & Biobased Research Institute (WFBR) in The Netherlands and the Dutch-speaking part of Belgium in 2020 (Zeinstra and van der Haar, 2020). To determine the consumers' perception of the TTI in comparison to commonly used expiry dates and to estimate its potential impact on food waste-related behavior, the survey tries to answer the following overarching research questions:

- Do the participants know the meaning of the commonly used expiry dates?
- How do the participants deal with expiry dates of different food types?
- How often are different food types thrown away and what are the most important reasons?
- How is the Keep-it® indicator perceived by the participants?
- What influence can the indicator have on the behavior of the participants regarding food waste?

With regard to the objective of this article, we focus on the answers given to fish. The questionnaire translated into English can be found in the supplementary materials B1 and B2. The survey was programmed via QuestionPro and conducted online. Pre-tests were carried out among non-participants in order to prove a proper technical run and to detect weak points in the content design of the questionnaire.

To investigate consumers' perception of the TTI and to explore its potential impact on food waste-related behavior, two survey groups were defined (cf. Zeinstra and van der Haar, 2020):

1) Test group: Participants in the test group received the TTI on salmon in their meal-kit box and an information leaflet explaining how the

[1] For further information about the research project, see https://www.thuenen.de/en/ma/projects/efficient-reduction-of-food-waste-in-wholesale-and-retail-trade/?no_cache=1.

indicator works. As current regulations require that a static (printed) date has to be present on a food product (EU regulation no. 1169/2011), the salmon packaging contained both the printed date and a Keep-it® indicator. The information leaflet indicates that the printed date is decisive.

2) Control group: Participants in the control group received salmon in their meal-kit box without a TTI and an information leaflet about general date marking. Hence, the control group was used to remove the effects of information provision by the leaflet, since providing information in itself is an intervention activity which may change consumer thoughts and behavior.

The information leaflets (see supplementary materials C1 and C2) in the meal-kit boxes of both groups further contained information about the correct fridge temperature as well as an invitation to participate in the consumer survey.

Participants were customers of the HelloFresh database in Germany and Austria during the trial. The test group consisted of 4182 customers that ordered salmon for the weeks 44 and 45 (November 4th to 11th of 202 1). About 15,000 other customers who ordered salmon in these two weeks formed the control group. Within a period of three weeks (November 4th to 28th 2021), the customers were invited to complete the 10 min survey. Following data collection, the anonymous datasets of both groups were provided to us by HelloFresh. Data analysis was done using the open source statistics program R. Differences between the groups were tested with two-samples t-tests (*t*-test, Mann-Witney-U-test or Welch-test depending on normal distribution and homogeneity of variance is given or not). The significance level is 0.05.

A total of 2044 customers started the online survey. 452 respondents were excluded due to incomplete questionnaires and 3 respondents were further excluded due to inconclusive statements in the socio-demographics resulting in a final sample consisted of 1589 respondents who completed the whole survey, of which 289 were in the test group (Response rate: 7%) and 1300 in the control group (Response rate: 9%).

2.2. Sustainability assessment

The evaluation of the food waste prevention measure described here follows the methodology proposed by the Joint Research Centre (JRC) of the European Commission (Caldeira et al., 2019) and outlined in Goossens et al. (2019), Goossens et al. (2021) and Laurentiis et al. (2020). A food waste prevention measure is hereby evaluated based on its effectiveness (food waste reduction potential) and its sustainability across the environmental, economic and social dimension (Goossens et al., 2020). Hence, in the context of the food waste reduction potential of TTIs, it is not only important to analyze consumers' perception of the Keep-it® indicator and its potential impact on food waste-related behavior (effectiveness), but the implementation of the Keep-it® indicator should also be evaluated by analyzing the environmental, economic and social effects associated with this measure (Goossens et al., 2019).

Unfortunately, it was not possible to quantify the actual amount of food waste prevented along the food chain by implementing the TTI on prepacked salmon to the meal-kit customers (effectiveness of the measure). For this purpose, it would be necessary to measure the amount of food waste generated before and after the implementation of the TTI at each stage and the resulting difference of both measurements would reflect the amount of prevented food waste. However, results of the customer survey can be used to calculate a theoretical potential of food waste prevention along the food chain (see section 3.2.1).

The sustainability assessment includes the calculation of the economic and environmental changes associated with the TTI implementation and is carried out by comparing the food chain situation before and after the implementation of the TTI. Fig. 1 shows the two defined scenarios. The baseline scenario (scenario 1) reflects the current situation, where the producer receives and processes the fresh fish and subsequently, the fish is portioned, packed and frozen. The fish is then dispatched frozen to a Third Party Logistics Provider (3PL), who applies the use-by date and stores the fish. After receiving the frozen fish from the 3PL, HelloFresh tempers it, picks and packs it into customer boxes and dispatches the chilled meal boxes to the customer. The customer stores the fish in the refrigerator until consumption. Scenario 2 comprises the implementation of the Keep-it® indicator at producer level, which would allow HelloFresh to receive the product directly from the producer without the intermediate step at the 3PL partner, where the products are usually date-coded (sticker with use-by date). Hence, 3PL becomes redundant in scenario 2 because its provided services (date-coding and storing) are taken over from the producer and HelloFresh, respectively. As current regulations require that a static (printed) date has to be present on a food product, scenario 2 is only a hypothetical situation. The producer receives and processes the fresh fish and subsequently, the fish is portioned and packed. During the packing process, the Keep-it® indicator is applied. The fish is then dispatched frozen to HelloFresh, where it is stored frozen first and then tempered, picked and packed into customers boxes and dispatched in chilled meal boxes to the customer. The customer stores the fish in the refrigerator until consumption. It must be noted that scenario 2 assumes that HelloFresh has

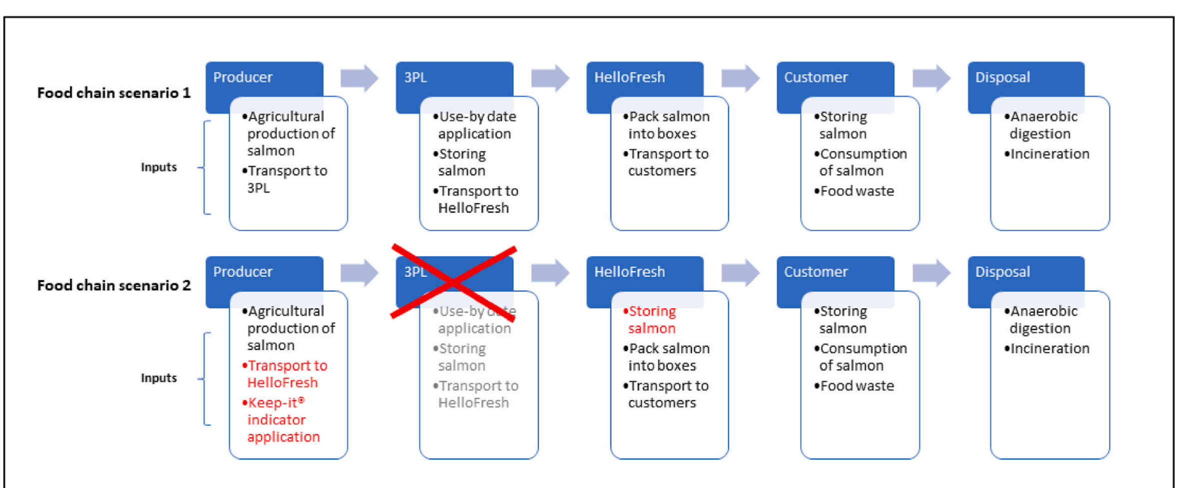

Fig. 1. Flow chart of scenarios developed for the sustainability assessment of the implementation of the Keep-it® indicator (differences between scenarios are colored in red). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

adequate storage space for the frozen fish.

Furthermore, Table 1 shows the cost and impact positions considered in the economic and environmental calculation of the sustainability assessment as well as the respective values and data sources used for each position. Both, the economic and environmental calculation, consider those positions that changed when switching from scenario 1 to 2, resulting in partly additional costs and impacts and partly in savings (column 4 in Table 1).

The sustainability assessment generally includes the social dimension in addition to the economic and environmental impacts. Possible indicators could be the effect on awareness of the meal-kit customers for food waste (outreach impact of the survey), the effect on the company's image if using a TTI on its products and the effect on jobs due to the measure. Further societal effects could relate to how the measure affects hunger and poverty. Based on the survey, these indicators could not be quantified, and thus, are beyond the scope of this study.

2.2.1. *Economic assessment*

The calculation of the economic effects associated with the TTI implementation is expressed in monetary values (€) and includes any monetary changes at each stage of the food chain (from production of salmon to its disposal) when switching from scenario 1 to 2. These changes refer to avoided embodied costs of salmon that is now no longer being wasted, the avoided disposal costs and the implementation costs or savings (cf. Goossens et al., 2019). Table 1 shows the cost positions considered in the calculation for each stage of the food chain (column 5). Unfortunately, the majority of values cannot be disclosed for matters of confidentiality. At producer level, additional costs include the indicator

Table 1
Scenario description as well as cost and impact positions considered in the economic an environmental calculation of the sustainability assessment.

Food chain stage	Scenario 1	Scenario 2	Difference 1 to 2[a]	Cost positions considered in the economic calculation			Impact positions considered in the environmental calculation		
				Position	Value	Data source	Position	Value	Data source
Producer	Processing of salmon: 108 kg	Processing of salmon: 108 kg							
		Applying Keep-it indicator	+	Indicator price and application cost	confidential	HelloFresh	Indicator production	assumed to be negligible	cf. Zhang et al. (2019)
	Transport of salmon to 3PL	Transport of salmon to HelloFresh	/(cost) - (impact)	Transport costs: no changes	0	HelloFresh	Net Transport distance between 3 PL and HelloFresh	47 km * 0.087 kg CO_2eq/tkm * 0.108t	HelloFresh Ecoinvent[b]
3 PL	Applying use-by date		–	Use-by date price and application cost	confidential	HelloFresh	Use-by date production	assumed to be negligible	cf. Zhang et al. (2019)
	Storing salmon frozen		–	Taken over from HelloFresh	0		Taken over from HelloFresh	0	
	Service		–	Service charge, cost for pallet handling	confidential	HelloFresh			
	Transport of frozen salmon		–	Transport costs	confidential	HelloFresh	Transport distance to HelloFresh	80 km * 0.087 kg CO_2eq/tkm * 0.108t	HelloFresh Ecoinvent[b]
HelloFresh	Packing and dispatch salmon to customers	Packing and dispatch salmon to customers							
		Storing Salmon frozen	+	Taken over from 3 PL	0		Taken over from 3 PL	0	
		Flyer and product sticker	+	Cost for flyer and product sticker	14,45 €	HelloFresh	Impact per flyer and product sticker	0.72 kg flyer * 2.35 kg CO_2eq/kg paper	HelloFresh Ecoinvent[c]
Customers (Test group participants)	Storing salmon in refrigerator	Storing salmon in refrigerator							
	Consumption: 89 kg salmon	Consumption: 92 kg salmon	–	Cost of avoided food waste	3 kg * 10€/kg	IMF (2022)	Impact of avoided food waste	3 kg * 4.48 kg CO_2eq/kg salmon	Agribalyse[d]
Disposal	19 kg Salmon	16 kg Salmon	–	Cost of avoided disposal	0.60 € (3 kg * 0.20€/kg food waste)	Manfredi and Cristobal (2016)[e]	Impact of avoided disposal	3 kg * 0.19 kg CO_2eq/kg food waste	Laurentiis et al. (2020)[f]

[a] Cost and impact positions, which are avoided (added) in scenario 2 compared to scenario 1, are considered as negative (positive) values.
[b] Product system: transport, freight, lorry>32 metric ton, EURO4; Reference process location: Europe.
[c] Product system: offset printing, per kg printed paper; Reference process location: Switzerland.
[d] CIQUAL Code: 26036; LCI Name: Salmon, raw, farmed; Stage: Agriculture.
[e] Weighted disposal cost factor using information from customer survey: 36% is disposed by anaerobic digestion and 64% by incineration, resulting in 0.20 €/kg food waste (0.36*193 €/t FW+0.64*208€/t FW).
[f] Weighted disposal impact factor using information from customer survey: 36% is disposed by anaerobic digestion and 64% by incineration, resulting in 0.19 kg CO_{2eq}/kg food waste (0.36*460 kg CO_{2eq}/t FW+0.64*34kgCO_{2eq}/t FW). Choices on how food waste is being disposed of, may affect the results, but our study found that the disposal savings obtained by our measure only refer to 3.7% of the total impact savings potential. Hence, a thorough investigation on this was not conducted.

price and costs for indicator application (including speed reduction of throughput rate). Additional investment costs for machines are so far not considered, because the machine for indicator application is already available at the fish supplier. The supplier has also been working with Keep-it® independently of HelloFresh for some time and routinely applies the indicators for other customers. As the transportation distance between producer and 3PL is comparable to the distance between producer and HelloFresh, no changes in transportation costs occur at producer level. When switching from scenario 1 to 2, the food chain stage 3PL is eliminated. Related savings refer to the elimination of the use-by date application, saved service charge including cost for pallet handling and transport costs (from 3PL to HelloFresh). As the storage of salmon at the 3PL partner is taken over by HelloFresh, changes in costs related to storage are assumed to be zero. At HelloFresh, costs related to the information leaflet about the indicator and the product sticker, which accompanied the implementation of the Keep-it® indicator at consumer level during the trial, are considered. At customer level, costs of food that is no longer wasted are calculated by multiplying the amount of salmon prevented from becoming waste (derived from the customer survey, see section 3.2.1) with the sale price of the salmon. In the meal-kit box, the sale price is set for all ingredients of one recipe, of which salmon is one of many different ingredients. Hence, a sale price for salmon cannot directly be derived. According to Bellemare et al. (2017) the use of sales prices is inappropriate for estimating the value of food gone wasted because a mark-up charged by the seller in order to make profit is included which leads to an overestimation of its value. We therefore use the purchasing price for the meal-kit provider to calculate embodied costs of saved food at customer level. Due to data confidentiality, HelloFresh was not able to provide us the purchase price of salmon. Instead, we use the export price of Norwegian salmon according to the International Monetary Fund (IMF, 2022). During the time of the trial (November 2021), the export price was 5.74 €/kg. Assuming that the processing step roughly doubles the price of salmon, we use a purchasing price of 10 €/kg. The end-of life stage is considered by calculating the avoided disposal costs at customer level. In the customer survey, the participants of the test group were asked how they would dispose the prepacked salmon when both, the use-by date and the Keep-it® indicator reveal that the salmon is no longer edible. 36% of the test group reported that they would dispose the salmon in organic waste (anaerobic digestion) and the package in plastic waste, 28% would dispose the salmon in residual waste and the package in plastic waste and another 33% of the test group would dispose the salmon and the package in the residual waste (incineration). A few participants reported that they do not know how to dispose of it due to the indicator or reported other ways of disposal (assumed to be disposed by incineration). Based on these respective shares of avoided disposal ways, a weighted disposal cost factor is calculated using disposal costs from Manfredi and Cristobal (2016) for the disposal ways anaerobic digestion and incineration. Avoided disposal costs are calculated by multiplying the amount of saved salmon with the weighted disposal cost factor.

2.2.2. Environmental assessment

For the calculation of the environmental effects associated with the TTI implementation, a life cycle assessment (LCA) approach is used. It is expressed in kg CO_2 equivalents and includes any changes of greenhouse gas emissions at each stage of the food chain (from production of salmon to its disposal) when switching from scenario 1 to 2. These changes refer to avoided embodied impacts associated with salmon that is now no longer being wasted (including the impact generated along the different stages of the salmon's life cycle), the avoided disposal impacts and environmental impacts related to the implementation of the TTI (cf. Goossens et al., 2019). Table 1 shows the impact positions considered in the calculation for each stage of the food chain (column 8). At producer level, additional impacts include the production of the indicator and transportation. To the authors knowledge, no studies dealing with the environmental impacts of producing time-temperature indicators exist so far. However, according to Zhang et al. (2019), who assessed the carbon footprint of nano-packaging, the nanomaterials used in their analyzed packaging systems usually accounts for less than 1% or at most for 5% considering the impacts of food, packaging and nanomaterials. Hence, impacts related with indicator production are assumed to be negligible. Environmental impacts of transportation can be calculated by multiplying the net transport difference between both scenarios (transport distance from the supplier to HelloFresh minus the transport distance saved from the supplier to 3PL) with impact values from the LCA database ecoinvent (Wernet et al., 2016). At 3PL, savings refer to the elimination of the use-by date and the storing and transport of salmon. Similar to the indicator production, impacts related to the use-by date production are assumed to be negligible. As storage of salmon at the 3 PL partner is taken over by HelloFresh, related environmental impacts are assumed to be the same in both scenarios and consequently zero. Savings of transportation (from 3 PL to HelloFresh) are calculated by multiplying the distance with impact values from the LCA database ecoinvent (Wernet et al., 2016). At HelloFresh, environmental impacts related to the information leaflet about the indicator and the product sticker, which accompanied the implementation of the Keep-it® indicator at consumer level during the trial, are considered by multiplying flyer weight and impact values from the LCA database ecoinvent (Wernet et al., 2016). At customer level, impacts of food that is no longer wasted are calculated by multiplying the amount of salmon prevented from becoming waste (derived from the customer survey, see section 3.2.1) with the product carbon footprint for salmon from the French LCA database Agribalyse 3.0 (ADEME-INRAE, 2020; Asselin-Balençon et al., 2020). The end-of life stage is considered by calculating the avoided disposal impacts at customer level. Similarly to the economic calculation, shares of avoided disposal from the customer survey are used to calculate a weighted disposal impact factor based on disposal impacts from Laurentiis et al. (2020) for the disposal ways anaerobic digestion and incineration. Avoided disposal impacts are calculated by multiplying the amount of saved salmon with the weighted disposal impact factor.

3. Results

3.1. Survey among meal-kit customers

The final sample consisted of 1589 meal-kit customers with an average age of 44 years (range 19–85 years) and an average household size of 2.5 persons (36% of the participants had children). 72.8% were female, 25.9% male, 0.3% non-binary and 1% of participants did not specify their gender. On average, participants in the test and control group answered the questions in 11 min. Sociodemographic characteristics for each group can be found in Table S2 the supplementary material A.

The first part of the survey dealt with the understanding of different expiry dates. Participants of both groups were asked about the meaning of the use-by date (question 3, Supplementary materials B1 and B2) and the best before date (question 4, Supplementary materials B1 and B2). For the use-by date, only one of the answer options was correct, which was chosen by 48% of the test group and 36% of the control group. However, these percentages also include participants choosing more than the correct option. This implies that some of them do not know exactly how to deal with the use-by date. Examining how many participants correctly answered the question by choosing only the correct option, results in slightly lower percentages with 38% for the test group and 30% for the control group. For the best before date, 50% of the test group and 49% of the control group chose the correct answers. For the best before date, correctly answering means to choose two of the answer options. Approximately, 90% and 60% of the participants in both groups correctly chose at least one of these answers, indicating that participants mostly know how to interpret the best before date (detailed results for this question can be found in Table S3 in the supplementary material A).

The second part of the survey dealt with the Keep-it® indicator. The participants of the test group were asked different questions regarding their first perception of the TTI. To be able to compare the answers of the test group with the control group, the control group was shown a figure of the Keep-it® indicator with a short explanation of how it works. Subsequently, they received the same questions as the test group. First, the participants should evaluate how well certain attributes fit the Keep-it® indicator (question 14, Supplementary material B1; question 12, Supplementary material B2). Results show that the test group found the Keep-it® indicator positive, reliable, helpful and intuitive to use. Furthermore, the participants of the test group agreed that the Keep-it® indicator represents an added value for a product. All mean values of these attributes range between 3.70 and 4.35 on a five-point Likert scale indicating a high agreement. The highest averages with values above 4 were found for the attributes positive and helpful. More than half of the participants completely agreed that these two attributes fit well to the Keep-it® indicator. In comparison, the results of the control group show a significant lower agreement to the positive attributes (p-values <0.001). However, the average values of the control group range between 3 and 4, which represents a rather agreement to the positive attributes.

Next, participants of both groups were asked questions regarding the understanding of the Keep-it® indicator (questions 17 + 18, Supplementary materials B1; questions 14 + 15, Supplementary material B2). Participants of the test group were confident about the correct working of the Keep-it® indicator, demonstrated by high average values above 4 for the statements that the indicator will help to determine how long a fresh product is safe to eat, that the indicator shows if products were stored with temperature abuses and shows the shelf-life of a product more precisely than a printed expiry date. Regarding the potential impact of the Keep-it® indicator on their food waste related behavior, participants of the test group mainly agreed that the indicator could have an impact on meal planning, storing food correctly and disposing less food (average values near to 4). When asked about a possible added value of the Keep-it® indicator, participants of the test group mainly agreed that a product gains in terms of quality by the indicator (mean 3.86) and they would prefer a product with a Keep-it® indicator for the same price in the supermarket (mean 4). For HelloFresh boxes, participants of the test group were mainly indifferent as to whether an indicator on salmon would make it more likely for them to order salmon (mean 3.33). In comparison, the average values of the control group were significantly lower for all statements regarding the understanding of the Keep-it® indicator and its potential impact on food waste related behavior, but nevertheless, also the participants of the control group mainly agreed with mean values near to 4. Regarding the possible added value of the Keep-it® indicator, the average values of the control group showed larger differences in absolute terms in particular. Here, participants of the control group were indifferent regarding quality gains for products with indicators and preferring products with indicators in the supermarket and HelloFresh boxes (detailed results for this question can be found in Table S4 in the supplementary material A).

The third part of the survey examined the potential impact of the TTI on food waste reduction in private households more closely. First, participants were asked what they normally do with different types of food when the expiry date has passed (question 8, Supplementary materials B1 and B2). Subsequently, participants of both groups were asked what they would do if the use-by date of fish were expired, but the Keep-it® indicator still showed two days left for eating the product without any safety risks (question 15, Supplementary material B1; question 13, Supplementary material B2). Fig. 2 compares the answers given for fish by the test group and control group for these two questions (results for other queried products can be found in Table S5 in the supplementary material A). When the use-by date is expired, the majority of participants (>50%), regardless of the group, answered that they would inspect the fish whether it is still edible before they decide to eat or dispose it. Almost all other respondents reported they would immediately dispose of the fish when the static date has passed. With a share of 40–50%, fish has the highest share of respondents choosing this answer compared to other products. When comparing these results with the proportions for the hypothetical situation, where the static date has passed, but the Keep-it® indicator shows two more days, the share of participants who answered that they would inspect the fish whether it was still edible before they decide to eat or dispose it increased, while the share of participants who answered to immediately dispose of the fish strongly decreased. Results also show an increase of respondents who answered that they would eat the fish within the next two days without inspecting it. No significant differences were found between the test group and the control group.

3.2. Sustainability assessment of using a time-temperature indicator

The implementation of the TTI is evaluated based on its effectiveness on reducing food waste (section 3.2.1) and its sustainability across the economic and environmental dimension (section 3.2.2).

3.2.1. Effectiveness of the measure

The warehouse of the meal-kit provider works with frozen fish ordered from the producer based on customer orders volume, which is only defrosted when necessary. As such, there is little food waste being generated along the supply chain and the use of an TTI will not change this. At consumer level, the theoretical potential of food waste reduction was estimated based on survey results. The total amount of salmon

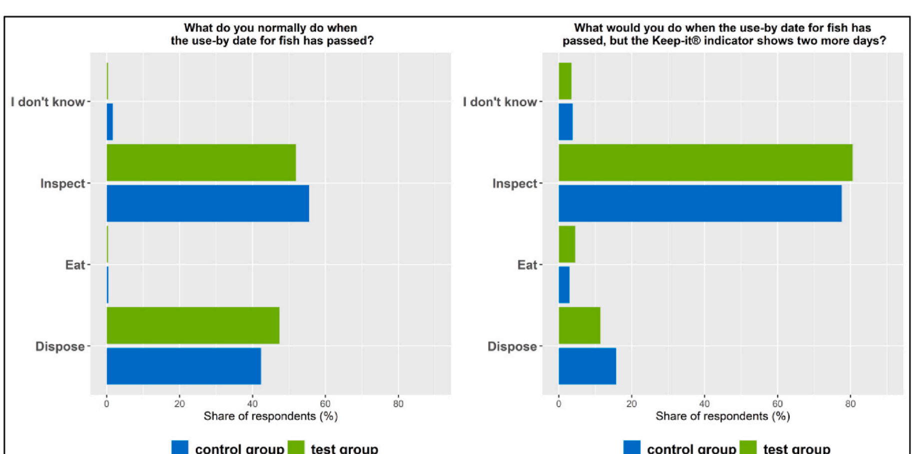

Fig. 2. Comparing the answers to questions related to the handling of fish with expired use-by date.

ordered by the participants of the test group was approximately 108 kg (N = 289, 375 g salmon/participant). In the survey, participants were asked how often they disposed of fish in the last month (related to all fish products in the household), whereby 82% answered never, 17% answered one to two times and 1% answered three to four times (question 6, Supplementary material B1). Based on this, we assume that, without a TTI, 18% of the test group participants discard the salmon when ordering a fish dish. Applied to the amount of 108 kg salmon ordered by the test group during the trial, this results to 19 kg of discarded salmon. This assumption thus refers to a maximum amount of disposed fish as we assume that respondents, who stated that they dispose fish, had discarded the total and not only a part of the fish portion. When it comes to handling fish with an expired static use-by date, the share of test group participants who reported to immediately dispose fish when the use-by date has passed decreased by 36% on average, when the Keep-it® indicator shows two more days, while the share of test group participants who answered to eat the fish within the next two days or inspect it first increased by approximately 4% and 29% on average, respectively (cf. Table S5 in supplementary material A). Assuming that 50% of participants inspecting the fish, will eat it afterwards, the reduction potential of the indicator is approximately 18.5% (4% + 0.5*29%). In order not to overestimate the salmon waste reduction potential of the TTI, the theoretical reduction potential is rounded down to 15%. This would mean that 15% of the 19 kg of previously discarded salmon (equaling about 3 kg) would now no longer be disposed of.

3.2.2. Economic and environmental assessment

Table 2 shows the results of the sustainability assessment regarding the effectiveness and the environmental and economic dimension. With the meal-kit provider, product specific savings, which refer to avoided embodied costs and the impact of salmon no longer wasted and avoided food waste disposal costs and impacts, are zero because there is no reduction of fish waste due to the indicator at this level. At consumer level, product specific savings relate to 3 kg salmon (or 5820 kcal) no longer wasted in the test group. This amount to 14 kg CO_2 equivalents and 30.61 €. By including the implementation related impacts and costs, the net environmental and economic benefit of the measure can be calculated. For this, impacts and costs either occur additionally or are saved in the upper supply chain when switching from scenario 1 to 2 (see column 4, Table 1), are considered. For the environmental assessment, greenhouse gas emissions can be saved due to a reduction of the transport distance, but additional emissions were released due to providing necessary information leaflets and product stickers in this trial. Summing up these impacts, result in additional 0.50 kg CO_2 equivalents, leading to a lower value of the net benefit of 13.50 kg CO_2 equivalents.

Table 2
Effectiveness and Resource efficiency of using a TTI as a food waste reduction measure.

Savings	Effectiveness		Environmental Assessment	Economic Assessment
	Mass	Nutritional value	Carbon Footprint	Costs
Unit	kg	Kcal	kg CO_2 equivalents	EUR
Product specific savings (Participants of test group)	3	5,820[a]	14.00	30.61
Net benefit			13.50	32.34
Cost-Benefit Ratio (per EUR invested)	0.10 kg/ EUR	188 kcal/ EUR	0.44 kg CO_2eq/ EUR	2.05 EUR/ EUR

[a] To calculate the kilocalories saved, we used the data set for "salmon, raw, farmed" of the Ciqual French food composition table, which is freely accessible (Anses, 2020).

For the economic assessment, costs can be saved from eliminating the food chain stage 3PL (use-by date price, application cost, service charge and cost for pallet handling and transport), but further costs occur at producer level (indicator price and application cost) as well as at HelloFresh (costs for flyers and product stickers). Summing up these costs, result in a further cost reduction of 1.73 €, leading to a higher value of the net benefit of 32.34 €. In a further step, the cost-benefit ratio was calculated which balances all benefits to all costs. For the environmental dimension, net benefits are related to the costs of the measure. For the economic dimension, benefits are related to the costs of the measure. Per Euro invested, 0.1 kg salmon, 188 kcal, 0.44 kg CO_2 equivalents and 2.05 Euros can be saved.

Overall, results show that the implementation of the TTI can slightly reduce costs and impacts on the environment at HelloFresh and consumer level. Furthermore, there is potential for further improvement. Both results are influenced by the costs and impacts related to the flyer accompanying the indicator implementation. After a short implementation period, costs for and related impacts with the flyer will drop to zero as the meal-kit provider would only use this kind of information material for the first four weeks of the introduction and then switch to online education via QR code on the product label itself. Accordingly, when the flyer is replaced by online education, cost savings would increase, while the relieving effect on the environment of the implementation would become larger.

4. Discussion

Our study combines survey results regarding consumers' perception of the TTI in comparison to commonly used expiry dates with an assessment of the economic and environmental impacts related to the use of a TTI in-stead of the commonly used use-by date for the test group participants of the trial and HelloFresh. The survey results reveal three main findings. First, results of this study point to the fact that quite a large group of German and Austrian HelloFresh customers do not understand exactly what the use-by date and (to a lower degree) the best before date means. Second, in contrast to the first finding, the majority of the participants of both groups positively perceive the Keep-it® indicator and are confident that the indicator can improve food safety and reduce food waste. Third, the potential of the indicator to reduce food waste is indicated as for fish, the share of test group participants who immediately dispose of fish when the use-by date has passed decreases by 36% when the TTI would show two more days (26.6% for the control group). These findings are in line with a comparable study on the perception of TTIs of HelloFresh customers in The Netherlands and Belgium by Zeinstra and van der Haar (2020) and with a study by Rossaint and Kreyenschmidt (2015) analyzing the food waste reduction potential of a TTI application in a typical German poultry supply chain. Furthermore, our study results confirm conclusions of prior studies (e.g. Schanes et al., 2018; WRAP, 2022) that optimizing date-labelling of pre-packed food has a big potential for reducing food waste on household level. Commonly used static expiry dates seem to be difficult to interpret correctly making expired food more likely to be thrown away, although they are actually still safe to eat. Accordingly, our results are able to contribute to the initiative of the European Commission to propose the revision of EU rules on date marking aiming to prevent food waste linked to misunderstanding and/or misuses of these dates. In this context, our results further confirm that new packaging technologies can contribute to a reduction of food waste not only on the consumer level, but along the entire food supply chain. For example, using the technology of TTIs at the meal-kit provider is a key enabler for managing a "frozen program" within the company resulting in an increase of process efficiency. A frozen program means to be able to keep a frozen inventory of certain stock keeping units such as meat and fish, as opposed to being 100% dependent on fresh, just-in-time deliveries. By keeping frozen stock, the need for additional buffer volumes needed to compensate for volume fluctuations can be reduced significantly, as it enables the company to pull from the frozen stock at any time without further operational efforts. On the one hand, the frozen program can contribute to an already implemented "make-to-order" system that leads to food waste reduction at the meal-kit provider through (1) reducing buffer volumes and (2) allowing for roll over stock utilization in case of orders that are too large. On the other hand, a frozen program can also reduce costs for meal-kit providers by reducing last-minute emergency orders at high on-cost. This demonstrates that food packaging is sometimes wrongly viewed as having a negative impact on the environment (cf. Brennan et al., 2021) as technologies like TTIs can reduce food waste by increasing process efficiency, monitoring the temperature history on single item level to improve the cold chain of perishable foods from packaging process to consumption (Albrecht et al., 2020; Mercier et al., 2017) and reducing confusion over the meaning of date labels. Key factors of success would be the acceptance and readiness of use of TTIs by the consumers and political support regarding the legal relief for the use of the indicator as an equivalent expiry date compared to the currently used static dates like use-by date and best be-fore date.

However, the study has also some limitations that need to be considered when interpreting the results. The potential amount of food waste reduction derived from the survey cannot be interpreted as the actual amount to which the indicator can reduce food waste. First, in the situation with indicators the majority of participants responded to inspect the product first before they decide to eat or dispose of the fish. Hence, it is not clear what will happen with the fish after the inspection. If participants decided to dispose of it anyway, the indicator would not reduce food waste to a large extent. However, when participants are willing to inspect the fish, there should still be a good chance that they won't dispose of it. Second, as the survey asked participants how they would behave in a hypothetical situation, it is not clear how they will act in a real situation when the known use-by date has passed and the new indicator shows a longer shelf life. A behavior-action-gap might exist, which cannot be estimated here. Third, the sample is not representative for the German (and Austrian) population. The sociodemographic characteristics show that the participants were predominantly female, well-educated and on average live in a slightly larger household compared to German conditions (Destatis, 2022). With regard to the household size and number of children, there were also significant differences between the test group and the control group, which might have an effect on handling food and the amount of food waste. The difference can be explained by the sampling which was influenced by operational reasons. For the case study, the number of available Keep-it® indicator units was limited and hence, a suitable customer batch had to be chosen. Accordingly, the Keep-it® indicators were attached to salmon sent to 3-person households as the respective customer number did not exceed the number of available indicator units. However, as the absolute differences of both characteristics between the groups were quite small and all other sociodemographic characteristics do not significantly differ, the results of the survey regarding group differences should not be greatly affected by the differences in household size and number of children.

5. Conclusions

This article evaluates the implementation of the time-temperature indicator Keep-it® as an alternative date coding method on prepacked salmon in HelloFresh meal boxes. The evaluation linked a survey for HelloFresh customers to investigate their perception of this innovative packaging technology with an assessment of the expected effectiveness of the TTI on reducing food waste, and of its sustainability across the economic and environmental dimension. Results reveal three key points to be highlighted here. First, the online survey approves findings of prior studies, that consumers have difficulties to correctly interpret the currently used expiry dates (use-by and best before). In contrast, the TTI was perceived to be reliable, helpful and intuitive to use. Second, results indicate a theoretical food waste reduction potential of the TTI at consumer level due to the information provided by the indicator. Furthermore, a food waste reduction potential is also identified for the meal-kit provider due to an increasing process efficiency, if the company would be allowed to use the indicator as an alternative expiry date. Even though the actual food waste reduction along the food chain by using a TTI cannot be exactly quantified, results of the study demonstrate the big potential of these innovative packaging technologies in tackling food waste. Third, the related sustainability assessment shows that using a TTI instead of the use-by date is beneficial from an economic and environmental perspective as the implementation of the indicator would lead to monetary savings and a reduction of greenhouse gas emissions at HelloFresh and consumer level. This is an important finding as only food waste reduction measures should be implemented that achieve the reduction with low costs whilst ensuring high environmental and social benefits.

Hence, further research should focus on the quantification of the actual food waste reduction potential of implementing time-temperature indicators on perishable foods based on representative samples. Hereby, not only food waste reductions at each stage of the food supply chain should be considered, but also possible rebound effects occurring at any stages due to food waste reduction at other stages. Respective quantifications of the food waste reduction potential of TTIs would make it possible to scale up results and provide the opportunity to calculate the economic, environmental and social benefits of avoiding food waste when using TTIs at sector level, or on a national and global scale. A better knowledge of the food waste reduction potential and its overall sustainability along the food chain could support the current political discussion about the revision of EU legislation on date marking aiming to prevent food waste linked to the misunderstanding of existing date labels. This may deliver the decisive arguments for allowing time-temperature indicators to be used as an equivalent expiry date and to take another step towards a more sustainable food chain.

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CRediT authorship contribution statement

Friederike Lehn: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Yanne Goossens:** Conceptualization, Methodology, Writing – review & editing. **Thomas Schmidt:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

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.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

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