

Article

The Potential for Reducing Food Waste through Shelf-Life Extension: Actionable Insights from Data Digitization

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Abstract: Digital, practical, user-friendly tools generate actionable insights for the food industry to develop effective food waste reduction strategies. This study aimed to develop a methodology behind a digital food waste estimator that may be used to calculate the potential food waste reduction and the environmental and nutritional reach impact by extending the shelf life of foods. The methodology for this tool incorporates a straightforward algorithm and robust data sources. Additionally, two case studies were analyzed and discussed to demonstrate the tool's application and effectiveness. The results from the food waste estimator revealed that by increasing the shelf life of poultry meat by 40%, waste could be reduced by 6–7%, CO₂ emission by 457–567 kg, and water usage by 656,571–814,149 L/1000 kg of product. Meanwhile, by increasing the shelf life of bread by 20%, waste can be reduced by 5–6%, CO₂ emission by 155–192 kg, and water usage by 248,000–307,520 L/1000 kg of product. This study demonstrated that the fundamental mathematical approach to and assumptions behind the food waste estimator can be effectively used to determine the potential for food waste reduction and environmental impact by extending a product's shelf life. Extending the shelf life of food may reduce environmental impact and food waste.

Keywords: food waste estimator; food waste reduction; shelf-life extension; life cycle analysis



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1. Introduction

According to the United Nations (UN), the global population will reach 8.5 and 9.7 billion by 2030 and 2050, respectively [1]. Current data indicate that approximately 815 million people globally lack adequate access to safe and nutritious foods, a figure that could increase with population growth [2]. A striking aspect of this challenge is the extent of food waste: about 30% of global food production each year, approximately 1.3 billion tons, is either lost or wasted in different parts of the food supply chain [3,4]. Food waste represents a substantial loss of water, energy, land, and labor resources and contributes significantly to greenhouse gas emissions. Furthermore, the potential for this wasted food to alleviate global hunger is significant, as highlighted in recent research linking food waste directly to food insecurity [5].

Food waste has become a critical global concern, posing significant economic, environmental, and social challenges. According to Wilson, Rickard, Saputo, and Ho [6], the topic of food waste has generated significant debate among industry stakeholders, policymakers, and consumers. As a result, it is likely one of the most pressing issues facing individuals and organizations involved in food marketing and policy in the US and internationally.

The United Nations underscored the urgency of reducing food waste globally in its 2030 Agenda for Sustainable Development (adopted by its members in 2015). This commitment is articulated in their Sustainable Development Goals (SDGs)—specifically, Goal #12, which aims to cut global food waste at the retail and consumer levels in half by 2030 while minimizing losses in the food supply chains [7,8]. Understanding food waste's multifaceted causes and significant economic, environmental, and social costs is critical to

identifying effective intervention strategies. Achieving this goal necessitates an integrated value chain approach, encompassing coordination among diverse stakeholders, including multidisciplinary researchers, policymakers, the private sector, and civil society [9].

Several strategies can be employed to reduce food waste, all centered on the fundamental [10] or improved version [11] of the food waste hierarchy. According to Papargyropoulou, Lozano, Steinberger, Wright, and bin Ujang [12], strategies to reduce food waste throughout the food supply chain should consider the three dimensions of sustainability: environmental, economic, and social. In addition, the materiality and temporality of food should be accounted for to offer a more holistic approach to addressing the food waste issue.

Strategies like extending the shelf life of food products can enhance sustainability by optimizing logistics and reducing food waste [13]. Several preservation methods are currently used to extend the shelf life of foods and reduce waste, including conventional methods such as refrigeration, freezing, drying, fermentation, canning, pasteurization, sterilization, high-pressure packaging, and natural and chemical preservatives, among others [14]. Furthermore, new food preservation technology includes high hydrostatic pressure, pulsed electric fields, UV decontamination, modified atmosphere and active packaging, natural antimicrobial compounds, biopreservation [15], and ohmic and microwave heating [16]. Some of these new techniques are currently being used in the food industry while others are still being researched further.

Digital technologies will play an active and critical role in combating food waste. Food quality monitoring, traceability, and logistics management innovations enable more efficient production, inventory management, and consumer decision-making [17]; for example, digital tools may allow food producers to optimize processes to minimize waste, while retailers can manage their inventory more efficiently, and consumers can make better decisions about the shelf life of the food they purchase. In addition, these technologies could foster collaboration across the food supply chain, thereby reducing food waste and enhancing business profitability [18]. Adopting digital solutions is crucial in modernizing the food industry and achieving the SDGs' ambitious targets.

Digital food waste estimators are pivotal in assessing and monitoring food waste, facilitating the implementation of effective food waste reduction strategies that mitigate environmental, economic, and social impacts. Online tools like the ReFED impact calculator, FLW value calculator, and those developed by the Paulig group and De Laurentiis Caldeira, and Sala [19] vary in their functionality, offering features like impact assessment, results sharing, and data downloading. Nevertheless, digital tools possess significant potential to address the issue of food waste, yet the modern food industry has yet to fully capitalize on them.

Digital tools use diverse methodologies to estimate different aspects of food waste and its impacts. For example, our food waste estimator, as mentioned earlier, uses a straightforward algorithm and robust data sources to calculate the potential food waste reduction and environmental and nutritional reach impact of extending the shelf life of foods. Emerging technologies such as artificial intelligence (AI), the Internet of Things (IoT), and blockchain, on the other hand, use predictive analysis to forecast product demand to lower the risk of overproduction, track food products through the supply chain in real-time to monitor and optimize inventories and optimize the supply chain by tracking food products to identify inefficiencies and implement changes that may reduce food spoilage and waste, respectively [20].

In this study, we hypothesized that developing a practical and user-friendly food waste estimator tool to generate actionable insights for the food industry could help develop effective food waste reduction strategies. Therefore, the objectives of this study are to present the methodology used to develop a food waste estimator that links shelf-life data with food waste reduction potential, quantify the environmental impact in terms of CO₂ emission and water usage equivalent reduction, and estimate the nutritional reach (i.e., people that could be fed through reduced waste). The methodology for this tool

incorporates a straightforward algorithm and robust data sources to assess these metrics accurately. Additionally, two case studies are used and explained to demonstrate the tool's application and effectiveness. These case studies will provide insights into the effectiveness of the tool in real-world scenarios, highlighting its potential to aid the food industry in achieving greater sustainability.

2. Materials and Methods

2.1. Underlying Principles of the Food Waste Estimator

The food waste estimator v1.1 is a free Microsoft Excel®-based online application (<https://explore.kerry.com/food-waste-estimator>, accessed on 1 August 2023) (Supplementary S1). It enables food manufacturers to perform a waste reduction potential simulation derived from extending the shelf life of a specific food product by an “x” number of days. Based on the results, the food waste estimator provides manufacturers with information regarding processing benefits, environmental savings, and social impact when the product shelf life is extended. The estimator has a user-friendly interface, provides readily available input data, and presents the results coherently. In addition, this digital tool allows users to download the results in a PDF format. To conduct the manufacturer's simulation, the user is asked to provide the following information: (a) product type (bread, poultry, beef, pork, meat—generic, and food—generic), (b) region where the operation is performed (North America, APMEA (Asia Pacific, Middle East, Africa), Europe, Latin America, and Global Average), (c) volume of product that is produced (either per day or per year), (d) product's current shelf life, (e) additional days of shelf life that the user would like to simulate, and (f) percentage of product that goes to waste across all stages of the food supply chain. Then, the food waste estimator performs the calculations based on two scenarios: (1) if the element (f) of the list is known, the estimator will perform the simulation using the user's input data, and (2) if the element (f) of the list is unknown, the estimator will simulate using proxy data.

The following sections will describe the approach used by the food waste estimator to conduct the different calculations under two scenarios and present the user with the following results: (a) potential food waste reduction, (b) potential food waste reduction as a percentage of production, (c) equivalent CO₂, (d) equivalent H₂O, and (e) equivalent nutritional reach. Mathematical equations and the sources of the background data adopted to perform the manufacturer's simulation are shown in the estimator.

2.1.1. Potential Food Waste Reduction if the Percentage of Product That Goes to Waste Is Unknown

When performing the potential waste reduction calculation, the hypothesis is that all other variables are constant except the shelf life. Therefore, equally applying the food waste percentage across the longer shelf life can be used to indicate the reduction in food waste. In other words, the estimator calculates how much the percentage of product wasted is reduced when the product's shelf life is increased. Potential food waste reduction is calculated using Equations (1)–(6).

$$\text{PFWR} = \text{CW} - \text{ESLW} \quad (1)$$

where PFWR = Potential food waste reduction, CW = Current waste, and ESLW = Extra shelf-life waste.

$$\text{CW} = \text{PV} * \text{WPWCSL} \quad (2)$$

where CW = Current waste, PV = Production volume, and WPWCSL = Weighted percentage waste on current shelf life.

$$\text{WPWCSL} = \text{AFWPPT} * \text{RWIPT} \quad (3)$$

where WPWCSL = Weighted percentage waste on current shelf life, AFWPPT = Average food waste percentage by product type, and RWIPT = Regional weighting impact on product type.

$$ESLW = PV * ISLIW \quad (4)$$

where ESLW = Extra shelf-life waste, PV = Production volume, and ISLIW = Impact of shelf-life increase on waste.

$$ISLIW = \frac{WPWCSL * CSL}{CSL + ASL} * 100 \quad (5)$$

where ISLIW = Impact of shelf-life increase on waste, WPWCSL = Weighted percentage waste on current shelf life, CSL = Current shelf life, and ASL = Additional shelf life.

$$WPWCSL = AFWPPT * RWIPT \quad (6)$$

where WPWCSL = Weighted percentage waste on current shelf life, AFWPPT = Average food waste percentage by product type, and RWIPT = Regional weighting impact on product type.

To obtain the current waste (CW) and the extra shelf-life waste (ESLW) terms in Equation (1), the average food waste percentage by product type and the regional weighting impact on product type are needed. The first term for the six available product type options was obtained from FAO [21]; meanwhile, the second term for the five available regions was obtained from the United Nations Environment Programme [22].

(a) Potential food waste reduction as a percentage of production

This value is obtained using Equation (7):

$$PFWRPP = \frac{PFWR}{PV} * 100 \quad (7)$$

where PFWRPP = Potential food waste reduction as a percentage of production, PFWR = Potential food waste reduction, and PV = Production volume.

(b) Equivalent CO₂ emissions

This value is calculated using Equation (8):

$$\text{Equivalent CO}_2 = PFWR * \text{CO}_2 \text{ equivalent by product type} \quad (8)$$

where PFWR = Potential food waste reduction.

The equivalent CO₂ emissions per kg of product for poultry, beef, pork, and the meat—generic option was obtained from the food loss and waste value calculator developed by the food loss and waste protocol as part of the food loss and waste accounting and reporting standard (FLW Standard) [23]. Meanwhile, for the food—generic option, this value was obtained from Poore and Nemecek [24] and Ritchie, Rosado, and Roser [25]. In addition, the equivalent CO₂ per kg value for bread was obtained by conducting a cradle-to-gate Life Cycle Analysis (LCA) using the openLCA software version 2.2 (Berlin, Germany) with the support of the Agri-footprint v6.3 and Agribalyse v3.1 databases. A typical industrial formulation for European bread consisting of wheat flour, salt, yeast, butter, dough conditioner, and water was used as a model for the LCA analysis (see the table in Section 2.3).

(c) Equivalent H₂O usage

This value is derived by applying Equation (9):

$$\text{Equivalent water} = PFWR * \text{Water equivalent by product type} \quad (9)$$

where PFWR = Potential food waste reduction.

The equivalent H₂O usage per kg of product for poultry, beef, pork, and the meat—generic option was obtained from the food loss and waste value calculator developed by the food loss and waste protocol [23]. Meanwhile, for the food—generic option, this value was obtained from Ritchie, Rosado and Roser [25]. Furthermore, the equivalent H₂O per kg of bread was derived from the LCA performed as explained in Section 2.1.1 (b). using the same formulation. An LCA analysis was conducted to determine both the CO₂ and H₂O-eq per kg of bread due to the differences found in the studies reporting these values in the literature, which can be attributed to variations in regional factors and formulations used. As a result, we decided to conduct an LCA using the databases Agri-footprint v6.3 and Agribalyse v3.1, which contain more robust data, as support. The obtained results were used as background data in the food waste estimator to calculate the equivalent CO₂ (Equation (8)) and equivalent H₂O (Equation (9)) values.

(d) Equivalent nutritional reach

According to the World Food Programme [26], one-third of the global food production is wasted, which represents about 1.3 billion tons per year. All this produced food that is never eaten could be sufficient to feed two billion people. These data were used to calculate the term “people fed per unit (weight) of food” in Equation (10).

$$\text{Equivalent nutritional reach} = \text{PFWR} * \# \text{ people fed per food unit (weight basis)} \quad (10)$$

where PFWR = Potential food waste reduction.

2.1.2. Potential Food Waste Reduction If the Percentage of Product That Goes to Waste Is Known

Similar to Section 2.1.1, the same hypothesis is utilized for this calculation. As mentioned earlier, for this scenario, the estimator will perform the simulation by employing the user’s input data and using Equations (11)–(14).

$$\text{PFWR} = \text{CW} - \text{ESLW} \quad (11)$$

where PFWR = Potential food waste reduction, CW = Current waste, and ESLW = Extra shelf-life waste.

$$\text{CW} = \text{PV} * \text{PPGW} \quad (12)$$

where CW = Current waste, PV = Production volume, and PPGW = Percentage of product that goes to waste.

$$\text{ESLW} = \text{PV} * \text{ISLIW} \quad (13)$$

where ESLW = Extra shelf-life waste, PV = Production volume, and ISLIW = Impact of shelf-life increase on waste.

$$\text{ISLIW} = \frac{\text{PPGW} * \text{CSL}}{\text{CSL} + \text{ASL}} * 100 \quad (14)$$

where ISLIW = Impact of shelf-life increase on waste, PPGW = Percentage of product that goes to waste, CSL = Current shelf life, and ASL = Additional shelf life.

When the percentage of product that goes to waste is known, the equations for calculating the potential food waste reduction as a percentage of production, equivalent CO₂, equivalent H₂O usage, and equivalent nutritional reach are the same as in Section 2.1.1 (b)–(d), respectively.

2.2. Case Study One: Poultry Meat

According to Statista [27], poultry was the most widely consumed meat in the world in 2021, with an estimated 132.3 million tons consumed. Due to this, and for illustrative purposes, poultry meat was selected as one of the models to demonstrate the use of the food waste estimator. The manufacturer’s simulation was performed to evaluate two scenarios:

the first scenario evaluates when the percentage of product that goes to waste is known, while the second scenario evaluates when the percentage of product that goes to waste is unknown. Thus, the following information was used as software input for scenario one: (a) Product: Poultry, (b) Region: Europe, (c) Production volume: 1000 kg/day, (d) Product shelf life: Twenty-five days, (e) Additional days shelf life: Ten days, and (f) Percentage of product that goes to waste: Known (which, for this scenario, 20% was used). This value was selected based on the literature that reports that between 20 and 23% of production in the meat sector is lost or wasted [28–30]. For the second scenario, components (a) through (e) are analogous to scenario one, whereas component (f) is unknown. Regarding the (e) component, a shelf-life extension of ten days was used as the input based on studies performed on poultry frankfurters and fresh/raw marinated poultry products [31–33]. Figure 1 depicts the overall approach for estimating poultry meat’s potential food waste reduction.

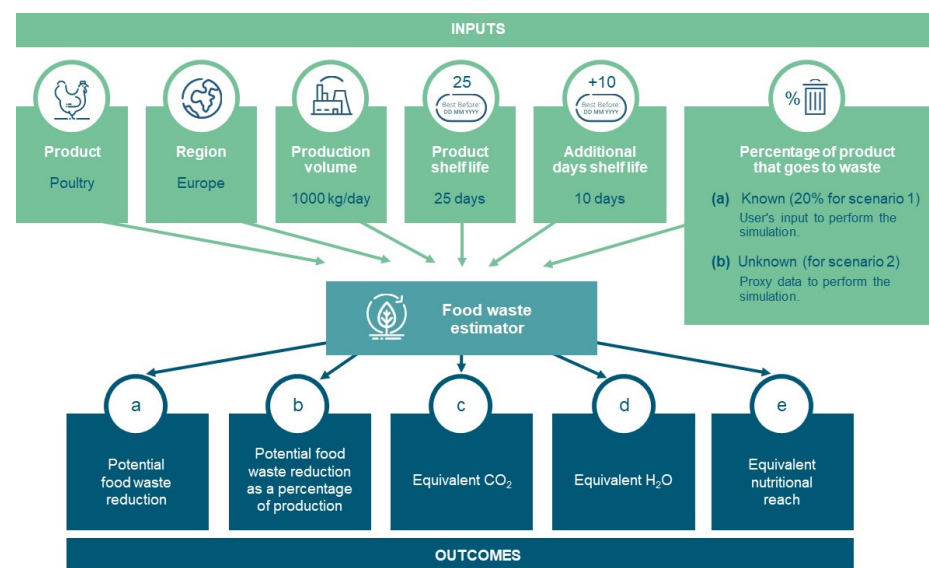


Figure 1. Inputs and outcomes derived from the food waste estimator for the poultry case study.

2.3. Case Study Two: Bread

Bread was also selected as a model to show the application of the food waste estimator because it is a staple food consumed daily in numerous countries worldwide [34,35]. Furthermore, bread has long been regarded as one of the most significant sources of nutrients in several civilizations [36]. Similar to the poultry meat case study, two scenarios were evaluated. In the first scenario, the percentage of product that goes to waste is known, while in the second scenario, the percentage of product that goes to waste is unknown. In Table 1, the formulation for European bread that was used to perform an LCA analysis is shown.

Table 1. Typical industrial formulation for European bread.

Ingredients	Weight (g)
Wheat Flour	588.90
Salt	10.60
Yeast	17.70
Butter	5.90
Milk powder skimmed (dough conditioner)	11.80
Water	365.10

The following information was used as software input for the first scenario: (a) Product: Bread, (b) Region: Europe, (c) Production volume: 1000 kg/day, (d) Product shelf life: Five days, (e) Additional days shelf life: One day, and (f) Percentage of product that goes to waste: Known (which, for this scenario, 30% was used). The Food and Agriculture

Organization of the United Nations (FAO) reported that 29.1% of global bread production was wasted in 2016 [37]. Additionally, Statista [38] reported that in the United States, as of 2016, 20% of bread is wasted in the kitchen and 12% of bread is wasted in the store. Hence, these reported values were used to assume that 30% of bread production is wasted. For the second scenario, components (a) through (e) are similar to scenario one, while component (f) is unknown. In Figure 2, the overall approach for the potential food waste reduction in bread is presented.

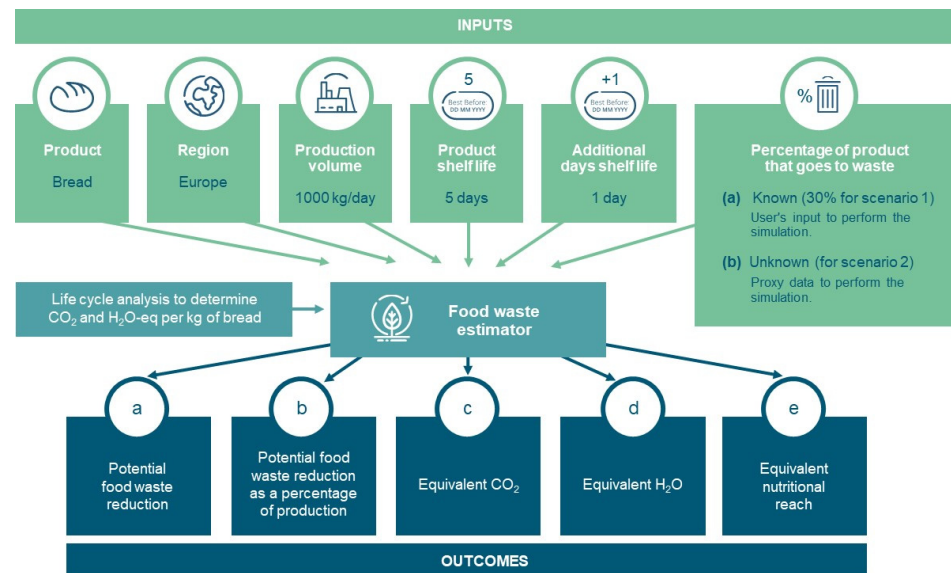


Figure 2. Inputs and outcomes derived from the food waste estimator for the bread case study.

3. Results

For illustrative purposes, in Figure 3, the food waste estimator's result output interface for scenario one of the poultry meat case study is shown.

Manufacturer simulation

For Meat - Poultry in Europe at a production scale of 1,000 kg per day the extension of shelf-life from 25 days to 35 days indicates:

Potential volume waste reduction	57 kg per day
Above reduction as a % of production	6 %
Equivalent CO ₂	457 kg per day
Equivalent H ₂ O	656 571 € per day
Equivalent nutritional reach (additional people fed)	32 people fed for one day

[Download results](#)

Sources: UN FAO (2011, 2015, 2020). Food Loss and Waste Accounting and Reporting Standard Calculations (2021) (Invering, Phoebe & Hemsley, David, & Lupton, et al. (2013) The carbon footprint of bread, Nazzari, et al. (2017) Energy, time and greenhouse gases of EU national breads using an LCA approach, Michael Clark et al. (2022) Estimating the environmental impacts of 57,000 food products, PNAS World Resources Institute: FLOW Value Calculator (Beta release v1.2 June 2, 2021), Food Waste Atlas, Data Environmental Impacts of Food Data Explorer by Our World in Data, Kerry Proprietary Database

Figure 3. Food waste estimator's result output interface for scenario one of the poultry meat case study.

3.1. Potential Food Waste Reduction Results for Poultry Meat

3.1.1. Scenario One

According to the findings derived from the food waste estimator and assuming an extended shelf life of poultry meat by ten days (40% shelf-life extension) with 20% of the product going to waste, it is possible to achieve a potential reduction in waste volume of 57 kg/day (at a production scale of 1000 kg/day). Furthermore, the quantity of 57 kg corresponds to a reduction of 6% in the total volume of poultry meat production per day, specific to food waste. In terms of environmental impact, a daily emission of 457 kg of CO₂-eq and a daily consumption of 656,571 L of H₂O-eq would be avoided. Lastly, the social impact of prolonging the poultry meat's shelf life by ten days would be that 32 people could be fed per day (Table 2).

Table 2. Food waste estimator overall results for poultry meat and bread case studies.

Metric	Units	Poultry Meat [†]		Bread [†]	
		Scenario 1	Scenario 2	Scenario 1	Scenario 2
Potential food waste reduction	kg/day	57	71	50	62
Potential food waste reduction as a percentage of production	%	6	7	5	6
Equivalent CO ₂	kg/day	457	567	155	192
Equivalent H ₂ O	L/day	656,571	814,149	248,000	307,520
Social impact	people fed/day	32	40	28	35

[†] Assuming a production of 1000 kg/day.

3.1.2. Scenario Two

Using the results from the food waste estimator for extending the shelf life of poultry meat by ten days (40% shelf-life extension) without knowing the amount of product that goes to waste across the stages of the supply chain, a potential volume waste reduction of 71 kg/day could be achieved from the production of 1000 kg/day of poultry meat (Table 2). The quantity of 71 kg corresponds to 7% of food waste that would be reduced from the total volume production of poultry meat in a single day. Regarding environmental impact, an emission of 567 kg of CO₂-eq and a consumption of 814,149 L of H₂O-eq would be avoided. Finally, the social benefit of extending the poultry meat product's shelf life by two days would be that 40 people could be fed per day.

A difference was observed in the values derived from the estimator in the two scenarios evaluated. The second scenario showed higher values than the first one, and this could be explained by the higher values obtained for the “weighted percentage waste on current shelf life” which is the second term of Equation (2) and the first term of Equation (5) where values from FAO [21] and UNEP [22] were used. This term depends on the average food waste percentage by product type and the regional weighting impact on product type. The value calculated by the food waste estimator for this term was 25%. The “weighted percentage waste on current shelf life” term can be considered analogous to the “percentage of product that goes to waste” term used in the equations for the first scenario, which is the second term of Equation 12 and the first term of Equation (14). The “percentage of product that goes to waste” value used for the first scenario was 20%. For the two scenarios modeled for this case, the only modified variable was the percentage of product that goes to waste, Known (Scenario One) and Unknown (Scenario Two), while the rest of the variables remained constant. However, in general, the results of the food waste estimator will vary depending on the type of product, region, production volume, product shelf life, additional days of shelf life modeled, and the amount of product that goes to waste.

3.2. Potential Food Waste Reduction Results for Bread

3.2.1. Scenario One

The findings from the food waste estimator revealed that by extending the shelf life of bread by one day, representing a 20% shelf-life extension, and modeling for 30% of wasted product, reducing the waste volume by 50 kg would be possible. This waste reduction would apply to a daily production of 1000 kg. Regarding food waste reduction, 50 kg would represent 5% of the total volume of bread produced in one day. Environmentally, a daily emission of 155 kg of CO₂-eq and a daily consumption of 248,000 L of H₂O-eq would be avoided. Furthermore, extending the bread's shelf life by one day, at this production volume, could potentially feed 28 individuals per day.

3.2.2. Scenario Two

The results from the food waste estimator revealed that by increasing the shelf life of bread by one day, equivalent to a 20% shelf-life extension, the volume of waste may be reduced by 62 kg/day. This reduction is based on a total daily production of 1000 kg of bread and assuming no knowledge of the specific amount of waste generated across the different stages of the supply chain. Furthermore, the 62 kg represents a food waste reduction of 6% from the daily bread production. Regarding the environmental effect, a daily emission of 192 kg of CO₂-eq and a daily consumption of 307,520 L of H₂O-eq would be avoided. Meanwhile, the social benefit of extending the bread's shelf life by one day would be that 35 people could be fed per day.

Similar results were observed in the values obtained by the food waste estimator in scenarios one and two compared to the scenarios in the poultry meat case study. The second scenario showed higher values than the first one, and the calculated value of "weighted percentage waste on current shelf life" was 37%. Meanwhile, the "percentage of product that goes to waste" value used for the first scenario was 30%. Similar to the first case study, the only modified variable between the two scenarios evaluated for the bread case study was the percentage of product that goes to waste, while all other variables remained constant. Table 2 shows the results of the two case studies modeled.

The results from the LCA analysis to determine the CO₂ and H₂O-eq per kg of bread are shown in Table 3. The calculated climate change and water use impact were 3.09 kg CO₂-eq and 4.96 m³-eq, respectively. As mentioned in Section 2.1.1 (b)–(c), these results were used as background data in the food waste estimator to determine the equivalent CO₂ (Equation (8)) and equivalent H₂O (Equation (9)) values for the two scenarios evaluated in each case study (poultry meat and bread). Wheat bread's global average water footprint has been reported to be 1608 L/kg [39,40]. According to Hoekstra [39], the precise water footprint of bread depends on the origin of the wheat, as well as where and how the wheat was grown. Regarding the climate change impact, research studies have reported values for different types of bread ranging from 0.495 to 6.6 kg CO₂-eq per kg of bread [35,36,41–52]. According to Notarnicola, Tassielli, Renzulli and Monforti [52], these reported values are for generic types of bread using basic recipes consisting of flour, yeast, salt, and water. The calculated climate change values for the bread formulation used in our study are comparable to the previously reported values. Also, in Table 3, the environmental evaluation of different impact categories for one kilogram of bread is shown.

Alamprese, Cappa, Ratti, Limbo, Signorelli, Fessas and Lucisano [53] point out that the shelf-life extension of foods can be achieved using different strategies, including formulation, processing conditions, packaging characteristics and functionality, and storage conditions during distribution, sale, and at the household level. Moreover, Spada, Conte, and Del Nobile [54] suggest that one of the most effective approaches to reducing food waste is through shelf-life extension solutions, particularly for products with middle shelf-life values (30–50 days). In that sense, the food waste estimator tool has the potential to assist manufacturers in effectively identifying products that may benefit from reformulation, thereby optimizing products with a short shelf life. Additionally, it could facilitate the identification of hot spots characterized by high levels of waste, thus enabling targeted

efforts toward reducing waste in areas where the impact would be most significant. Implementing this approach could result in favorable environmental and economic outcomes, as the embodied impacts and costs associated with food no longer being wasted are avoided. Furthermore, Laurent, Bakas, Clavreul, Bernstad, Niero, Gentil, Hauschild, and Christensen [55] suggest that positive environmental impacts of extending the shelf life of foods are related to the avoided manufacturing efforts and the reduction in the volume of waste management requirements.

Table 3. Environmental impact of one kilogram of a typical European bread formulation [†].

Impact Category	Impact Assessment Result	Unit
Acidification	2.70×10^{-2}	mol H ⁺ eq
Climate change	3.09	kg CO ₂ -eq
Ecotoxicity, freshwater	5.33×10^1	CTUe
Eutrophication, freshwater	3.36×10^{-4}	kg P eq
Eutrophication, marine	1.21×10^{-2}	kg N eq
Eutrophication, terrestrial	1.27×10^{-1}	mol N eq
Human toxicity, cancer	1.44×10^{-9}	CTUh
Human toxicity, non-cancer	6.80×10^{-8}	CTUh
Ionizing radiation	1.26×10^{-1}	kBq U-235 eq
Land use	1.37×10^2	Pt
Ozone depletion	1.26×10^{-7}	kg CFC11 eq
Particulate matter	2.23×10^{-7}	disease incidence
Photochemical ozone formation	6.31×10^{-3}	kg NMVOC eq
Resource use, fossils	1.14×10^1	MJ
Water use	4.96	m ³ depriv.

[†] Values are obtained from the LCA analysis.

Moreover, extending the shelf life of a product may also represent social benefits, as less wasted food means more food available for malnourished or hungry people around the world. An additional social indicator relates to the potential for the creation of employment opportunities along various stages of the food supply chain where food waste is being prevented [56]. It should be emphasized that any action taken throughout the different stages of the food supply chain to reduce food waste should ideally be carried out using a unified evaluation framework, as exemplified in the approach used by De Laurentiis, Caldeira, and Sala [19]. According to these investigators, this would permit a systematic and consistent quantification of the environmental, economic, and social benefits, as well as potential trade-offs between benefits and impacts or costs incurred by such actions. Additionally, this harmonized approach should include qualitative and descriptive evaluation criteria, such as quality of the action design, sustainability over time, transferability and scalability, and intersectoral cooperation to tackle food waste [56]. However, Amani and Gadde [57] point out that the relationship between shelf-life extension and food waste reduction may not necessarily reduce waste. They attribute this to the complexity of food supply chains, complex consumption behaviors, and the perception that products with longer shelf lives are less fresh. Furthermore, Bacenetti, Cavaliere, Falcone, Giovenzana, Banterle, and Guidetti [58] have indicated that shelf-life extension may not always be an appropriate environmental mitigation solution and that its effectiveness is contingent upon the extent to which it reduces product loss.

Nevertheless, Al-Obadi, Ayad, Pokharel, and Ayari [59] have recently indicated that preventing food waste is recognized as the most eco-friendly option in the hierarchy of food waste management solutions. Furthermore, they reported that greenhouse gas emissions could be reduced by 706–896 kg CO₂-eq per ton of food waste. New methods for CO₂ reduction and food waste utilization have been recently proposed. For example, Yang et al. [60] suggest food waste as a source of novel materials for applications in packaging and biomedical devices.

However, food waste prevention is also the most intangible and difficult to measure among all the solutions in the hierarchy of food waste management [61]. De Laurentiis, Caldeira, and Sala [19] have also emphasized this point, noting that no information is available regarding the detailed breakdown of the food waste avoided by food types. This made it difficult to compare our results for the scenarios evaluated using the food waste estimator. However, it is intended that this study can guide the food industry through early improvements in waste reduction through shelf-life extension until more detailed studies on food waste prevention initiatives are available. Other appropriate and effective prevention measures to reduce food waste at the manufacturing stage have been addressed. For example, Lee, Osborn, and Whitehead [62] identified five opportunities for retailers and manufacturers to reduce food waste by extending product life without making changes to packaging or product formulations or compromising safety and quality. The authors proposed that increasing the actual shelf life by at least one day and passing it on in full to the consumer could significantly impact food waste reduction and improve economic performance. This could be achieved by transferring the product through the supply chain more quickly or extending shelf life through preservation. ReFED [63] pointed out that the top three prevention waste solutions in businesses and homes with the most significant economic value per ton of product are related to shelf-life extension, including standardized date labeling, consumer education campaigns, and packaging adjustments.

For manufacturers, addressing food waste should involve close collaboration with other stages of the food supply chain, both upstream and downstream. The primary areas of opportunity at the manufacturing stage to prevent food waste are improving processing practices, reformulation, finding innovative packaging solutions, offering a diversity of portion sizes, raising consumer awareness on date marking, redistributing surplus food, and promoting circularity through food, feed, and non-food uses [64]. Effective collaboration and communication among several stakeholders are crucial in mitigating food losses, as these losses can greatly affect the nutritional and financial status of producers, market operators, and consumers [65]. Due to the interdependency of stakeholders along the food supply chain, Chaboud and Daviron [66] noted that a transfer mechanism of food waste and its costs from one actor to another is created. They stated that this calls for a comprehensive study to ensure that stakeholders' interactions and influences on food waste are considered. Furthermore, Mourad [61] suggested that transitioning from "weak" to "strong" prevention actions in the food system is the most sustainable solution to achieve more radical changes that address the underlying causes of food waste, adding that only structural transformations of both food and economic systems would ensure universal access to nutritious food in adequate but not excessive quantities for a continually growing population.

4. Conclusions

Reducing food waste is a multifaceted issue that requires engagement amongst several stakeholders with different interests, including those in the food supply chain, multidisciplinary scientific researchers, policymakers, the private sector, civil society, public health, etc. Extending the shelf life of foods can be an effective way to reduce food waste. Tools such as food waste estimators can help drive this process by providing valuable data for implementing targeted waste reduction strategies. The results of our study showed that regardless of the difference between the two case studies modeled, using the food waste estimator constructed on the principle of shelf-life extension may help reduce food waste and negative environmental impacts while also making a positive contribution to social equity. This work is expected to contribute to the ongoing scientific research on alternative tools that the global food industry may find useful in developing interventions to effectively reduce food waste across the food supply chain. Thus, it is crucial to keep pushing for innovation and involvement in reducing food waste at every level to achieve the ambitious SDG 12.3.

Supplementary Materials: The supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su16072986/s1>, Supplementary S1–S5 are included in the supplementary file. References [67–70] are cited in the Supplementary Materials.

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Nomenclature

AFWPPT	Average food waste percentage by product type
ASL	Additional shelf life
CSL	Current shelf life
CW	Current waste
ESLW	Extra shelf-life waste
ISLIW	Impact of shelf-life increase on waste
PFWR	Potential food waste reduction
PFWRPP	Potential food waste reduction as a percentage of production
PPGW	Percentage of product that goes to waste.
PV	Production volume
RWIPT	Regional weighting impact on product type
WPWCSL	Weighted percentage waste on current shelf life

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