Food waste management during the COVID-19 outbreak: a holistic climate, economic and nutritional approach

Aldaco, R.[1], Hoehn, D. [1], Laso, J. [1], Margallo M. [1], Ruiz-Salmón, J. [1], Cristobal, J. [1], Kahhat, R.[2], Villanueva-Rey. P.[3], Bala, A.[4], Batlle-Bayer, L. [4], Fullana-i-Palmer, P. [4], Irabien A. [1], Vazquez-Rowe, I. [2]

1 University of Cantabria, Avda. de los Castros s/n, 39005, Santander, Spain

2 Peruvian LCA Network (PELCAN), Department of Engineering, Pontificia Universidad Católica del Perú, Av. Universitaria 1801, San Miguel, Lima 15088, Peru

3 EnergyLab, Fonte das Abelleiras s/n, Campus Universidad de Vigo, 36310 Vigo, Galicia, Spain

4 UNESCO Chair in Life Cycle and Climate Change, Escola Superior de Comerç International (ESCI-UPF), Pg. Pujades 1, 08003 Barcelona, Spain

Corresponding author: aldacor@unican.es

Full postal address: Departamento de Ingenierías Química y Biomolecular, ETSIIyT, Universidad de Cantabria, Avda. de los Castros, 39005, Santander, Spain

Abstract

Improving the food supply chain efficiency has been identified as an essential means to enhance food security, while reducing pressure on natural resources. Adequate food loss and waste (FLW) management has been proposed as an approach to meet these objectives. The main hypothesis of this study is to consider that the "strong fluctuations and short-term changes" on eating habits may have major consequences on potential FLW generation and management, as well as on GHG emissions, all taking into account the nutritional and the economic cost. Due to the exceptional lockdown measures imposed by the Spanish government, as a consequence of the emerging coronavirus disease, COVID-19, food production and consumption systems have undergone significant changes, which must be properly studied in order to propose strategies from the lessons learned. Taking Spain as a case study, the methodological approach included a deep analysis of the inputs and outputs of the Spanish food basket, the supply chain by means of a Material Flow Analysis, as well as an economic and comprehensive nutritional assessment, all under a life cycle thinking approach. The results reveal that during the first weeks of the COVID-19 lockdown, there was no significant adjustment in overall FLW generation, but a partial reallocation from extra-domestic consumption to households occurred (12% increase in household FLW). Moreover, the economic impact (+11%), GHG emissions (+10%), and the nutritional content (-8%) complete the multivariable impact profile that the COVID-19 outbreak had on FLW generation and

management. Accordingly, this study once again highlights that measures aimed at reducing FLW, particularly in the household sector, are critical to make better use of food surpluses and FLW prevention and control, allowing us to confront future unforeseen scenarios.

KEYWORDS

COVID-19, food loss waste (FLW), life cycle assessment (LCA), eating habits, GHG emissions, nutritional impact

1. Introduction

The emergent coronavirus disease, COVID-19, presents a significant and critical threat to worldwide health since its outbreak in early December 2019 (Wu et al., 2020). In order to reduce and delay community transmission, diminishing the burden on healthcare systems, while also providing the best possible care for patients, most regions and nations have enforced exceptional public health measures together with unprecedented social and economic interventions (IMF, 2020). Community-based measures include actions taken by national and/or regional governments, and companies to protect vulnerable groups, employees and the overall population. The measures carried out, which include interventions within workplaces, educational centers, public transportation, spiritual and cultural venues, among others, aim to decrease transmission through changes in behavior to levels that can be managed by current health care capacity (Cornwall, 2020).

Consequently, almost all avoidable outdoor human activities have ceased worldwide in some way or another. Lockdown measures affect different supply chains, leading to a reduction of economic growth or a foreseeable economic recession. Food supply chains (FSC), referring to the processes describing how food from a farm ends up on our tables, are not exempt from these disruptions. In fact, since the beginning of the pandemic, COVID-19 has created huge shifts in terms of food access, food security and food loss and waste (FLW) (ReFED, 2020). Accordingly, the exceptional nature of food production and consumption habits due to COVID-19 may have influence on the generation of FLW along the supply chain (Jribi et al, 2020) and on other aspects of sustainability (Song et al.2019). Considering the previously described scenarios, the conclusions and strategies depend on a large number of variables that should be subject to assessment.

Likewise, changes in eating habits, as a consequence of lifestyle disruptions and psychological stress due to lockdowns, may produce an important hotspot that could sway the generation and distribution patterns of FLW along the supply chain. The Spanish Ministry for Agriculture, Fisheries and Food (MAPA) offers detailed information on how COVID-19 is impacting Spanish consumers' food preferences and behaviors. The reports show, in general terms, that household consumption has increased significantly across all food categories. Spanish consumers are stockpiling non-perishable food and other supplies, eating more indulgent and comfort foods (i.e., food craving), drinking more wine, beer and other spirits, as well as snacks throughout the day (MAPA, 2020a). Obviously, these behavioral patterns imply not only changes in food supply chains and in the generation of FLW, but also repercussions in the dietary pattern, which may be detrimental to the health and also other environmental attributes offered by the

Spanish Mediterranean diet (Batlle-Bayer et al. 2019a), triggering obesity, sleep disruptions or impacts on the immune system (Muscogiuri et al.,2020).
After years of awareness, FLW has gradually become a mainstream concern (Vázquez-Rowe et al, 2019). The Food and Agriculture Organization of the United Nations (FAO) considers a distinction between food loss (i.e. a decrease of quantity or quality in edible food mass, intended for human consumption, that occur in the primary stages of the supply chain – production, postharvest and processing stages) and food waste (i.e. food losses occurring at the end of the food chain – retail and final consumption – related to retailers' and consumers' behaviour) (FAO, 2011). Albeit, usually both terms are considered together as FLW when quantifying them for further analysis (Corrado and Sala, 2018; Wunderlich and Martinez, 2018). Thus, approximately 20% of all food is lost or wasted in the European Union throughout the supply chain (EU Fusions, 2016).
Therefore, the reduction of FLW is key to achieving sustainability as recognized in the literature (e.g. Lemaire and Limbourg, 2019), and more recently by the EU Farm to Fork (F2F) strategy for sustainable food (EC, 2020), which aims at making food systems fair, healthy and environmentally-friendly. F2F is a key component of the European Green Deal, released in 2019, that is the roadmap for making EU's economy sustainable with the final goal of making Europe a climate-neutral continent by 2050 (EC, 2019). Besides, F2F is also central to the commitment of the European Commission (EC) to halving *per capita* food waste at retail and consumer level by 2030 in line with the target established by the United Nations' Sustainable Development Goal (SDG) 12.3 (UN, 2019). Thus, F2F foresees specific measures such as proposing for EU-level legally binding targets for food waste reduction by 2023 and reviewing the EU rules on date marking ('use by' and 'best before' dates) by the end of 2022 (EC, 2020).
Furthermore, the importance of FLW is highlighted in other blocks of actions. Within the stimulation of sustainable food processing, wholesale, retail, hospitality and food service practices, the EC intends to promote circular business models that make use of food waste. Special attention is given to food packaging materials which legislation will be revised to support the use of packaging solutions environmentally-friendly, re-usable and recyclable materials, using LCA to choose the best option (Abejón et al., 2020), and to contribute to food waste reduction. In addition, the EC will revise marketing standards to reinforce the role of sustainability criteria taking into account the possible impact of these standards on FLW. Finally, within the promotion of sustainable food consumption, the EC will strengthen educational messages on the importance of reducing food waste within school schemes.
In the short term, the real cost of a healthy diet may rise because of the increase in the cost of perishable commodities, which would have a particularly adverse impact on lower-income households and slow the progress towards complying with SDGs (FAO, 2020).
In recent years, many studies and other supporting documents have assessed FLW, covering all three dimensions of sustainability. The environmental variable has been mostly assessed under a life cycle approach, including energy assessments. Laso et al. (2018) combined life cycle assessment (LCA) and data envelopment analysis (DEA) to assess the efficiency of Spanish agri-food system and to propose improvement actions in order to reduce energy usage and GHG emissions. Hoehn et al. (2019) performed an energy flow analysis through the calculation of the primary energy demand of four stages and 11 food categories

of the Spanish food supply chain in 2015. Batlle-Bayer et al. (2020a) introduced a method to quantify environmental impact together nutritional values, also further including with food affordability (Batlle-Bayer et al., 2020b). Finally, Usubiaga-Liaño et al. (2020) used a global multi-regional environmentally extended input–output database in combination with newly constructed net energy-use accounts to provide a production- and consumption-based stock-take of energy use in the food system across different world regions for the period 2000–2015. In addition, the estimation of embodied greenhouse gas (GHG) emissions were also assessed. Kim and Kim (2010) evaluated different food waste disposal options from the perspective of global warming and resource recovery, whereas Slorach et al. (2020) evaluated the life cycle environmental and economic sustainability of five plausible scenarios for food waste treatment in UK. On the other hand, FLW have also been addressed under a nexus approach (Laso et al., 2018b). Only a limited number of case studies have been reported in the literature linked to economic aspects, mostly related to municipal FLW management (De Menna et al., 2018). Thus, the economic factor has been considered from a market perspective (McCarthy et al., 2020); the economy and the environmental hierarchy (Redlingshöfer et al., 2020; García-Herrero et al., 2018), from a life cycle cost thinking approach (De Menna et al., 2018) or combining LCA and life cycle costing (LCC) (De Menna et al., 2020; Slorach et al. 2019). The social scope has been studied to include important aspects, such as food security, food safety and nutrition. Markov et al. (2020) explored whether the sharing economy can provide meaningful assistance to reducing food waste in a relatively low-impact and environmentally-sound way. On the other hand, Morone and Imbert (2020) stated food waste represents a valuable option as it allows for the production of a wide range of bio-based products ranging from biofuels to bioplastics. Furthermore, it must be noted that not all food is of equal calorific and nutritional value. Therefore, the nutritional content of food waste should be considered in the decision-making process (Bradshaw, 2018). In this context, Vázquez-Rowe et al. (2019) have developed a novel approach to facilitate the FLW management decision-making process, including the nutritional content of FLW along the supply chain of several food categories, allowing the most appropriate management strategies. A few of these approaches have foreseeably concluded in half done strategies, which, although valid, would require additional efforts to integrate large number of variables in the decision-making process.

Under this overall framework, the main hypothesis of this study is to consider that the ‘strong short-term fluctuations and changes’ of eating habits could have significant direct and/or indirect consequences in FLW generation and management. The COVID-19 outbreak, and the follow-on measures taken by the Spanish government to mitigate its effects, produced some retail and consumption disruptions. These could have major consequences on the potential generation and management of FLW, as well as on the GHG emissions associated with food production and consumption, all considering the nutritional and the economic cost and under a holistic perspective. Moreover, understanding the main effects should be useful in the decision-making process of food systems, and the learned lessons could be a virtuous opportunity to propose strategies for future unforeseen events.

2. METHODS

The methodology developed in this study was established under a life cycle thinking approach since it involves all the stages of the food supply chain (ISO 2006a). The methodology, which follows the LCA standards, is divided into four steps (ISO 2006a, b). The Spanish food supply chain was selected as the case study. The reasons for this choice include, data availability and the fact that Spain has been one of the countries most affected by the coronavirus pandemic in its first wave, in terms of infections and mortality, and the strict lockdown regulations that were set in place in mid-March 2020. In fact, the coronavirus has caused high reported cases of COVID-19 in Spain that resulted in numerous deaths (Ministry of Health, Consumer Affairs and Social, 2020). However, this pandemic has had several positive, but temporal, implications on the environment, such as the decrease of concentrations of NOx and particulate matter due to strict traffic restrictions, the drop in energy and resources demand and GHG emissions due to low the industrial activity, the reduction of environmental noise level or the improvement of the quality of water bodies (Zambrano et al., 2020). Moreover, some negative impacts require a detailed evaluation, such as the amount of food consumed and wasted, the diet followed in the lockdown, or the economic consequences.

In the current study, a deep analysis of the inputs and outputs of the Spanish food basket along their supply chain by means of a Material Flow Analysis (MFA) was necessary (García-Herrero et al., 2018), as well as an economic (Vázquez-Rowe et al. 2019) and comprehensive nutritional assessment (Laso et al., 2019). Moreover, three impact indicators were evaluated: nutritional, economic and the environmental impact, in terms of GHG emissions.

2.1 Goal and Scope definition

The goal and scope of this study is to assess the economic, nutritional and environmental (i.e., climate change) consequences along the Spanish food supply chain in terms of FLW during the COVID-19 outbreak by means of the definition of a methodology that considers the production and consumption of different food categories included in the typical Spanish food basket. On the one hand, the nutritional FLW (N-FLW) was calculated using the Nutrient Rich Foods (NRF9.3) score (Fulgoni et al. 2009), which was previously used as an indicator of the nutritional content of FLW (Vázquez-Rowe et al, 2019). On the other hand, the economic FLW (E-FLW) index was introduced to consider the economic value (profit or loss) of FLW caused for each food product and category. Both indicators, together with the embodied GHG emissions linked to FLW in food production and consumption (GHG-FLW) establish the multivariable framework for potential decision-making.

The results are expected to test the viability of the new multivariable approach to provide an overview regarding the food supply chain and FLW management of the different food categories under study when a food system is exposed to unexpected market stressors. Hence, the most inefficient food categories and stages along the food supply chain from a nutritional, economic and climate point of view will be identified. A successful outcome of the coupled decision-making process and the consequent strategies proposed could mean important impacts on the efficiency of food systems.

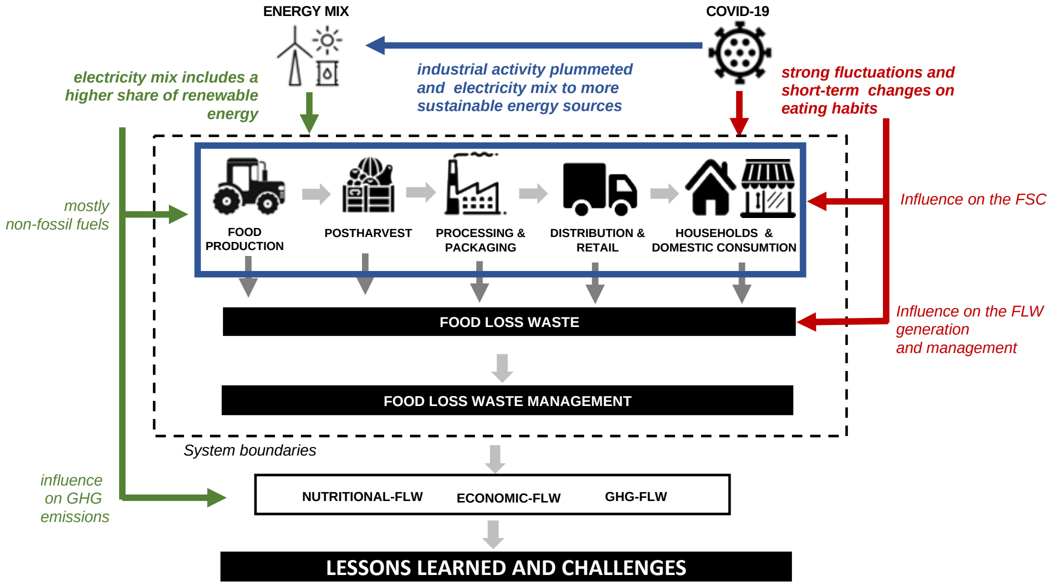


Figure 1. Overview of the functionality and system boundaries of the Spanish food system influenced by the COVID-19 pandemic.

2.2. Functionality and System Boundaries

The function of the system is the provision of food to an average Spanish citizen, minimizing the economic, nutritional and GHG impacts associated with the FLW generated and managed under the strong short-term fluctuations and changes of eating habits generated by the COVID-19 outbreak. In order to measure this function, it is necessary to define a suitable functional unit (FU), to which all the inputs and outputs will be referred. Considering that the daily supply of food for a Spanish citizen is expected to vary with respect to the usual conditions, the FU was defined as the supply of food for a Spanish citizen in terms of food categories, referred to 1 kcal per person and day (kcal/cap-day).

The system boundaries comprise the entire supply chain of a food system, following recent studies developed by García-Herrero et al. (2018) and Batlle-Bayer et al. (2019). Therefore, the stages of food production and postharvest, processing and packaging, distribution, consumption and end-of-life were considered, as shown in Figure 1, as well as FLW throughout the entire food supply chain (Vázquez-Rowe et al, 2019), acknowledging that, as mentioned before, depending on the stage of food production, either food losses or food wastes are considered.

2.3. Spanish food supply chain and FLW scenarios

The scenarios proposed in this study are summarized in Table 1 and described in detail in sections 2.3.1 and 2.3.2. These scenarios are established to differentiate two temporal frameworks: before COVID-19 pandemic (P1) and the period of COVID-19 (P2). In order for the comparison to be feasible, the same weeks in 2019 and 2020 were evaluated. These scenarios allow determining the influence and impacts of COVID-19 on the environment, economy and health spheres of Spain.

Table 1. Spanish production and consumption scenarios.

Code	Time frame	Mix Consumption (%)		Electricity Mix[a]
		Household	Extra-domestic	
P1	Weeks 11-15, 2019	86.1	13.9	Mostly fossil fuels
P2	Week 11, 2020	86.1[b];	13.9[b];	Mostly non-fossil fuels
	Weeks 12-15, 2020	100[c]	0[c]	

(a) Detailed information about the electricity mix is included in Table S1 of the SM.
(b) Extra-domestic consumption was available for most of week 11, excepting the (c) Weeks 12-15.

2.3.1. P1. Pre-COVID-19 Scenario: to define the pre-COVID-19 outbreak scenario, the consumption of foods and beverages in Spain before declaring the state of emergency were considered (BOE, 2020a). Hence, food consumption during 2019 was established as the baseline scenario, from which the inventory of food production and consumption has been developed, as well as the resulting FLW inventory.
This scenario includes the entire supply chain, i.e. agricultural production, postharvest and storage, industrial processing, distribution (i.e. retail/wholesale) and consumption. The latter involves household and extra-domestic. Based on the reported data during weeks 11-15 of 2019 from MAPA (2019a, 2019b), extra-domestic was assumed to represent 13.9% of total consumption. Moreover, the electricity mix was dominated by fossil fuels.

2.3.2. P2. COVID 19 Scenario: the scenario describing the COVID-19 outbreak corresponds to the production of food, its consumption and the FLW management during weeks 11-15 (from March 9, 2020 to April 12, 2020). In this case, consumption was assumed to occur entirely in households, based on the fact that extra-domestic consumption has been reduced to a minimum as a consequence of the lockdown.

Table 2. Food purchase rates during weeks 11-15 of COVID-19 and the same period of 2019 (kg/cap-week). Data source: MAPA, 2020a.

Food category	March 2019	April 2019	Week 11	Week 12	Week 13	Week 14	Week 15
Eggs	0.183	0.184	0.233	0.190	0.238	0.238	0.292
White meat	0.395	0.375	0.355	0.347	0.372	0.355	0.395
Red meat	0.626	0.615	0.672	0.642	0.702	0.669	0.681
Fresh fish	0.302	0.298	0.268	0.265	0.270	0.262	0.266
Frozen fish	0.099	0.098	0.103	0.100	0.104	0.102	0.122
Processed fish	0.111	0.119	0.137	0.093	0.100	0.090	0.101

Dairy	2.260	2.282	2.554	2.068	2.270	2.173	2.302
Cereals	0.885	0.872	1.062	0.905	0.934	0.922	1.043
Sweets	0.458	0.460	0.511	0.454	0.507	0.496	0.548
Pulses	0.272	0.267	0.417	0.325	0.304	0.277	0.278
Vegetable fats	0.296	0.316	0.424	0.318	0.339	0.303	0.351
Roots and tubers	0.539	0.551	0.559	0.567	0.589	0.582	0.605
Vegetables	1.840	1.777	1.854	1.743	1.840	1.786	1.883
Fruits	1.755	1.716	1.739	1.787	1.894	1.893	1.936
Beverages	1.191	1.198	0.581	0.630	0.640	0.826	0.898

Week 11 in 2020 presented an increase in purchases of 29.8% with respect to food purchases made in the same week in 2019. Meanwhile, in week 12 the increase in purchases with respect to 2019 was 10.9% (MAPA, 2020a). The assessment shows that in the first fortnight of lockdown, substantial amounts of food were stored in households and, therefore, it was not necessary to buy with the same intensity in subsequent weeks. In fact, week 13 showed a reduction of 20.3% in terms of food purchase. Table 2 shows food consumption rates throughout weeks 11-15 related to the average consumption during the same weeks in 2019. It is important to remark that during week 11 extra-domestic consumption was hardly altered, since the state of emergency did not start until March 14 (Saturday), i.e., from Monday 11 to Friday 13[1], extra-domestic consumption was fully available. Thus, an 86.1% of household consumption was assumed during week 11.

The scenario includes the electricity mix under the COVID-19 outbreak. Considering that industrial activity plummeted since the beginning of the pandemic, so did energy demand. The new electricity mix includes a higher share of renewable energy (REE, 2020). Therefore, the pandemic has moved the electricity mix to more sustainable energy sources, producing a positive impact on the environment.

2.4. Life Cycle Inventory (LCI)

Data for representative commodities were sourced from the consumption database released by the MAPA for March and April 2019 (MAPA, 2019a, 2019b) and for the five first weeks of the quarantine in Spain during the same period in 2020 (MAPA, 2020a). An MFA was developed considering a total of 57 demonstrative food and beverage supplies, classifying them in 15 categories. Beyond the 13 categories, suggested by the FAOSTAT classification (FAO, 2014), wine and beer were also included as additional categories due to the substantial increase in consumption. Other beverages, as well as sauces, spices,

[1] Please note that in Spain the official week is from Monday to Sunday.

broths and other minor products, were not included in the study. Categories were also based on the available classification offered by the Spanish Ministry of Agriculture, Fisheries and Food (MAPA, 2020a). This allows to recognize, for instance, independent categories for fresh, frozen and processed fish but does not split fresh and frozen meats and vegetables.

To estimate FLW along the whole supply chain, different allocation, conversion and FLW factors based on Gustavsson et al. (2011) were used. Thereby, FLW for each category, considering if the product was consumed processed or fresh, and for each life cycle stage were calculated. For wine and beer, the factors for processed fruit and processed cereals were used, respectively.

Regarding the generation of GHG emissions in the production, distribution and consumption of each food product, most data were collected from Batlle-Bayer et al. (2019). The production of eggs was taken from Abín et al. (2018), potatoes from Frankowska et al. (2019) and wine and beer from Saxe (2010). In addition, mushrooms and strawberries were also considered due to their availability in the Spanish context (Leiva et al., 2015; Romero-Gámez and Suarez-Rey, 2020).

There are considerable differences among autonomous communities in Spain in terms of integrated waste management systems. Some models have fostered recycling based on separate collection, other territories have promoted mechanical-biological treatment and subsequent recycling processes, whereas a final group of regions have focused on energy recovery (i.e., incineration) (PEMAR, 2015). Regardless of the management systems, 2% of generated FLW was considered to be avoided by donating extra-food to food banks, soup kitchens and shelters (FESBAL, 2020). The remaining 98% was assumed to be managed by the different waste management treatment techniques, based on the percentage distribution available in annual reports published by the Spanish government. According to this information, 4.4% of waste was incinerated and 2.8% landfilled. The biological treatment of the FLW collected separately was carried out by composting (C) to obtain compost (7,5%), while the FLW collected with the remaining fraction is subject to a mechanical separation to obtain organic matter, which is subsequently treated in a process of biostabilization by composting (58.2%), or by anaerobic digestion (AD) (25.1%).

The different FLW treatment techniques have been developed according to the following models:

i. Landfilling of FLW including biogas recovery. Biogas and leachate treatment and deposition were included in the modelling. Sealing materials (e.g., clay or mineral coating) and diesel for the compactor were also included. Leachate treatment includes active carbon and flocculation/precipitation processing. The modelling was based on the average of municipal household FLW for landfill processes from the Sphera database (Sphera, 2019). According to the model, 17% of the biogas naturally released is assumed to be collected, treated and burnt to produce electricity. The remaining biogas is flared (21%) and released to the atmosphere (62%). A rate of 50% transpiration/runoff and a 100 years lifetime for the landfill were considered. Additionally, a net electricity generation of 0.0942 MJ per kg of municipal solid FL was assumed (Sphera, 2019).

ii. Incineration with energy recovery. Incineration was based on the Sphera dataset for the biodegradable waste fraction in municipal solid waste (MSW) (Sphera, 2019). To model a single fraction, the environmental burdens, energy production and credits of MSW incineration were attributed to the biodegradable waste fraction. The plant consists of an incineration line fitted with a grate and a steam generator. Grate is the most common technology in Europe, applied in 80% of the Spanish plants (Margallo et al., 2014). The plant produces 495 MJ of electricity and 1277 MJ of steam per metric ton of waste, which are considered to be exported to industry or households. The model mixes the most recurrent technologies for flue gas treatment (FGT) in Europe. Hence, one third of plants were assumed to use a wet system to treat acid gas, while the remaining two thirds were assumed to use a dry system. In the case of NO_X reduction, two thirds using Selective Non-Catalytic Reduction (SNCR) and one-third using Selective Catalytic Reduction (SCR) was used. Regarding solid residues, the incineration of one metric ton of waste produces 220 kg of bottom ash (BA) and 42 kg of boiler ash, filter cake and slurries. Once metal recovery and ageing is performed, 60% of the produced BA is reused as construction material. The remaining 40% is disposed of in a landfill. Re-melting and reprocessing of scrap were also included in the system boundaries. Boiler ash, filter cake and slurries are disposed of in salt mines (43%) or landfills (57%) (Sphera, 2019).

iii. Composting. Composting was modelled based on the Sphera dataset, which partly or fully takes place in closed halls or so-called composting boxes or rotting tunnels. The input waste is supposed to be an average mixture of biodegradable waste consisting of biodegradable garden and park waste, as well as food and kitchen waste with a 35% content. The model includes the pre-treatment (mixing process) to adjust and optimize the input substrate. Subsequently, the rotting allows aerobic biological degradation and alteration. Finally, the post-treatment based on a sieving process allows achieving compost quality requirements. Output fractions are compost, sieving rest and impurities (Sphera, 2019). For the selective collection fraction, the composting system includes the energy requirements of a mechanical separation unit (Cimpan and Wenzel, 2013).

iv. Anaerobic digestion and composting (AD&C). This treatment was modelled using Ecoinvent (Ecoinvent, 2016). The treatment includes storage (and 10% of the total pre-treatment storage emissions) of the substrates, anaerobic fermentation, as well as the storage of digestate after fermentation. It was considered that one cubic meter of biogas produces 2.07 kWh of electricity (Junta de Andalucía, 2011).

The electricity recovered in all scenarios was assumed to be sent to the national grid, displacing electricity from the average electricity mix. However, this value could be lower if energy losses and uses for other purposes are considered. All these assumptions are explained in section 2.6.

Nutritional data were obtained from the food composition tables of the Spanish Institute for Education in Nutrition and Dietetics (Farran et al. 2004). Table S2 of the Supporting Material collects the nutritional composition of each food commodity studied in terms of the nutrients needed to estimate the NRF9.3 index.

Prices at origin, wholesale and retail were obtained from the Spanish Ministry of Economy and Competitiveness (MINECO, 2020) and MAPA (2020b) (see Table S3 in the SM). The same costs were assumed for FLW for agricultural production and postharvest and processing stages. Otherwise, wholesale prices were used for distribution stage. It was assumed that extra-domestic services can buy their food at lower prices than private households. A 5% volume discount was considered (Beretta et al., 2013). Data from the Food Consumption Panel of MAPA shows no significant fluctuation in prices, despite the fact that the food chain had higher costs related to the acquisition of personal protective equipment and the enforcement of new hygienic-sanitary requirements. The Consumer Price

Index for food, in March 2020, increased by 6.9%, which was considered as an overall food price increase for all food categories (INE, 2020).

2.5. Main assumptions and limitations of the study

The most significant source of uncertainty is linked to the FLW percentages used for the calculations. Data reported by Gustavsson et al. (2013) represent the average conditions for Europe, disregarding differences among countries. Nonetheless, although they are considered as a good benchmark, they may lead to errors when used for a specific country. Hence, they have been updated with Spanish data when available, according to García-Herrero et al. 2018.

Nutritional data available in databases were used to describe and quantify the edible parts of food. While this approach is not exactly aligned with FLW composition, the current study assumes that these data can be used as a good proxy to describe inedible parts of food as well.

Weeks 13, 14 and 15 showed had an increase in online food purchasing of 84.4%, 843.9% and 101.3% higher than the same week in 2019, respectively (MAPA, 2020a). It is assumed as part of the household consumption increment analyzed along the study.

2.6. Allocations

The scenarios under study are multi-output processes in which the management of FLW is the main function of the system and the production of electricity and compost represent additional functions. Hence, environmental burdens must be allocated among the different functions. To handle this problem, ISO 14040 establishes a specific allocation procedure in which system expansion should be prioritized (ISO 2006a). Regarding the landfill scenario, it must be noted that electricity generation depends on methane concentration in the landfill biogas. Consequently, electricity from FLW was allocated to the amount of total carbon available in the disposed organic residue. The energy produced in waste decomposition (i.e., landfilling and anaerobic digestion) and combustion (i.e., incineration) was assumed to substitute the equivalent amount of electricity from the grid. The variation per week in the electricity mix composition was considered according to the information provided in Table S1 of the SM. The pandemic has influenced the energy sources of the Spanish mix. The use of hydropower and solar energy have increased during this period, whereas nuclear, hard coal, fuel oil and natural gas have shown a decrease, reducing the environmental impact of the mix per kWh produced. Low industrial activity, which is highly dependent on non-renewable sources, has fostered this positive change. Steam generation in waste incineration substituted steam generation from natural gas combustion. Moreover, the environmental credits of compost are also considered. Compost is assumed to replace mineral fertilizer, with a substitution ratio of 20 kg N equivalent per metric ton of compost (Righi et al., 2013). The fertilizer production as total N is obtained from the Sphera Database (Sphera, 2019).

2.7. Life cycle impact assessment

2.7.1. Nutritional Food Loss Waste (N-FLW)

The assessment approach suggested by García-Herrero et al. (2019) was applied to determine the nutritional impact of FLW (i.e., N-FLW). It is based on the nutrient profile model developed by Drewnowski et al. (2019) to the eating habits under study. Accordingly, the NRF9.3 algorithm, which is based on 9 nutrients (protein, fiber, minerals calcium, iron, magnesium and potassium, and vitamins A, C and E) that should be encouraged and 3 nutrients (saturated fat, added sugar and sodium) that should be limited, was used as shown in Equation 1.

$$\mathrm{NRF9.3}=\sum_i w_i\left(\sum_{l=9}\frac{NR_l}{DV_l}\cdot 100-\sum_{m=3}\frac{LIM_m}{MRV_m}\cdot 100\right) \qquad (1)$$

where NR is the intake of nutrient l (to encourage), DV is the daily recommended value of nutrient l, LIM is the intake of nutrient m (to limit), and MRV is the maximum daily recommended value for the nutrient m. W_i is the weighting factor of food category i and can be estimated using kcal or weight basis. In this study, the weight basis has been selected to avoid the overrepresentation of calorie-dense foods.

The daily (RV) and maximum recommended values (MRV) for all nutrients are based on the data published by EFSA (2017). To avoid crediting overconsumption of encouraged nutrients, their intakes were capped (Drewnowski, 2009). Hence, when a certain nutrient intake was higher than its RV, the intake of this nutrient was set to its RV.

2.7.2. Economic Food Loss Waste (E-FLW)

In terms of the economic variable, it must be considered that value is generally accumulated as the supply chain advances to the retail stage, linked mainly to successive phases of the elaboration of the final product. Therefore, the economic quantification of FLW was determined according to the Equation 2, from Vázquez-Rowe et al. (2019).

$$\text{E-FLW}_i=\sum_j \mathrm{FLW}_{i,j}\cdot V_{i,j} \qquad (2)$$

where E-FLW_i represents the economic FLW of food category i, $\mathrm{FLW}_{i,j}$ is the food loss and waste of food category i in the supply stage j, and $V_{i,j}$ their corresponding economic value.

2.7.3. GHG emissions (GHG-FLW)

FLW contributes to the generation of GHG emissions in two ways. On the one hand, GHG emissions emitted along the food supply chain, considering the production, postharvest processing, distribution and consumption of foods that are wasted. On the other, GHG emissions also result from the management of this FLW. In fact, the technological alternatives to treat FLW may tip the balance in favor of a particular optimized FLW management system.

GHG emissions associated with FLW were calculated by multiplying the FLW by the respective emission factor per food item according to Equation 3.

$$\text{GHG-FLW}_i=\sum_j \mathrm{FLW}_{i,j}\cdot \mathrm{GHG}_{i,j} \qquad (3)$$

where GHG-FLW_i represents the climate FLW of food category i, $\mathrm{FLW}_{i,j}$ is the food loss and waste of food category i in the supply stage j, and $\mathrm{GHG}_{i,j}$ their corresponding GHG equivalent emission factor according to the Ecoinvent or Sphera database.

3. RESULTS AND DISCUSSION

3.1. Overall FLW assessment

Figure 2 shows the results for scenarios P1 and P2. According to the assessment, the COVID-19 outbreak had a slight influence on the total amount of FLW. Under a similar overall production and consumption of food (1.5-1.75 Kg/FU), a greater FLW generation in households (H) occurred, approximately 12% higher during the COVID-19 outbreak (Figure 2a). However, if extra-domestic consumption absorbed by households during the outbreak are considered, overall FLW generation remains similar as compared to 2019. Therefore, no significant change in the amount of FLW is reported, but just a partial reallocation to households. FLW variations have implications in the waste management system. A larger demand for the FLW collection service, together with the unusual challenge of managing high amounts of municipal waste with a potential sanitary risk, have highlighted the need to address exceptional measures, even though modifications of environmental permits, such as the use of incineration as a priority to reduce its potential hazardous (BOC, 2020; BOE, 2020b).

The nutritional content of food consumption during the outbreak decreased between 6% and 8% (see Figure 2b). The increase in consumption of alcoholic beverages, sweetmeats, snacks and processed foods constitutes the largest contributor to poor nutritional waste. The nutritional content per FU in households was higher during the state of emergency. Nevertheless, if extra-domestic consumption is considered, the nutritional content is higher in the pre-COVID-19 scenario. These results are of special interest when the management strategy, according to the FLW hierarchy, consists in re-using human consumption. The impoverishment of the nutritional content of FLW during COVID-19 makes its use as secondary feed less suitable. For instance, the fact that fast food restaurant chains used their surplus stock as menus for children can be interpreted as a paradigm of this tendency. Although it represents a correct procedure in terms of FLW management, it is also a questionable and doubtful strategy, with repercussions on nutrition, especially for children belonging to vulnerable families.

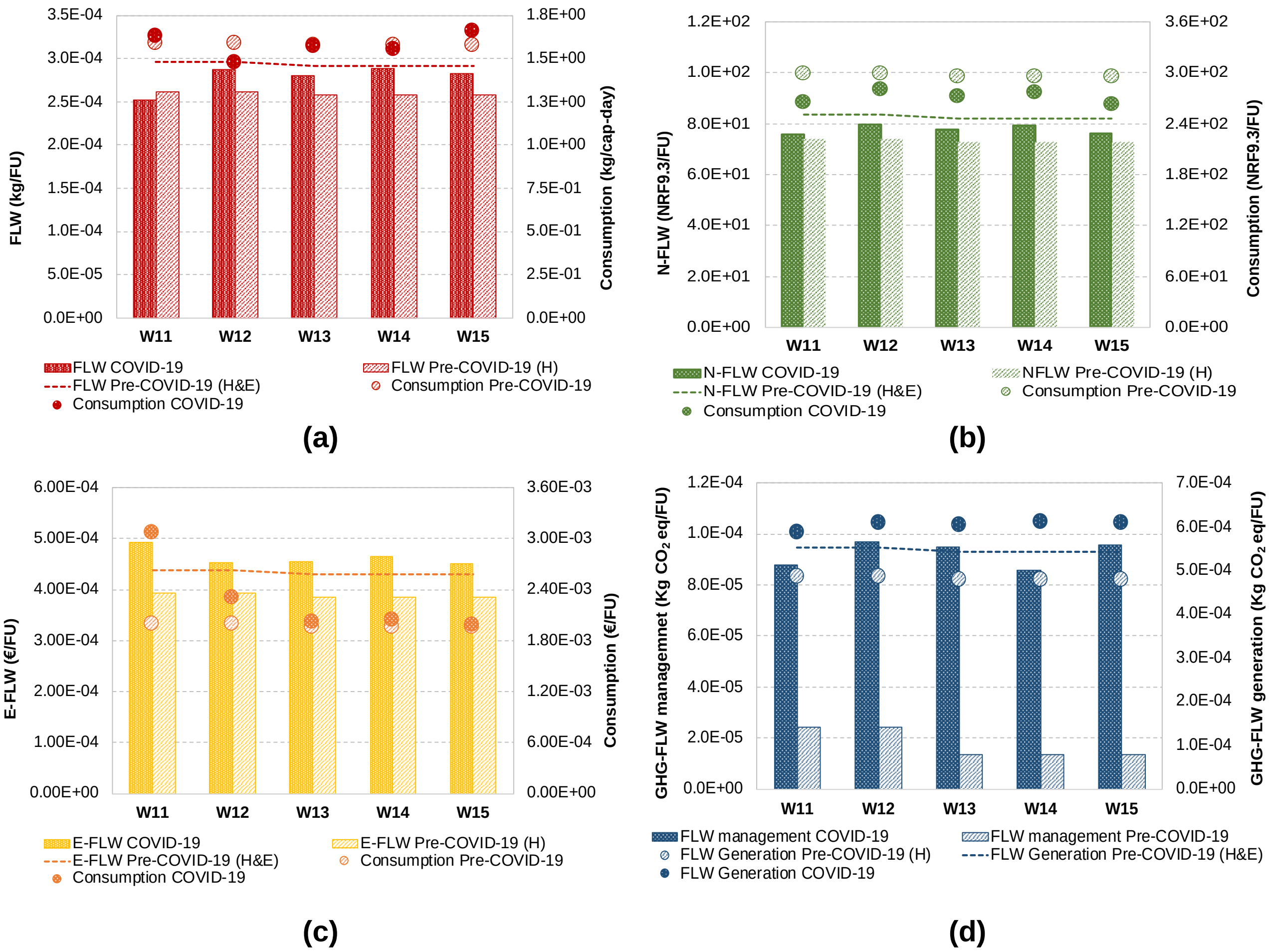
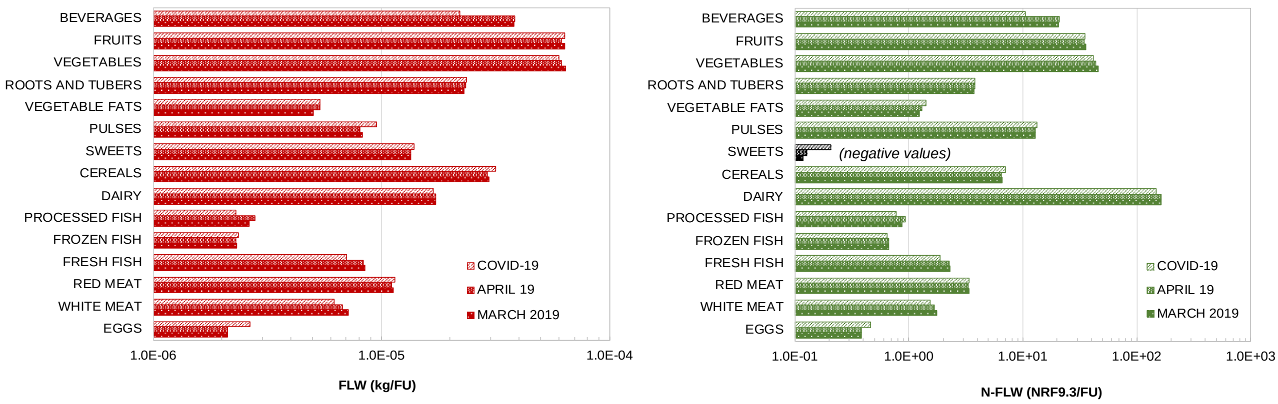


Figure 2. Overall FLW during pre-COVID-19 (P1) and COVID-19 scenarios (P2). (a) Total amount of FLW and food consumption; (b) FLW Nutritional assessment; (c) FLW Economic assessment; (d) FLW Greenhouse gas (GHG) assessment.

As shown in Figure 2c, when comparing the FLW costs, the previously described pattern is reversed. The FLW cost per FU is higher in the COVID-19 scenario, increasing by 17% when only household consumption is considered, and 11% if extra-domestic consumption is included. The increase in waste generation and food prices during the period assessed contributes to this higher FLW cost. Our analysis estimates that each citizen disposed of ca. 4.7€ of food per week (i.e., 7.5€ along the full supply chain) during the emergency period, as compared to 3.8€ (i.e., 6.4€ along the whole supply chain) before lockdown.
GHG emissions follow a similar trend when compared with FLW generation. CO_2eq emissions per FU increased during the outbreak by 21% compared to the generation in households in the pre-COVID-19 scenario. When extra-domestic consumption is included, the emissions are 10% higher (see Figure 2d). Overall, considering the impact of production and management, FLW has a clear impact on global warming. In fact, even though the Spanish electricity mix during the outbreak was based primarily on low-carbon energy sources, FLW was responsible for 12 kg CO_2eq per capita and week, 43% higher than in the business-as-usual scenario (i.e., 8.4 Kg CO_2 eq/cap-week).

3.2. Assessment of food categories

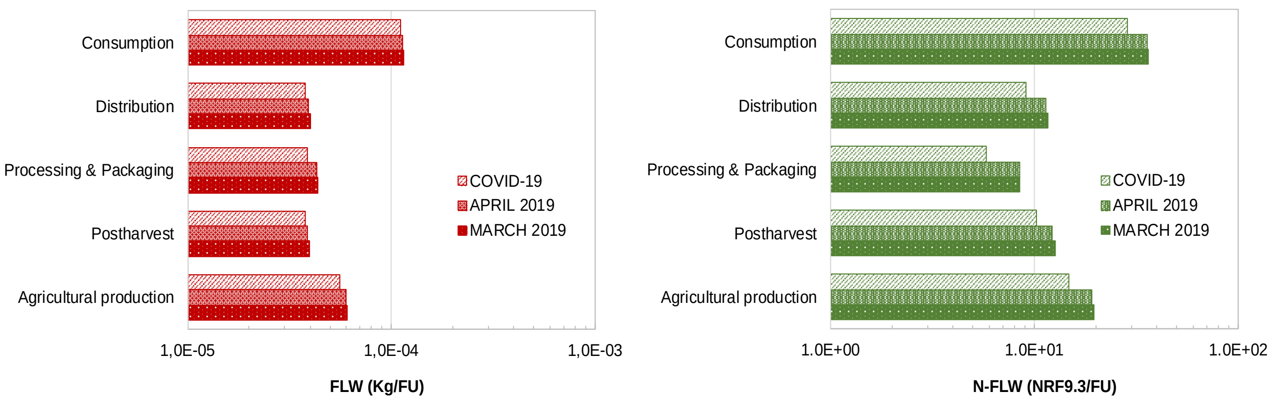
The assessment of food categories shows that fruits and vegetables are the categories most affected by the inefficiencies in the food supply chain. Their relative contribution to FLW was estimated to be 22.9% and 21.5% in the COVID-19 scenario, respectively, followed by cereals (11.4%). As presented in Figure 3a, no remarkable difference is observed in terms of food mass lost and wasted per FU among the scenarios studied, since the majority of the losses are shared by these categories. Only FLW in the beverage category changes moderately, from 13.1% in the pre-COVID 19 scenario to 7.9% in the COVID-19 scenario, probably motivated by the closure of bars and restaurants.
Concerning nutritional content, the slight decrease in nutritional quality during the outbreak is linked to animal fats present in processed foods, snacks, pastries and sweets, whose consumption increased especially during the first weeks of lockdown.



(a) (b)

Figure 3. Assessment of food categories during pre-COVID-19 (P1) and COVID-19 (P2a) scenarios. (a) Total amount of FLW and food consumption; (b) FLW Nutritional assessment; (c) FLW Economic assessment; (d) FLW Greenhouse gas (GHG) assessment.

From an economic perspective, Figure 3c shows that red meat, cereal, fruits and vegetables emerge as the largest contributors to economic waste, representing 60.2% in the COVID-19 scenario (€ 4.5/cap−week) of total FLW, as compared to 47.3% in the pre-COVID-19 scenario (€ 2.85/cap−week). In contrast, lamb, fresh fish and especially beverages, contributed to reducing the FLW cost during the COVID-19 scenario (12.5% vs. 17.6% in pre-COVID-19 scenario) due to lower demand and to a moderate decrease in price due to excess stock.
Finally, red meat appeared as the main contributor in terms of GHG emissions, contributing to over 30% of the total impact, despite only representing 4% in weight of total FLW. Cereals and vegetables were also two categories that had important contributions, with slight absolute increases with respect to the business-as-usual scenario. In fact, practically all food categories presented higher emissions during the outbreak.



(a) **(b)**

Figure 4. Holistic FLW assessment during pre-COVID-19 (P1) and COVID-19 (P2) scenarios. (a) Total amount of FLW and food consumption; (b) FLW Nutritional assessment; (c) FLW Economic assessment; (d) FLW Greenhouse gas (GHG) assessment.

3.3. Holistic assessment

Under a holistic approach, it is observed that the closer to the consumption FLW is produced, the costlier it becomes (see Figure 4a) from an economic (Betz et al., 2015) and environmental (Chen et al., 2020) perspective. Subsequently, consumption in the household results in the main economic, nutritional and climate hotspot in terms of FLW, accounting for approximately 60%, 41% and 40% of total waste, respectively. This is especially important from an economic perspective, since a 1-2% decrease of FLW implied a rise in economic losses up to 12% (see Figure 4c), due to a 6.9% increase in food prices. Accordingly, it would be highly recommendable, in addition to reducing FLW generation in the consumption stage, to protect the food market, avoiding cost escalations along the supply chain that especially damage small producers and make the product inaccessible for vulnerable families. Hence, self-regulatory mechanisms, fair prices and tools for their control should be put in place rather than government interventions in food markets.

Usually, FLW management strategies have been designed according to the FLW hierarchy. Based on our assessment, the FLW hierarchy must focus on delivering the best environmental, nutritional and economic options, but also considering the best option of each stage along the FSC (Vázquez-Rowe et al. 2019). The COVID-19 outbreak has only reaffirmed this statement.

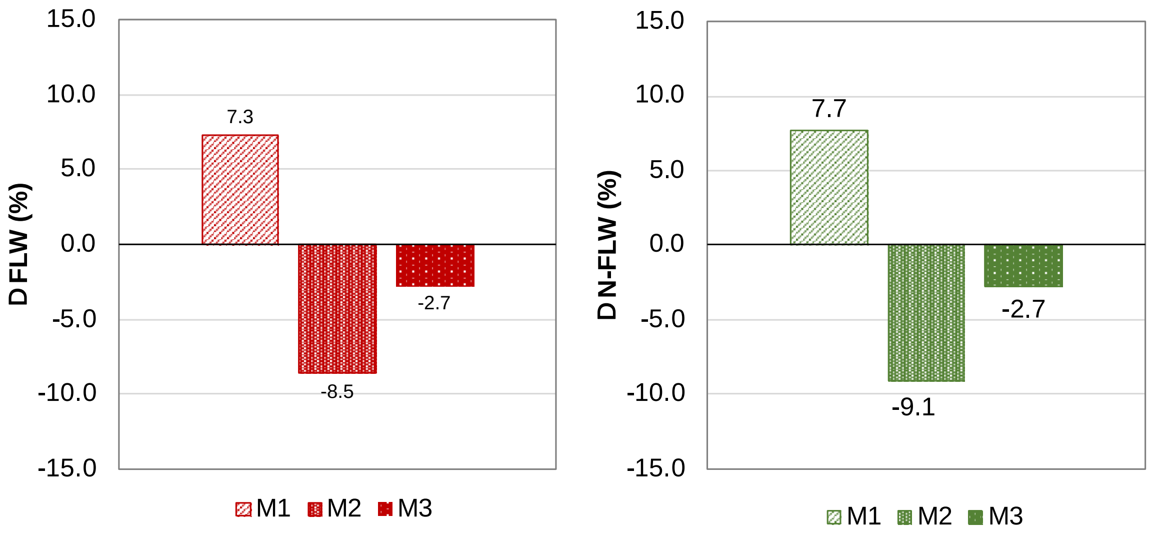


Figure 5. Sensitivity analysis for the considered scenarios during the COVID-19 outbreak: (M1) increase of 20% in the generation of FLW in households; (M2) reduction of 20% in the generation of FLW in households; (M3) losses in distribution and sales decrease by 20%.

3.4. Sensitivity analysis

Considering that the COVID-19 outbreak could further modify FLW generation, a sensitivity analysis was executed to assess this influence on the results in order to determine their robustness (Guo and Murphy, 2012). FLW generation variables both in households and distribution were parameterized in the model and new values for the calculation of new scenarios were proposed.

The generation of FLW was estimated from a qualitative point of view, based on the existing knowledge available. For instance, at a household consumption level, hoarding may be leading to an increase in the amount of waste generated , as consumers are abandoning their regular routines and probably not managing the additional food efficiently. At the same time, the outbreak could actually help achieve a reduction in FLW: the fear of infections reduces purchase frequency, forcing buyers to be more strategic on how to use up food at home. To assess these assumptions, two alternate scenarios considering an increase (scenario M1) and a reduction (scenario M2) of 20% in the generation of FLW in households were introduced (see Table 3).

In terms of wholesaling and retailing, an increase in food sales was observed and the shelves were empty during the first weeks of the state of emergency. Therefore, it is plausible to assume that FLW has diminished. Over time, as the lockdown progressed, and shoppers continued to bulk-buy, food sector stakeholders jumped into action in order to implement emergency policies to meet these skyrocketing demands. Scenario M3 builds on this assumption that losses in distribution and sales decreased by 20% in the first weeks of lockdown.

Table 3. Parameters and alternative scenarios evaluated in the sensitivity analysis.

Code	Time frame	Parameter	Baseline Value	Modified Value
M1	COVID-19	FLW generation in households	(a)	+20%
M2	COVID-19	FLW generation in households	(a)	-20%
M3	COVID-19	FLW generation in distribution	(a)	-20%

a. FLW factors based on Gustavsson et al. (2011)

Equation (4) was used to calculate the changes in overall FLW generation of the systems due to each parameter:

$$\Delta IA = 100\,\frac{IA_M - IA_B}{IA_B} \quad (4)$$

where ΔIA is the impact variation, IA_M the impact with the modified parameter and IA_B the impact of the baseline scenario. Therefore, a positive value implies that the option analyzed is worse than the baseline scenario, while a negative value means that the modified option has less environmental impact than the baseline scenario (Abejón et al., 2020).

The results, shown in Figure 5, revealed that the second alternative evaluated has a remarkable influence on FLW from all four perspectives assessed. In fact, scenario M2, characterized by a greater efficiency of food consumption in households, would imply substantial reductions in terms of nutrition (-9.1%), GHG emissions (-8.9%), and cost (-14.7%)

4. LESSONS LEARNED AND CHALLENGES

The COVID-19 pandemic has stressed the relevance of performing a deep review regarding the robustness of current food production and consumption systems. In fact, the health crisis derived from the outbreak has directly influenced lifestyle habits throughout the planet, including food consumption and its related FLW generation. The preliminary assessment performed in this study on FLW management during the early stages of the outbreak allows learning some lessons and drawing conclusions about future challenges. Interestingly, the hierarchical approach of this study facilitates the analysis along the whole food supply chain.

In fact, as defended by Hobbs (2020), the pandemic has offset a series of demand- and supply-side shocks that have disrupted food supply chains enormously. On the one hand, from a demand-side perspective, the coronavirus crisis has really affected the way in which citizens purchase and consume food. For example, the fear of contagion has translated, after the panic purchases at the beginning of the outbreak, to food purchase behaviors that are more spaced out over time. In some cases, this has led many families to generate more food waste due to lack of foresight, whereas for others it has supposed a greater use of food due to the fear of recurrent purchases. For many citizens the lockdown measures have also prompted an accelerated learning process of food purchase management and, although probably in an indirect way, a novel awareness of responsible consumption (Jribi et al., 2020), that should lead to reduced FLW generation.

These strong disruptions in citizen purchase behavior have triggered what is commonly referred to as the “ripple effect”, generating an upstream propagation of the disruptions to all other actors throughout the supply chains (Dolgui et al., 2020). Hence, supply chain stakeholders have had to adapt their routines and discovered their strengths, and weaknesses. For instance, those activities already familiar with digital tools or with high supplier and client diversification, were readier to resist economic crises like the one caused by the COVID-19 outbreak and they were able to effectively respond to the increase of the online food demand up to 80% in this period. Consequently, a huge effort is required by governments to support essential activities, such as the primary sector, in terms of digitalization, economy planification and quality product labeling. In this latter aspect, ecolabelling is growing in recent decades but further efforts related to nutrient, energy and water impacts under a nexus approach must be performed (Batlle-Bayer et al., 2020c, Leivas et al., 2020). Thus, producers will increase the quality and the specificities of their products and consumers will receive relevant information for filling the food basket.

The COVID-19 crisis has revealed an unprecedented flow of solidarity. Considering that the number of vulnerable social groups and families has rocketed in the matter of weeks, it is imperative to apply the FLW management hierarchy throughout food supply chains, favoring secondary feeding strategies by means of effective donations and, fostering, therefore, the circularity of the agri-food sector. In this sense, the control of the nutritional quality of surpluses and their food security must be guaranteed by introducing rigorous health and nutritional controls.

On the other hand, from a supply-side approach, it is important to note that the aforementioned “ripple effect” triggers the so called “bullwhip” or “whiplash effect”, through which smaller distortions in consumer demand tend to amplify upstream through the supply chain (Wang and Disney, 2016). The short window of time between the appearance of the new virus and application of draconian social distancing policies in most of the world constituted the perfect storm that led to inaccurate demand forecasting and higher inefficiencies in the delivery of food to citizens (Patrinley et al., 2020), and, consequently, to the increase of FLW. While many enterprises have adapted and developed improved methods to predict future short- and midterm demand, these techniques tend to apply exponential smoothing on available historical data. However, these may be insufficient when dealing with additional extreme disruptions generated by events with long recurrence intervals (e.g., extreme seismic events, pandemics or volcano eruptions). But, this disruption or perturbation to the food´s system is highly important for understanding its resilience under these types of events.

Considering the backward propagation of effects through the supply chain, primary sector workers, whose role is placed in the early phases of food supply chains, have been forced to discard huge amounts of food due to the complex logistics of the chains. In fact, the outbreak highlights the importance of fostering a more decentralized food supply chain by including small producers. This would provide a more resilient network and increased food security to local communities across socioeconomic levels (Ricciardi et al., 2018), especially for those in a vulnerable position. Harnessing their potential is a challenge that must be maintained and supported by governments, distributors and consumers when the crisis ends, as it will help reinforce resilience in the food sector. The survival of our lifestyle is impossible without the primary sector, especially in urban environments, strongly dependent on food production from the rural world. The pandemic has highlighted the weakness of current citizen consumption habits, especially among vulnerable communities (Raja, 2020).

Another aspect to be considered from the supply-side is the difficulty to access fresh food in small street markets (i.e., "neighborhood markets"), since the lockdown forced many to shut. This has derived in many sectors of the population having limited access to fresh products, namely fish and white meat, which has forced many small-scale producers and retailers to dispose of their stock, with the subsequent effects in terms of FLW. Hence, an important challenge emerges in order to promote strategies and policies favoring shorter food supply chains that would enhance resilience of regional and local food systems, including the purchase of food from local suppliers. In fact, 'zero km food strategies', which in some cases lower the environmental impact, can introduce social and economic benefits for local communities, generating a less complex web between the farmer and the final consumer. Moreover, the COVID-19 pandemic has underlined the importance of a more flexible and forthcoming food distribution system, which allows the adaptability under unforeseen conditions, prioritizing local products in order to avoid FLW associated with the difficulty of small producers accessing the market. Moreover, it would have been preferable to have allowed local markets to remain open in order to sustain supply chains, while putting in place best available social distancing and hygiene practices to minimize the risk.

A final aspect linked to supply-side shocks is linked to the closure of most extra-domestic establishments: school canteens and kitchens, restaurants, bars or hotels are just some examples. COVID-19, by leading these important sources of food delivery to a total shutdown, has highlighted the need to introduce tools that facilitate the interconnection of the different supply chains (Caldeira et al. 2019). For instance, in the case of schools, local authorities have the opportunity to improve collaboration between domestic and extra-domestic supply chains by offering a direct (or semi) food service to the students through local, fresh and seasonal production and consumption. This will strengthen the local economy (i.e. primary sector, small food stores and processing industries), reducing the environmental impact and offering more healthy sustainable diets to students. Moreover, we should not forget that the canteen service in schools is usually the main meal for children from vulnerable families. Improving the nutritional and environmental profile of school menus, therefore, would constitute an excellent pathway to reduce inequalities and mitigate the prevalence of food-related non-communicable diseases in children and adolescents from these groups. In order to avoid public authorities sourcing unhealthy menus for children during long time periods, it is urgent to define minimum mandatory criteria for sustainable food procurement.

At European level, farm-to-fork (F2F) policies should be the framework for a fair transition for all food value chain stakeholders, especially after the irruption of the

COVID-19 pandemic and the economic downturn. Although this crisis has highlighted the strength and resilience of the Spanish food system, there is an opportunity to re-orient and transform the food system to be more resilient and sustainable. This should be an opportunity to move towards a food democracy model that provides citizens with opportunities to actively contribute in the way that sustainable food systems are built to allow complementary perspectives on how food should be produced and consumed (Petetin, 2020).

Therefore, policies should be aligned with global international strategies, including efforts to align with SDGs 2 and 12, but also with other international strategies, such as GHG emissions mitigation in the frame of the Paris Agreement or the minimization of ozone-depleting cooling agents (e.g., HCFCs) used in the food industry to comply with the Kigali Agreement. Lessons learnt from this accelerated sanitary and economic crisis are providing speedy data that allow steering policy towards these objectives. However, despite the priority lines described above, the consideration of social, economic and environmental trade-offs in other indicators must be taken into account (Brears, 2018).

5. CONCLUSIONS

Reducing FLW is critical to achieve certain Sustainable Development Goals (SDGs), especially SDG 2 (Zero Hunger) and SDG 12 (Ensuring sustainable consumption and production patterns). The COVID-19 outbreak has caused significant shocks in most food supply chains. From an overall perspective, the crisis has shown that during the lockdown the amount of FLW generated in households has increased by 12%. Nevertheless, this increase does not offset the FLW generated before the outbreak if extra-domestic consumption is taken into account (only 1-2%). Likewise, the CO_2 emissions and the associated economic cost of FLW generation increased by up to 10% and 11%, respectively. In contrast, the nutritional content of FLW was reduced by 8% as a consequence of a relaxation in healthy eating habits.

The study demonstrates that the ‘strong short-term fluctuations and changes’ of eating habits have significant direct and indirect consequences on FLW management. Accordingly, it has confirmed the need to review and enhance FLW control strategies after the coronavirus crisis. Measures aimed at reducing FLW are very important to make better use of food residues, the use of food surpluses or the prevention of FLW. All of them have been affected during the COVID-19 outbreak, and all of them require an in-depth review that allows us to be prepared for future unforeseen scenarios. Almost all food categories, stakeholders in the food chain, industry and governments, and especially consumers have a very important role in this matter. Thus, further research should address additional scenarios analyzing the influence on the economic, nutritional and environmental cost along the food supply chain of the different food waste management options available, as well as possible food waste prevention measures (intended as diversion from landfill) and alternative valorization routes (such as biorefineries) in the context of unexpected food demand patterns. From an European perspective, we hypothesize that the results obtained are highly extrapolated to other regional contexts, although it would be interesting to analyze future scenarios considering the actions and the goals proposed in the framework of the EU F2F strategy. Studies in other geographical areas, in which food security and food supply chains are not as robust as in a European context should also be analyzed, as the behavior of FLW trends could be subject to a completely different set of logistic, economic and behavioral variables.

It may be politically incorrect to say so, but the COVID-19 pandemic is an opportunity to reduce over the longer term the prevalence of lifestyles based on large volumes of energy and material. However, facts speak for themselves. To the extent of our possibilities, we should all work to ensure that the actions in the aftermath of the coronavirus outbreak contribute to a sustainable consumption transition. This may be our last chance. What if it never comes again?

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References

Abejón, R., Laso, J., Margallo, M., Aldaco, R., Blanca-Alcubilla, G., Bala, A., Fullana-i-Palmer, P., 2020. Environmental impact assessment of the implementation of a Deposit-Refund System for packaging waste in Spain: A solution or an additional problem?. Science of the Total Environment 721,137744. doi: 10.1016/j.scitotenv.2020.137744

Abín, R., Laca, A., Laca, A., Díaz, M., 2018. Environmental assessment of intensive egg production: A Spanish case study. Journal of Cleaner Production 179, 160-168. doi: 10.1016/j.jclepro.2018.01.067

Batlle-Bayer L., Bala A., Lemaire E., Albertí J., García-Herrero I., Aldaco R., Fullana-i-Palmer P., 2019a. An energy- and nutrient-corrected functional unit to compare LCAs of diets. Science of the Total Environment, 671, 175-179.

Batlle-Bayer, L., Bala, A., Roca, M., Lemaire, E., Aldaco, R., Fullana-i-Palmer, P 2020a. Nutritional and environmental co-benefits of shifting to “Planetary Health” Spanish tapas. Journal of Cleaner Production, *in press*.

Batlle-Bayer L, Bala A, Albertí J, Xifré R, Aldaco R, Fullana-i-Palmer P, 2020b. Food affordability and nutritional values within the functional unit of a food LCA. An application on regional diets in Spain. Resources, Conservation & Recycling, 160, 104856.

Batlle-Bayer L., Aldaco R., Bala A., Fullana-i-Palmer P., 2020c. Toward sustainable dietary patterns under a water–energy–food nexus life cycle thinking approach. Current Opinion in Environmental Science & Health, 13, 61-67.

Batlle-Bayer, L., Bala, A., García-Herrero, I., Lemaire E., Song G., Aldaco R., Fullana-i-Palmer P., 2019. The Spanish Dietary Guidelines: A potential tool to reduce greenhouse gas emissions of current dietary patterns. Journal of Cleaner Production 213, 588-598. doi: 10.1016/j.jclepro.2018.12.215

Betz, A., Buchli, J., Göbel, C., Müller, C., 2015. Food waste in the Swiss food service industry–Magnitude and potential for reduction. Waste Management 35, 218-226. doi: 10.1016/j.wasman.2014.09.015

Beretta, C., Stoessel, F., Baier, U., Hellweg, S., 2013. Quantifying food losses and the potential for reduction in Switzerland. Waste Management 33 (3), 764-773. doi: 10.1016/j.wasman.2012.11.007

BOC, 2020. Resolución sobre Modificación Excepcional de la Autorización Ambiental Integrada 02/2005, en relación con la autorización temporal para incinerar residuos de servicios médicos o veterinarios o de investigación asociada, por motivo de la situación de emergencia de salud pública provocada por el COVID-19. BOC num. 65. In Spanish.

BOE, 2020a. Real Decreto 463/2020, de 14 de marzo, por el que se declara el estado de alarma para la gestión de la situación de crisis sanitaria ocasionada por el COVID-19. BOE num. 67. In Spanish.

BOE, 2020b. Orden SND/271/2020, de 19 de marzo, por la que se establecen instrucciones sobre gestión de residuos en la situación de crisis sanitaria ocasionada por el COVID-19. BOE num. 79. In Spanish.

Bradshaw, C., 2018. Waste law and the value of food. Journal of Environmental Law 30(2), 311–331. doi: 10.1093/jel/eqy009

Brears, R.C., 2018. Policy Tools to Reduce Water-Energy-Food Nexus Pressures. In The Green Economy and the Water-Energy-Food Nexus, 51-80, Palgrave Macmillan, London.

Caldeira et al., 2019. Assessment of food waste prevention actions, JRC Technical Reports. EUR 29901 EN

Chen, C., Chaudhary, A., Mathys, A., 2020. Nutritional and environmental losses embedded in global food waste, Resources, Conservation and Recycling 160, 104912. doi: 10.1016/j.resconrec.2020.104912

Cimpan, C., Wenzel, H., 2013. Energy implications of mechanical and mechanical–biological treatment compared to direct waste-to-energy, Waste Management 33, 1648–1658. doi: 10.1016/j.wasman.2013.03.026

Cornwall, W., 2020. Crushing coronavirus means 'breaking the habits of a lifetime. Behavior scientists have some tips, Science. doi: 10.1126/science.abc2922

Corrado, S., Sala, S., 2018. Food waste accounting along global and European food supply chains: State of the art and outlook. Waste Management 79, 120 – 131. doi: 10.1016/j.wasman.2018.07.032

De Menna, F., Davis, J., Östergren, K., Unger, N., Loubiere, M., Vittuari, M., 2020. A combined framework for the life cycle assessment and costing of food waste prevention and valorization: an application to school canteens. Agricultural and Food Economics 8 (2). doi: 10.1186/s40100-019-0148-2

De Menna, F., Dietershagen, J., Loubiere, M., Vittuari, M., 2018. Life cycle costing of food waste: a review of methodological approaches. Waste Management 73, 1–13. doi: 10.1016/j.wasman.2017.12.032

Dolgui, A., Ivanov, D., Rozhkov, M., 2020. Does the ripple effect influence the bullwhip effect? An integrated analysis of structural and operational dynamics in the supply chain. International Journal of Production Research 58(5), 1285-1301. doi: 10.1080/00207543.2019.1627438

Drewnowski, A., Maillot, M., Darmon. N., 2009. Testing nutrient profile models in relation to energy density and energy cost, European Journal of Clinical Nutrition 63, 674-683. doi: 10.1038/ejcn.2008.16

EC, 2019. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. COM(2019) 640 final.

EC, 2020. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system. COM(2020) 381 final.

Ecoinvent, 2016. Ecoinvent v3 database, Ecoinvent Centre http://www.ecoinvent.org/. Last access May 21, 2020.

EFSA, 2017. Dietary Reference Values for Nutrients Summary Report, 10.2903/sp.efsa.2017.e15121

FAO, 2011. Global Food Losses and Food Waste – Extent, Causes and Prevention, Rome.

FAO, 2014. Definitional Framework of Food Loss. Working paper, Rome.

FAO, 2020. Questions and Answers. COVID-19 pandemic - impact on food and agriculture. http://www.fao.org/2019-ncov/q-and-a/en/. Last access April 20, 2020.

Farran, A., Zamora, R., Cervera, P., 2004. Tablas de composición de alimentos del CESNID. Retrieved from: http://www.sennutricion.org/es/2013/05/13/tablas-de-composicin-de-alimentos-del-cesnid. Last access May 5, 2020. In Spanish.

FESBAL, 2020. Spanish Federation of Food Banks. https://www.fesbal.org.es/. Last access May 5, 2020. In Spanish.

Frankowska, A., Jeswani, H.J., Azapagic, A., 2019. Environmental impacts of vegetable consumption in the UK. Science of the Total Environment 682, 80-105. doi: 10.1016/j.scitotenv.2019.04.424

Fulgoni, V.L., Keast, D.R., Drewnowski, A., 2009. Development and validation of the nutrient-rich foods index: A tool to measure nutritional quality of foods. The Journal of Nutrition 139(8), 1549-1554. doi: 10.3945/jn.108.101360

FUSIONS, 2016. Reducing food waste through social innovation. Estimates of European food waste levels, European Commission (FP7), Coordination and Support Action –CSA.

García-Herrero, I., Hoehn, D., Margallo, M., Laso, J., Bala, A., Batlle-Bayer, L., Fullana, P., Vázquez-Rowe, I., Gonzalez, M.J., Durá, M.J., Sarabia, C., Abajas, R., Amo-Setien, F.J., Quiñones, A., Irabien, A., Aldaco, R., 2018. On the estimation of potential food waste reduction to support sustainable production and consumption policies, Food Policy 80, 24-38. doi: 10.1016/j.foodpol.2018.08.007

García-Herrero, I. Margallo, M., Laso, J., Batlle-Bayer, L., Bala, A., Fullana-i-Palmer, P. Vázquez-Rowe, I., Gonzalez, M. J., Amo-Setien, F., Durá, M.J., Sarabia, C., Abajas, R., Quiñones, A., Irabien, A., Aldaco, R., 2019. Nutritional data management of food losses and waste under a life cycle approach: Case study of the Spanish agri-food system. Journal of Food Composition and Analysis 82, 103223. doi: 10.1016/j.jfca.2019.05.006

Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R., Meybeck, A., 2011. Global Food Losses and Food Waste: Extent, Causes and Prevention, Swedish Institute for Food and Biotechnology (SIK), Gothenburg (Sweden), and FAO. Rome, Italy.

Guo, M., Murphy, R.J., 2012. LCA data quality: sensitivity and uncertainty analysis. Science of the Total Environment, 435-436, 230-243. doi: 10.1016/j.scitotenv.2012.07.006

Hobbs, J.E., 2020. Food supply chains during the COVID-19 pandemic. Canadian Journal of Agricultural Economics/ Revue canadienne d'agroeconomie, 1-6. doi: 10.1111/cjag.12237

Hoehn, D., Margallo, M., Laso, J., García-Herrero, I., Bala, A., Fullana-i-Palmer, P., Irabien, A., Aldaco, R., 2019. Energy embedded in food loss management and in the production of uneaten food: Seeking a sustainable pathway. Energies 12(4), 767. doi: 10.3390/en12040767

IMF, 2020. International Monetary Fund. Policy responses to COVID-19. https://www.imf.org/en/Topics/imf-and-covid19/Policy-Responses-to-COVID-19. Last access June 18, 2020.

INE, 2020. Información estadística para el análisis del impacto de la crisis COVID-19. Instituto Nacional de Estadística. https://www.ine.es/covid/covid_economia.htm. Last access May 9, 2020.

ISO, 2006a. ISO 14040: Environmental management-life cycle assessment - principles and framework. International Standards Organization, Geneva.

ISO, 2006b. ISO 14044: Environmental management-life cycle assessment – requirements and management. International Standards Organization, Geneva.

Jribi, S., Ben Ismail, H., Doggui, D., Debbabi, H., 2020. COVID-19 virus outbreak lockdown: What impacts on household food wastage?. Environment, Development and Sustainability 22, 3939-3955. doi: 10.1007/s10668-020-00740-yJunta de Andalucía, 2011. https://www.agenciaandaluzadelaenergia.es/sites/default/files/documentos/estudio_basico_del_biogas_0.pdf. Last access May 21, 2020.

Kim, M.H., Kim, J.W., 2010. Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global warming and resource recovery. Science of the Total Environment 408(19), 3998-4006. doi: 10.1016/j.scitotenv.2010.04.049

Khoshnevisan, B., Rafiee, S., Omid, M., Mousazadeh, H., 2013. Comparison of GHG emissions of efficient and inefficient potato producers based on data envelopment analysis, Journal of Agricultural Engineering and Biotechnology 1 (3), 81-88. doi: 10.18005/JAEB0103005

Laso, J., García-Herrero, I., Margallo, M., Vázquez-Rowe, I., Fullana, P., Bala, A., Gazulla, C., Irabien, A., Aldaco, R., 2019. Finding an economic and environmental balance in value chains based on circular economy thinking: An eco-efficiency methodology applied to the fish canning industry. Resources Conservation and Recycling 133, 428-437. doi: 10.1016/j.resconrec.2018.02.004

Laso, J., Hoehn, D. Margallo, M., García-Herrero, I. Batlle-Bayer, L. Bala, A., Fullana-i-Palmer, P. Vázquez-Rowe, I., Irabien, A., 2018a. Assessing energy and environmental efficiency of the Spanish agri-food system using the LCA/DEA methodology. Energies 11 (12), 3395. doi: 10.3390/en11123395

Laso, J., Margallo, M., García-Herrero, I., Fullana, P., Bala, A., Gazulla, C., Polettini, A., Kahhat, R., Vázquez-Rowe, I., Irabien, A., Aldaco, R., 2018b. Combined application of Life Cycle Assessment and linear programming to evaluate food waste-to-food strategies: Seeking for answers in the nexus approach. Journal of Waste Management 80, 186-197. doi: 10.1016/j.wasman.2018.09.009

Leiva, F.J., Sáenz, J.C., Martinez, E., Jimenez, E., 2015. Environmental impact of Agaricus bisporus cultivation process. European Journal of Agronomy 71, 141-148. doi: 10.1016/j.eja.2015.09.013

Leivas, R., Laso, J., Abejón, R., Margallo, M., Aldaco, R., 2020. Environmental assessment of food and beverage under a NEXUS Water-Energy-Climate approach: Application to the spirit drinks. Science of The Total Environment 720, 137576. doi: 10.1016/j.scitotenv.2020.137576

Lemaire, A., Limbourg, S., 2019. How can food loss and waste management achieve sustainable development goals?, Journal of Cleaner Production 234, 1221 – 1234. doi: 0.1016/j.jclepro.2019.06.226

Makov, T., Shepon, A., Krones, J., Gupta, C., Chertow, M., 2020. Social and environmental analysis of food waste abatement via the peer-to-peer sharing economy. Nature Communications 11(1), 1156. doi: 10.1038/s41467-020-14899-5

MAPA, 2019a. Spanish Ministry of Agriculture, Fisheries and Food (MAPA), press releases, March, Madrid, Spain. Retrieved from: https://www.mapa.gob.es/es/alimentacion/temas/consumo-y-comercializacion-y-distribucion-alimentaria/informemesamesalimentacionmarzo2019_tcm30-511984.pdf. In Spanish.

MAPA, 2019b. Spanish Ministry of Agriculture, Fisheries and Food (MAPA), press releases, April, Madrid, Spain. Retrieved from: https://www.mapa.gob.es/es/alimentacion/temas/consumo-y-comercializacion-y-distribucion-alimentaria/informemesamesalimentacionabril2019_tcm30-513408.pdf. In Spanish.

MAPA, 2020a. Spanish Ministry of Agriculture, Fisheries and Food (MAPA), press releases, March/April, Madrid, Spain. Retrieved from: https://www.mapa.gob.es/es/prensa/ultimas-noticias/los-hogares-espa%C3%B1oles-estabilizan-sus-compras-de-alimentos--/tcm:30-537374. In Spanish.

MAPA, 2020b. Ministry of Agriculture, Fishery, Food and Environment. Agricultural statistics-National average prices. Retrieved from: https://www.mapa.gob.es/app/precios-medios-nacionales/pmn_tabla.asp. Last access May 6, 2020. In Spanish.

Margallo, M., Aldaco, R., Irabien, A., Carrillo, V., Fischer, M., Bala, A., Fullana, P., 2014. Life cycle assessment modelling of waste-to-energy incineration in Spain and Portugal. Waste Management and Research 32, 492–499. doi: 10.1177/0734242X14536459

McCarthy, B., Kapetanaki, A.B., Wang, P., 2020. Completing the food waste management loop: Is there market potential for value-added surplus products (VASP)?. Journal of Cleaner Production 256, 120435. doi: 10.1016/j.jclepro.2020.120435

MINECO, 2020. Ministry of Economy and Competitiveness. Prices at source and destination. Retrieved from: http://www.comercio.gob.es/es-ES/comercio-interior/Precios-Comerciales/Informacion-de-precios-(bases-de-datos)/Paginas/Precios-Origen-Destino-.aspx Last access May 6, 2020. In Spanish.

Morone, P., Imbert, E., 2020. Food waste and social acceptance of a circular bioeconomy: the role of stakeholders. Current Opinion in Green and Sustainable Chemistry. Article in press. doi: 10.1016/j.cogsc.2020.02.006

Muscogiuri, G., Barrea, L., Savastano, S., Colao, A., 2020. Nutritional recommendations for CoVID-19 quarantine. European Journal of Clinical Nutrition 74, 850–851. doi: 10.1038/s41430-020-0635-2

Patrinley, J.R., Berkowitz, S.T., Zakria, D., Totten, D.J., Kurtulus, M., Drolet, B.C., 2020. Lessons from Operations Management to Combat the COVID-19 Pandemic. Journal of Medical Systems 44(7), 129. doi: 10.1007/s10916-020-01595-6

PEMAR, 2015. Spanish Ministry of Agriculture, Fisheries and Food (MAPA), Secretaría de Estado de Medio Ambiente, Dirección General de Calidad y Evaluación Ambiental y Medio Natural, Madrid, Spain. In Spanish.

Petetin, L. 2020. The COVID-19 Crisis: An Opportunity to Integrate Food Democracy into Post-Pandemic Food Systems. European Journal of Risk Regulation, 11, (2) (Taming COVID-19 by Regulation), 326-336. DOI: https://doi.org/10.1017/err.2020.40

Raja, S., 2020. Planning and pandemics COVID 19 illuminates why urban planners should have listened to food advocates all along. Agriculture and Human Values 11, 1–2. doi: 10.1007/s10460-020-10090-0

Redlingshöfer, B., Barles, S., Weisz, H., 2020. Are waste hierarchies effective in reducing environmental impacts from food waste? A systematic review for OECD countries. Resources Conservation and Recycling 156, 104723. doi: 10.1016/j.resconrec.2020.104723

REE, 2020. Red Eléctrica de España.Estructura de generación por tecnologías. https://www.ree.es/es/datos/generacion Accessed 20 abril 2020. In Spanish.

ReFED COVID-19 U.S. Food system review. https://www.refed.com/content-hub/refeds-covid-19-u-s-food-system-review/. Accessed 20 April 2020.

Ricciardi, V., Ramankutty, N., Mehrabi, Z., Jarvis, L., Chookolingo, B., 2018. Global Food Security, 64-72. https://doi.org/10.1016/j.gfs.2018.05.002

Righi, S., Oliviero, L., Pedrini, M., Buscaroli, A., Della-Casa, C., 2013. Life Cycle Assessment of management systems for sewage sludge and food waste: Centralized and decentralized approaches. Journal of Cleaner Production 44, 8–17. doi: 10.1016/j.jclepro.2012.12.004

Romero-Gámez, M., Suarez-Rey, E., 2020. Environmental footprint of cultivating strawberry in Spain. The International Journal of Life Cycle Assessment 25, 719-732. doi: 10.1007/s11367-020-01740-w

Saxe, H., 2010. LCA-based comparison of the climate footprint of beer vs. wine & spirits. Fødevareøkonomisk Institut, Københavns Universitet. Report, No. 207.

Spanish Ministry of Health, Consumer Affairs and Social, 2020. https://cnecovid.isciii.es/covid19/#documentaci%C3%B3n-y-datos. Last access June 18, 2020.

Slorach, P.C., Jeswani, H.K., Cuéllar-Franca, R., Azapagic, A., 2020. Assessing the economic and environmental sustainability of household food waste management in the UK: Current situation and future scenarios. Science of the Total Environment 710,135580. doi: 10.1016/j.scitotenv.2019.135580

Sluik, D., Streppel, M.T., Van Lee, L., Geelen, A., Feskens, E.J.M., 2015. Evaluation of a nutrient-rich food index score in the Netherlands. Journal of Nutritional Science 4, e14. doi: 10.1017/jns.2015.4

Sphera, 2019. GaBi 9.2: Software-System and Databases for Life Cycle Engineering. Stuttgart-Echterdingen.

Guobao Song, Xiaobing Gao, Pere Fullana-i-Palmer, Daqi Lv, Zaichun Zhu, Yixuan Wang, Laura Batlle Bayer, 2019. Shift from feeding to sustainably nourishing urban China: A crossing-disciplinary methodology for global environment-food-health nexus. Science of The Total Environment, 647, 716-724.

UN, 2019. Sustainable Development Goal 12 – ensure sustainable consumption and production patterns. United Nations. Retrieved from: https://sustainabledevelopment.un.org/sdg12. Last access April 20, 2020.

Usubiaga-Liaño, A., Behrens, P., Daioglou, V., 2020. Energy use in the global food system. Journal of Industrial Ecology. doi: 10.1111/jiec.12982

Vázquez-Rowe, I., Laso, J., Margallo, M., García-Herrero, I., Hoehn, D., Amo-Setién, F., Bala, A., Abajas, R., Sarabia, C., Durá, M.J., Fullana-i-Palmer, P., Aldaco, R., 2019. Food loss and waste metrics: a proposed nutritional cost footprint linking linear programming and life cycle assessment. The International Journal of Life Cycle Assessment. doi:10.1007/s11367-019-01655-1

Wang, X., Disney, S.M., 2016. The bullwhip effect: Progress, trends and directions, European Journal of Operational Research 250 (3), 691-701. doi: 10.1016/j.ejor.2015.07.022

Wu, F., Zhao, S., Yu, B., Chen, Y.M., Wang, W., Song, Z.G., Yuan, M.L., 2020. A new coronavirus associated with human respiratory disease in China. Nature 579(7798), 265-269. doi: 10.1038/s41586-020-2008-3

Wunderlich, S.M., Martinez, N.M., 2018. Conserving natural resources through food loss reduction: Production and consumption stages of the food supply chain. International Soil and Water Conservation Research 6, 331 – 339. doi: 10.1016/j.iswcr.2018.06.002

Zambrano-Monserrate M.A., Ruano M.R., Sanchez-Alca L., 2020. Indirect effects of COVID-19 on the environment. Science of the Total Environment 728, 138813. doi: 10.1016/j.scitotenv.2020.138813

Table Captions

Table 1. Spanish production and consumption scenarios.

Table 2. Food purchase rates during weeks 11-15 of COVID-19 and the same period of 2019 (kg/cap-week).Data source: MAPA, 2020a.

Table 3. Parameters and alternative scenarios evaluated in the sensitivity analysis.

Figure Captions

Figure 1. Overview of the functionality and system boundaries of the Spanish food system influenced by the COVID-19 pandemic.

Figure 2. Overall FLW during pre-COVID-19 (P1) and COVID-19 scenarios (P2). (a) Total amount of FLW and food consumption; (b) FLW Nutritional assessment; (c) FLW Economic assessment; (d) FLW Greenhouse gas (GHG) assessment.

Figure 3. Assessment of food categories during pre-COVID-19 (P1) and COVID-19 (P2a) scenarios. (a) Total amount of FLW and food consumption; (b) FLW Nutritional assessment; (c) FLW Economic assessment; (d) FLW Greenhouse gas (GHG) assessment.

Figure 4. Holistic FLW assessment during pre-COVID-19 (P1) and COVID-19 (P2) scenarios. (a) Total amount of FLW and food consumption; (b) FLW Nutritional assessment; (c) FLW Economic assessment; (d) FLW Greenhouse gas (GHG) assessment.

Figure 5. Sensitivity analysis for the considered scenarios during the COVID-19 outbreak: (M1) increase of 20% in the generation of FLW in households; (M2) reduction of 20% in the generation of FLW in households; (M3) losses in distribution and sales decrease by 20%.